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Design Practices for Multiple-Seam Room-and-Pillar Mines

By Gregory J. Chekan and Jeffrey M. Listak

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	lb/ft^3	pound per cubic foot
ft	foot	m	meter
kg/m^3	kilogram per cubic meter	pct	percent
kPa	kilopascal	psi	pound per square inch
kPa/m	kilopascal per meter	psi/ft	pound per square inch, per foot

DESIGN PRACTICES FOR MULTIPLE-SEAM ROOM-AND-PILLAR MINES

By Gregory J. Chekan[1] and Jeffrey M. Listak[1]

ABSTRACT

Effective mine planning and design are essential for avoiding ground problems related to multiple-seam interactions. This U.S. Bureau of Mines report presents design practices when room-and-pillar methods are used in the multiple-seam environment and is a review of relevant literature on multiple-seam ground control, mine planning, and mine design. Its objective is to provide mine planners and operators with practical information for designing safe and productive mines.

The key aspects of mine design that control room-and-pillar interactions are examined. These include the sequencing of seams, pillar and entry design, and the layout of workings. Theories that describe stress transfer between multiple seams and the mechanics of interaction are addressed in relation to geology. Commonly used mine designs were further investigated using a boundary-element computer model called MULSIM/NL. The model provided insight into relative stress transfer and distribution that occur between room-and-pillar operations in multiple seams.

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INTRODUCTION

The U.S. Bureau of Mines (USBM), as part of its mission to improve coal conservation and utilization, has been investigating multiple-seam room-and-pillar designs to increase coal recovery and reduce interactions between operations. Interactions between multiple-seam mining operations are a common occurrence, resulting in loss of coal reserves and increased operating costs. Studies estimate that 156 billion tons of coal, representing 68 pct of the minable reserves in the United States, are subject to multiple-seam mining (*1*).[2] In the past, mining sequence was based primarily on availability and economics, with little regard for the effects mining would have on coalbeds above and below the one being mined. This practice of random extraction has strong implications for resource conservation, especially if it continues. For instance, West Virginia, Virginia, and Kentucky have over 90 minable coalbeds, and many of them are classified as "low sulfur" (*1*). Many coal analysts speculate that the new Clean Air Act and compliance coal standards may shift future mining to these reserves. In this region, coalbeds that once were considered minable reserves may not be, owing to interactions from other operations. To avoid higher mining costs and coal prices, future considerations should focus on adopting practices and procedures that prevent and control interactions in multiple seams.

Mine design solutions for improving stability in multiple seams have been sought through empirical and analytical techniques. This research has added considerably to our knowledge of multiple-seam interactions and the geologic and mine design parameters that influence stress transfer. Early empirical and observational studies (*2-5*) identified the main design and geologic factors that contribute to interactions between operations. Stemple (*4*) conducted the first extensive study of multiple-seam mining in the Appalachian coalfields. He recognized that depth, interburden thickness, and interburden physical characteristics are significant factors influencing the transfer of stress. His study showed that strong, massive strata, such as sandstone in the interburden, tend to dampen the effect of seam interaction. Other empirical research was conducted to investigate the relationship between mine design and geology in multiple-seam operations. The USBM, in several case studies (*6-12*), used convergence and stress-measuring instrumentation to quantitatively assess mine design and the transfer and redistribution of stress between operations. Other researchers (*13-24*) used physical models combined with empirical information from case studies to establish statistical relationships between mine design and geology. This research has led to a better understanding of the interaction mechanisms as well as the factors that influence stress transfer.

In some instances, eliminating interactions between operations can be a difficult task because the relationship between mine design and geology is very complex. The use of numerical methods for predicting interactive problems is receiving more research attention for application as a design and planning tool. Researchers have combined case study results with numerical methods in an attempt to develop optimum mining plans for different multiple-seam conditions. USEAM and MSEAM are integrated-design computer programs developed by Virginia Polytechnic Institute and State University (*22-24*). These models were developed for room-and-pillar mining and can be used to predict interactions over or under a remnant pillar or a gob-solid coal boundary. Su (*20*) used finite-element analysis to identify possible causes of ground problems due to multiple-seam interactions. The findings established a good correlation between actual case studies and model results. The USBM has recently developed a boundary-element computer model called MULSIM/NL for calculating stresses and displacements in tabular deposits. The model provides the capability to analyze many coal mining situations and to determine the effects of the three-dimensional stress redistributions caused by mining in either single or multiple seams. The MULSIM/NL model was used in this study to evaluate different design layouts when mining occurs beneath overlying workings and to determine which layouts produce the most favorable loading conditions in the lower mine.

Factors that influence interactions between operations can be classified as either "geologic" or "mine design." The geologic parameters include the depth, interburden thickness and its physical characteristics, coalbed thickness and its physical characteristics, immediate roof and floor stratigraphy, and in situ stress fields. The mine design parameters include seam sequencing, pillar size and strength, entry widths and roof spans, percent extraction, mining height, geometric layout of the workings, support methods, and time delay between mining seams. Optimization of the mine design factors is arguably the primary means for controlling interactions between operations. Of the design factors, three are considered primary and of significant influence in seam interaction. These factors are very closely related and should be weighed equally for effective mine planning: first, the sequence or order in which the seams will be mined, which will determine the type of interaction; second, the design of pillars and entries, which will determine the magnitude of the interaction; third, the geometric layout of the workings, which will determine the location of the interaction.

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[2] Italic numbers in parentheses refer to items in the list of references at the end of this report.

Other parameters fixed by the geologic environment such as depth and interburden thickness will influence interaction magnitude and location and must also be considered in the design process.

In this report, these three primary design factors are discussed in detail. Theories that describe stress transfer between multiple seams and the mechanics of interaction are also reviewed. The geological effects on mine design are also addressed. Finally, practices for effective multiple-seam design together with MULSIM/NL model results are presented. Consequently, this information should assist operators in planning safe and productive multiple-seam mines.

SEAM SEQUENCING

The sequence in which the seams will be mined is notably the first fundamental decision confronting mine planners. In the past, coalbeds were mined in no particular order with regard to controlling interactions and reducing ground control problems. Seam sequencing was based mostly on economics, availability, and ownership. Unfortunately, this practice still continues today in many instances. Research shows there are four possible mining sequences involving multiple seams (*16*, *21*):

1. Seams are mined in a descending order, with mining completed in the upper seams before any mining is initiated in the lower seams (fig. 1).
2. Seams are mined in an ascending order, with mining completed in the lower seams before any mining is initiated in the upper seams (fig. 2).
3. Seams are mined simultaneously, and mine plans may or may not be coordinated with one another (fig. 3).
4. Seams are mined randomly (fig. 4).

The mining sequence will determine the type of interaction the operations will experience. Discussed below are the primary types of interaction and the supporting theories that describe the mechanism of interaction, with special reference to geological considerations.

DESCENDING ORDER OF EXTRACTION

A descending order of extraction is considered the most preferable practice for optimum control over seam interaction. Seams sequenced in this order are impacted by stress transferred from the overlying pillars, gob-solid

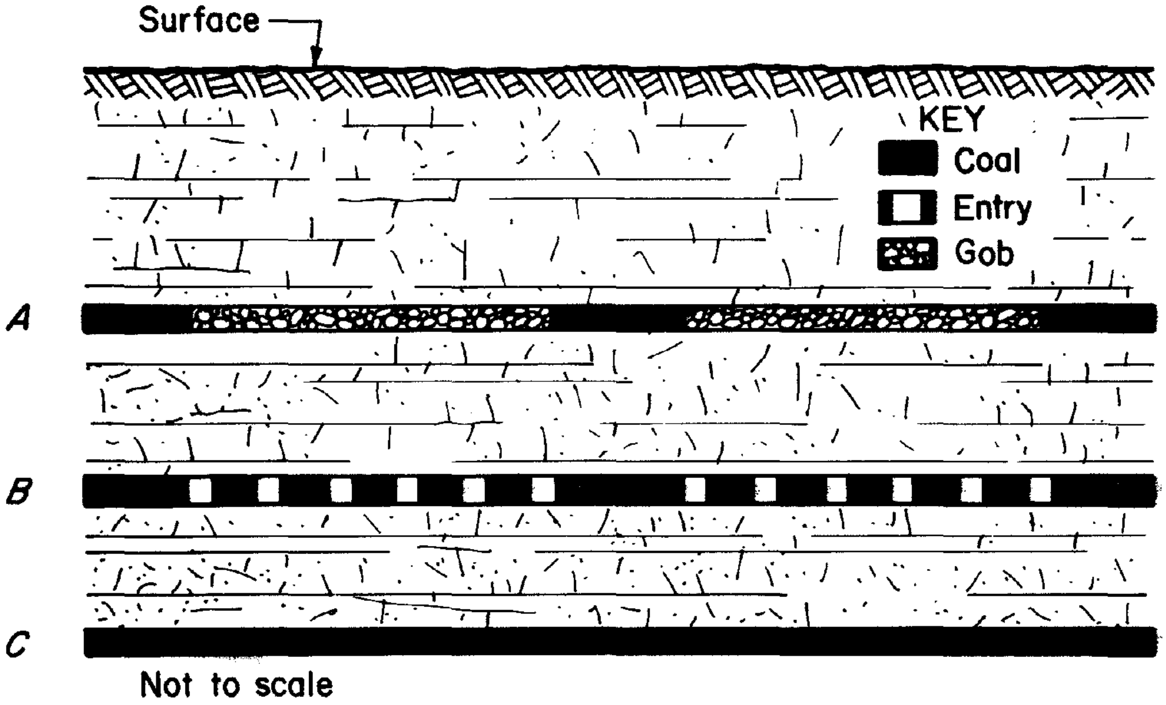

Figure 1.—Descending order of extraction.

boundaries, and barriers. Referred to as "pillar load transfer," this interaction can usually be predicted with reasonable accuracy, and design changes can be implemented to minimize damage to underlying operations. The mechanics of stress transfer between workings has been analyzed extensively through case study documentation and the use of mathematical and photoelastic models. Two theories have been developed to explain interactions due to load transfer from overlying workings: "pressure bulb" theory and "arching" theory (*13*).

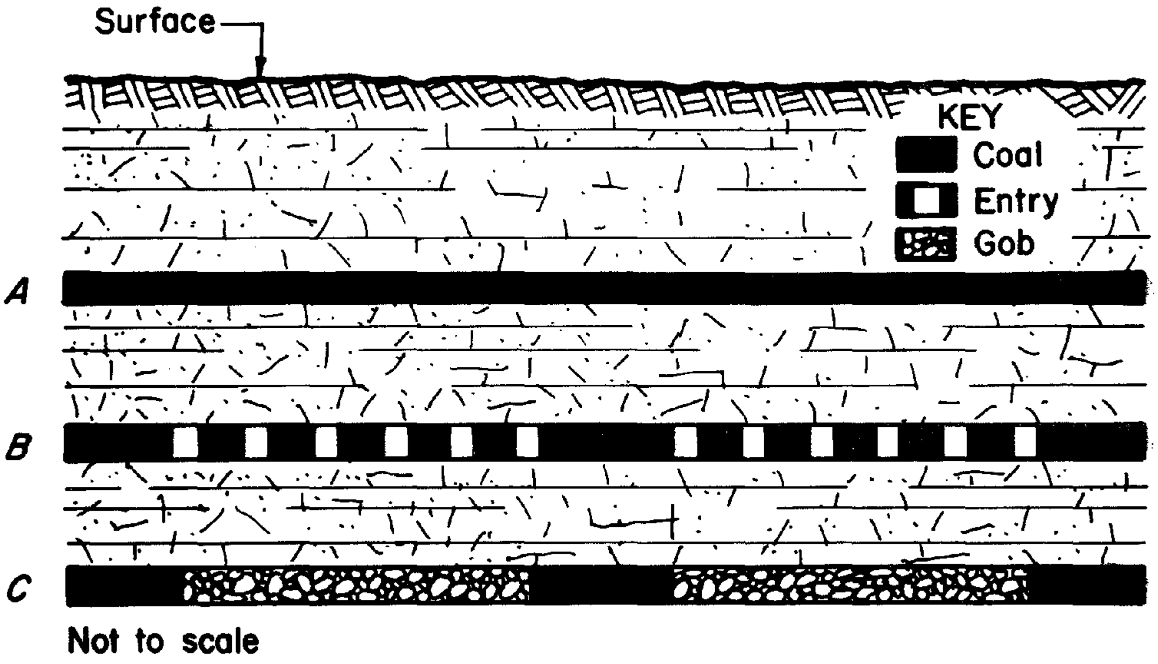

Figure 2.—Ascending order of extraction.

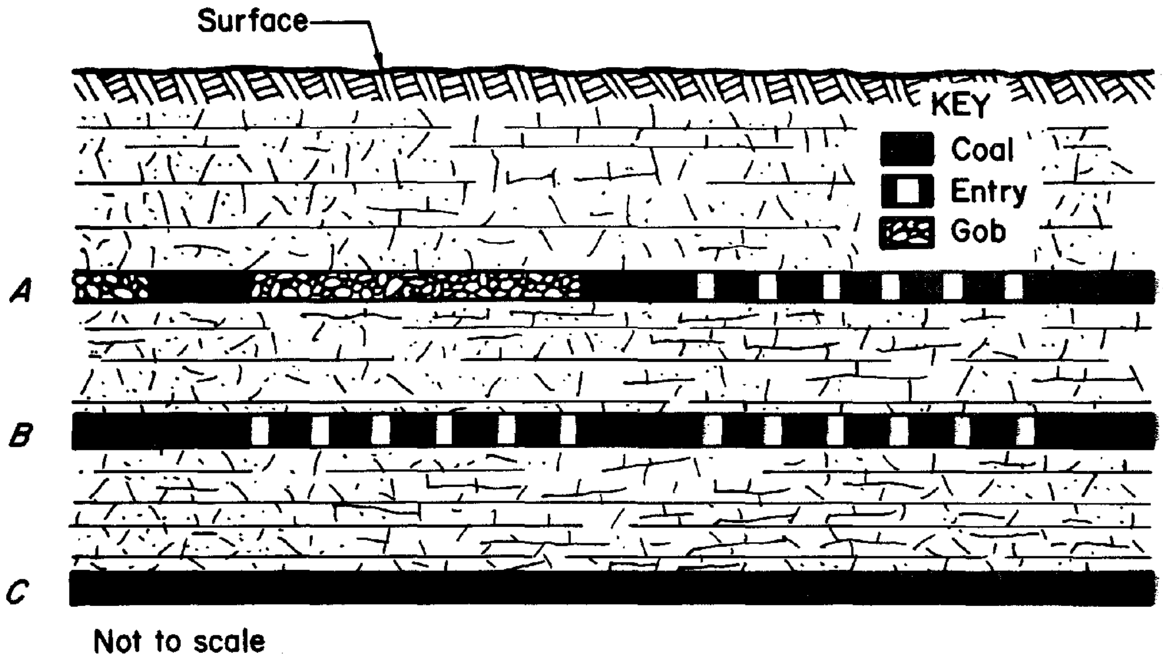

Figure 3.—Simultaneous extraction.

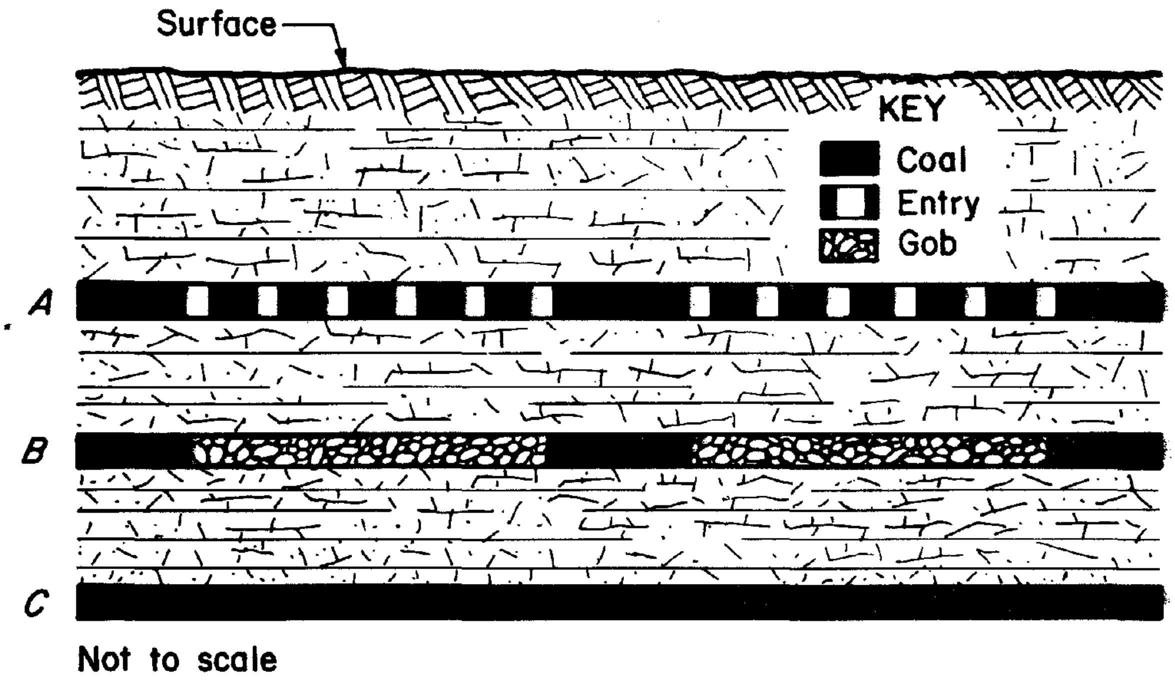

Figure 4.—Random extraction sequence.

Pressure Bulb Theory

In pressure bulb theory, the pillar is assumed to be the major structural element in the transfer of stress. The pressure bulbs are best represented as contour lines of stress as shown in figure 5. In this simplified example developed by Peng (*18*), the pillars are superpositioned and the weight of the vertical load is equally shared by neighboring pillars using the tributary area method. The highest stress occurs near the top and bottom of the pillar, decreasing vertically to zero influence at a distance approximately four times the pillar width. The vertical stress at a given distance below the pillar can be estimated by selecting the appropriate stress multiplication factor based on the pillar width. The stress is then determined by multiplying the factor by the load on the pillar, but because of pillar superpositioning, this analysis should also include additional stress from neighboring pillars. This analysis was developed for perfectly elastic, isotropic, and homogeneous materials.

Haycocks (*13*) used photoelastic models to further investigate the pressure bulb concept under anisotropic conditions representative of various geological conditions. The models simulated stress transfer and dissipation as a function of three major variables: pillar geometry and loading, interburden layering (stratification), and interburden elastic modulus. The effects of depth and pillar geometries were studied using pillars of varying widths loaded with stress profiles ranging from uniform to several types of peak-trough profiles. Interburden stratigraphy was simulated using layered materials of varied thickness and elastic properties. This research showed the following:

1. The distribution of stress on the pillar (stress profile) affects both the distance and the magnitude of the load transfer.
2. Peak-trough stress profiles dissipate stress with less influence than uniform stress profiles.
3. High-modulus layering of the interburden tends to inhibit pressure bulb formation, while low-modulus layering increases the vertical and horizontal distances stress can be transferred from overlying pillars.

Su (*20*) studied pillar load transfer mechanisms with the aid of finite-element modeling. This work led to the following conclusions:

1. Pillar shape influences the transfer of stress: A rectangular pillar will transfer less load, and also, the interactive distance will be less than would be the case for a square pillar of equal load-bearing capacity.
2. The elastic modulus of the coal pillar has a negligible effect on the transfer of load. In situ horizontal stresses also have a negligible effect on the downward transfer of stress.

3. Strata inclination will not distort the pressure bulb contours below a large pillar. However, as pillar size decreases, the contours will be increasingly distorted under the same strata inclination.
4. The absolute values of the pressure bulb contours are proportional to overburden, and interactions will become more severe as depth increases.

The important geologic factors that influence pressure bulb formation include depth and the thickness and stratigraphy of the interburden. The significance of depth in load-transfer mechanics is apparent, as stress increases with depth. The physical characteristics of the interburden are equally important, because the magnitude and distance of load transfer are largely dependent upon the thickness, stratification, and the degree of fracturing. In general, interaction potential between seams decreases as the interburden increases. The relative stiffness of the individual strata that make up the interburden and the ability of these strata to deform under load is a function of their elastic modulus. Strata that have a high elastic modulus, such as sandstone, tend to dampen stress transfer but are more prone to shear failure. Strata that have low elastic modulus, such as shale, transfer load and bend more readily. The number of individual strata that characterize the interburden can also influence the magnitude and distance of stress transfer. A high degree of strata layering transfers load in greater magnitude and distance than does thick monolithic strata. Fracture zones created by adverse in situ conditions weaken the strata and, therefore, will lower the elastic modulus and increase interactive potential (*13-14*).

Haycocks (*13-16*) studied the effects of geology on pressure bulb mechanics and load transfer. He developed three basic geologic relationships based on stable or unstable lower mine conditions. These relationships are shown in the graphs in figures 6 through 8.

First, to study the effects of depth, Haycocks plotted stable and unstable lower mine conditions as a function of overburden above the upper mine versus interburden thickness. This relationship is shown in figure 6. The results are not totally conclusive because of a shortage of data on greater depths and larger interburden intervals, but the graph does demonstrate the effects of depth on lower mine stability. The data indicate that increasing depth becomes a critical factor in lower seam stability as the interburden decreases.

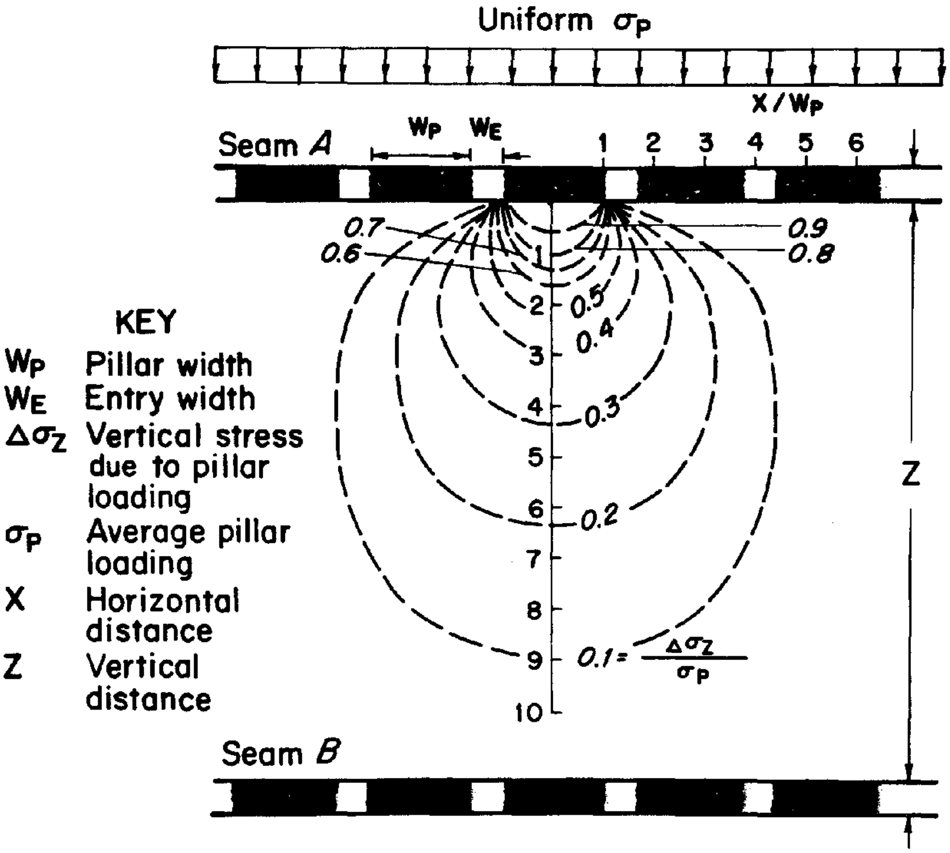

Figure 5.—Simplified model of pressure bulb interaction between pillars. After Peng (*18*).

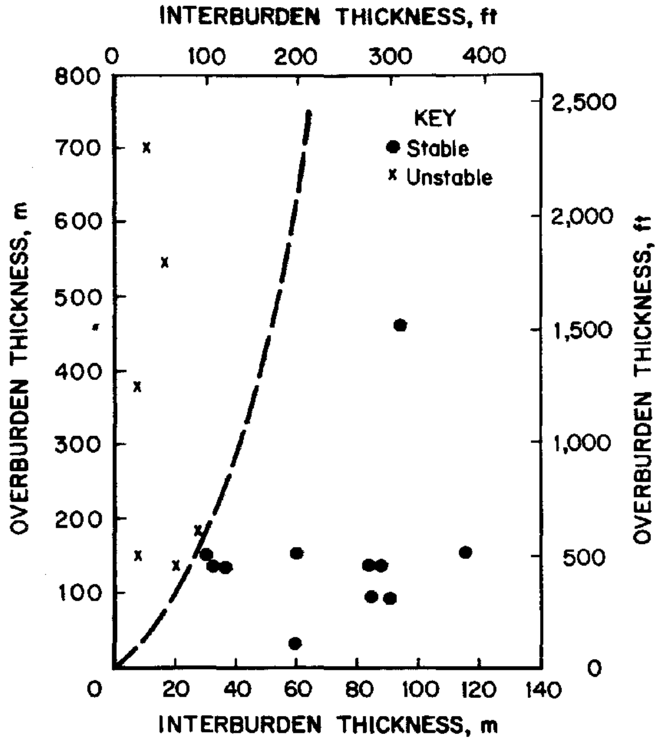

Figure 6.—Interburden versus overburden for stable and unstable lower seam conditions. After Haycocks (*13*).

Second, to study the characteristics of the interburden in the transfer of load, Haycocks plotted stable and unstable mine conditions as a function of interburden thickness versus the percent sandstone in the interburden. The results are shown in figure 7. This relationship agrees with observations made by Stemple (*4*) that sandstone tends to dampen the effects of load transfer from an overlying mine. The graph suggests that interactions may be limited to 33.5 m (110 ft) for entire shale interburdens and to about 13.7 m (45 ft) for solid sandstone. Haycocks notes that this relationship makes no allowance for pillar size in the upper mine, structural condition of the interburden, or the magnitude of damage experienced in the lower mine.

The third relationship Haycocks developed to study the interburden behavior was stratification or strata layering. Figure 8 plots stable or unstable lower mine conditions as a function of interburden thickness versus number of innerbeds in the interburden. The innerbeds are defined as the interfaces between the shale, sandstone, and coal. The graph follows a trend similar to that as in figure 7, indicating that about 15.2 m (50 ft) of interburden is required for solid sandstone whereas a 10-strata interburden would require a separation of approximately 36.6 m (120 ft). The graph suggests that highly layered or stratified interburdens are more likely to transfer load over a larger interval than are massive rock types.

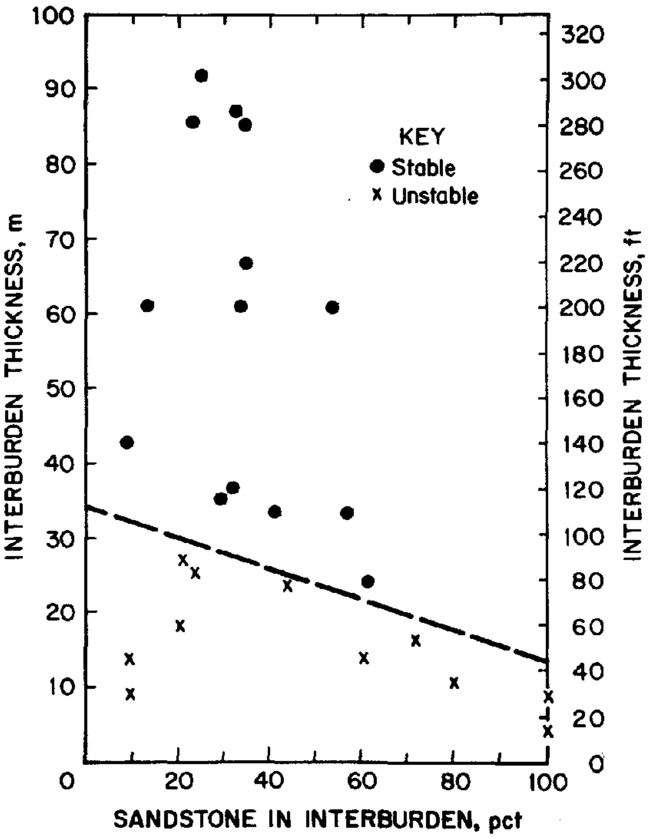

Figure 7.—Percent sandstone in interburden versus interburden thickness for stable and unstable lower seam conditions. After Haycocks (*13*).

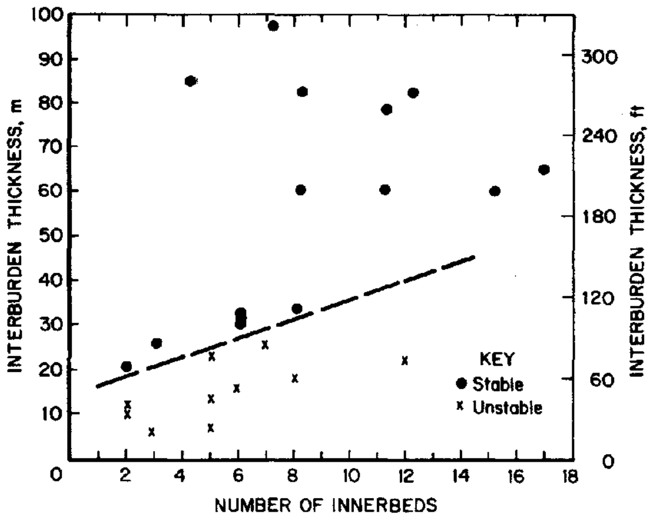

Figure 8.—Number of innerbeds versus interburden thickness for stable and unstable lower seam conditions. After Haycocks (*13*).

Haycocks concluded that the pressure bulb theory is useful in analyzing pillar load transfer when a "passive" interaction occurs. This condition can apply when pillars in the lower seam are sufficiently large and are designed to accept the entire transferred load to which they are subjected. However, in the case in which the lower seam loading is altered so that the transferred load from the overlying mine is not completely supported by the underlying pillars, the pressure bulb concept is not applicable. In actual mine conditions, this can occur when the panel pillars yield and redistribute the transferred load to nearby abutment and barrier pillars. Haycocks refers to this change in lower seam loading as a "reactive" interaction, which is best analyzed and described through the use of arching principles.

Arching Theory

Theories of arching have dominated rock mechanics research for decades, and the concept was first introduced into mining literature as early as 1885 (*13*). Arching theory assumes the mine opening is the major factor in the transfer of stress. Stress transfer is the result of the pressure arch that can form around a mine opening upon excavation. Dinsdale (*25*) presented the first significant work on this theory. He showed that the arch is usually elliptical in shape and that it exists both above and below the mine opening. As shown in figure 9, it consists of "intradosal ground" (tensile zone) enveloped by the "extradosal ground" (compressive zone). Large abutment pillars or barriers support the extradosal ground, which is known as the abutment pressure.

Dinsdale (*25*) refers to the formation of "minor" and "major" pressure arches in underground excavations. Minor pressure arches can form independently from pillar to pillar, as shown in figure 10, provided the strength of the pillar, in situ, exceeds that of the abutment pressure. If the pillars yield or fail because of excessive pressure, their load is transferred to neighboring barriers or abutment pillars and a major pressure arch will form as shown in figure 11. The magnitude of the abutment pressure and the shape and height of the arch are dependent upon the depth, the opening width, and the physical nature of the strata. Dinsdale noted that a relationship exists between

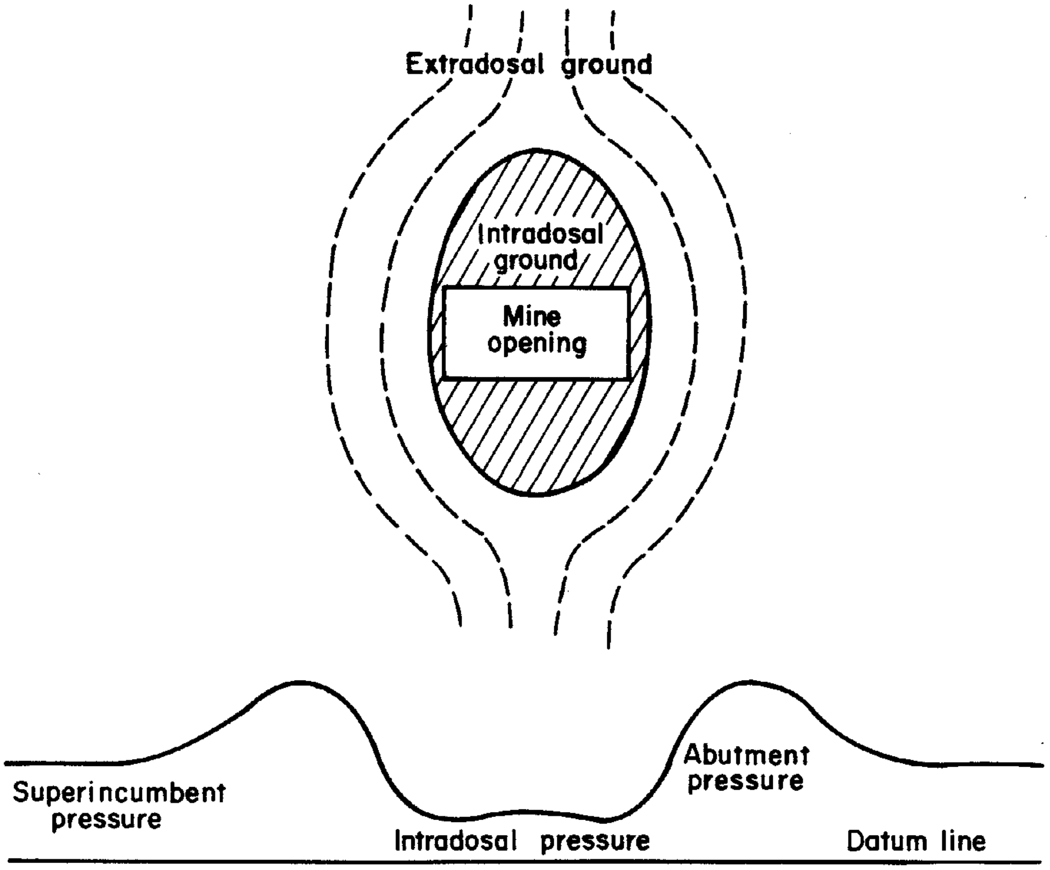

Figure 9.—Pressure arch formation around mine opening. After Dinsdale (25)

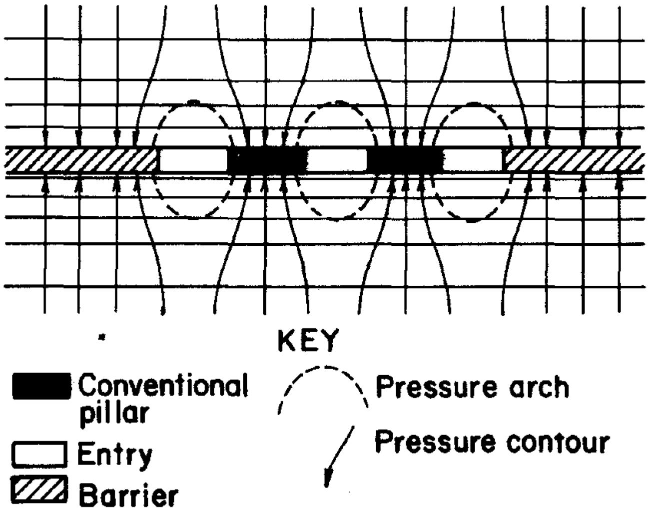

Figure 10.—Minor pressure arches forming from pillar to pillar.

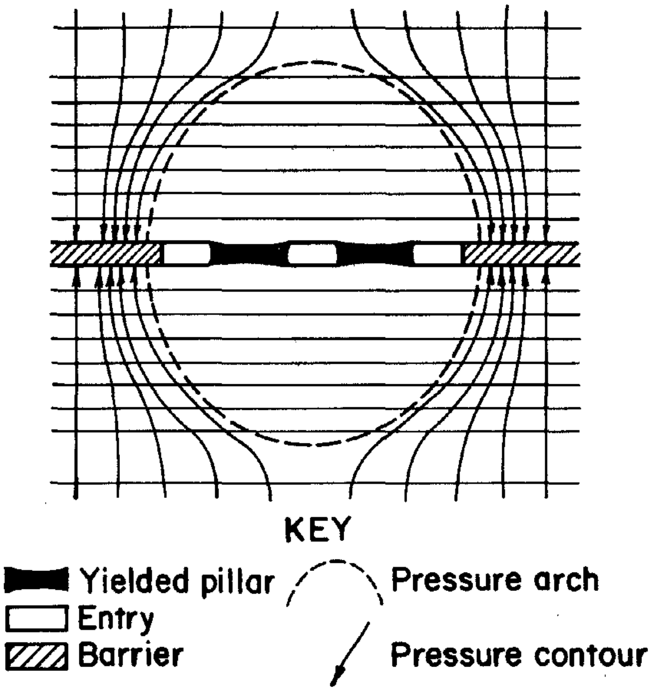

Figure 11.—Major pressure arches forming because of pillar yielding.

panel width and depth. He theorized that if the mine opening became too wide, the arch would no longer span the opening and the extradosal ground would fail, leading to subsidence on the surface.

Haycocks (*13-14*) studied the effects of minor and major arching through the use of finite-element and stress-vector plots. His research led to an improved understanding of arching mechanisms under multiple-seam conditions. The models 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 wide openings, such as those created by full-extraction room-and-pillar or longwall mining, major pressure arch formation is likely to create zones of excessive pressure in seams above or below. Minor pressure arches are more applicable in describing interactions between narrow entries in close proximity, whereas major pressure arches describe the larger interactive distances associated with wide, deep openings.

In empirical studies, researchers have attempted to describe the height and width of the major pressure arch in actual mining conditions. The National Coal Board, referenced in Holland (*26*), estimated the width of the arch as 15 pct of the seam depth plus 18.3 m (60 ft). Holland (*27*) theorized that the arch was elliptical in shape and the maximum height was approximately twice its width. Peng (*18*) estimated the height of the arch to be 30 to 50 times the seam thickness. Haycocks (*15*) stated that caving and arching are closely related strata movements and that it is the caving and sagging of the gob that create the major pressure arch and ultimately its influence on overlying and underlying seams. He gives several formulas for determining the width and height of the arch (*15*).

Haycocks (*13, 15*) also found that the arches can have various shapes; these shapes range from a dome to a modified parabolic shape, depending on geology. The primary considerations are rock type, the degree of bedding in the strata, and the presence of natural fractures and joints. In strong, monolithic strata with little jointing, the arch formation may be low or the strata may bridge for narrow panel widths. In weak, highly bedded, and jointed strata, the arch will have difficulty supporting itself regardless of panel width. In actual mining practices, most geologic conditions fall somewhere in between, as strata are composed of innerbedded units of shale and sandstone of varying thicknesses and strengths. The height and shape of the arch can vary greatly under these conditions and should be studied on a case-by-case basis with consideration for width-to-depth ratios.

Studies show that arching stresses can either hinder or benefit mining in overlying and underlying seams (*2-4, 6, 13-15, 18*). The extradosal ground forms the zone of high compressive stress that can cause ground control problems related to the roof, floor, and pillars (*2-4, 13-15*). As shown in figure 12 from Stemple (*4*), this zone of high stress can create ground problems in seams both above and below. Other studies show that arching may be beneficial to mining. The intradosal ground or tension zone is actually a destressed region in relation to the surrounding strata, and conceivably the stress encountered in this zone may actually be less than that created by the cover load (*12-20*).

ASCENDING ORDER OF EXTRACTION

Coalbeds that are mined in an ascending order can experience interactions resulting from subsidence when full-extraction room-and-pillar mining is used in the lower mine. This sequence of extraction causes the superincumbent strata to fail and is characterized by different zones of movement. The extent of each zone is a function of the subsidence process and the geologic composition of the overlying strata. Subsidence can produce two types of ground failure in overlying coalbeds. In the first type, the strata bend in response to subsidence, causing a trough to form. The second type, known as interseam shearing, occurs when subsidence produces highly inclined shear or shear-tensile failures displacing the coalbed to lower elevations (*2*, *13*). Design and geologic factors will be further addressed as they relate to these two types of subsidence failure.

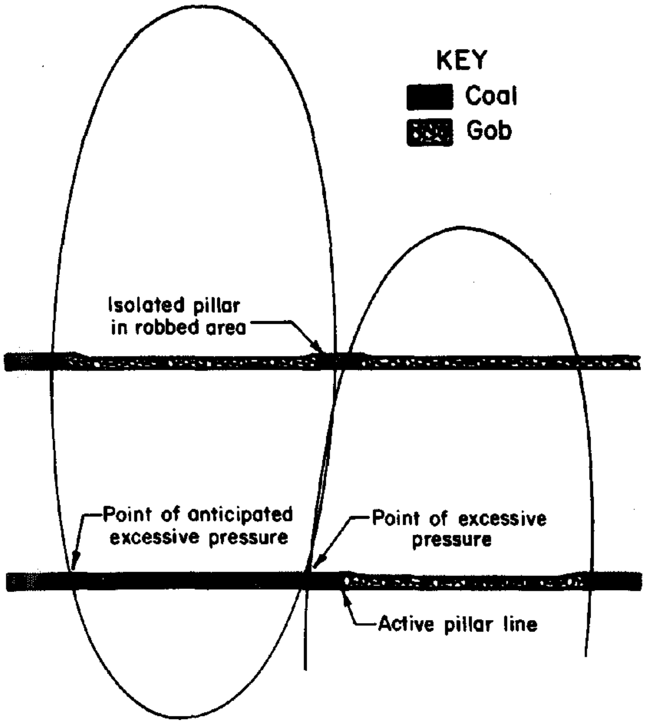

Figure 12.—Major pressure arch formation in multiple seams. After Stemple (*4*).

Subsidence Trough

Full-extraction room-and-pillar mining and longwall mining usually lead to uniform and predictable subsidence, as documented by surface measurements (*28-31*). A surface profile for supercritical and critical panels consists of a subsidence trough, the outer limits defined by the angle of draw, and an area of maximum subsidence in the center, as shown in figure 13. The subsidence trough is identified by distinct zones of tension and compression. An inflection point, typically located directly superjacent to the ribline, distinguishes the two zones on the surface: the tension zone over the solid coal and the compression zone over the mined-out panel. Recent subsidence measurements over longwall panels in the Appalachian Coalfield indicate that the inflection point actually develops over the mined-out panel (*30*). For subsurface subsidence, this implies that the tension zone would be located over the gob. Field studies of room-and-pillar operations affected by subsidence support this assumption because the most severe roof conditions have been shown to occur over the lower mine gob when development crosses the ribline from the solid coal to the gob (*9*, *32-34*). The factors that influence the exact location of the tension zone require further study and are likely related to caving behavior and bending of the individual beds.

The magnitude of roof problems in the subsidence trough is dependent upon the extent of the tension zone. This zone is associated with the formation of fractures and opening of joints, which lead to poor roof conditions. Increased flows of methane and water are frequently encountered as fractures provide pathways for their migration (*2-4*, *10*, *18-20*). The compression zone has been observed to cause only minor ground problems related to

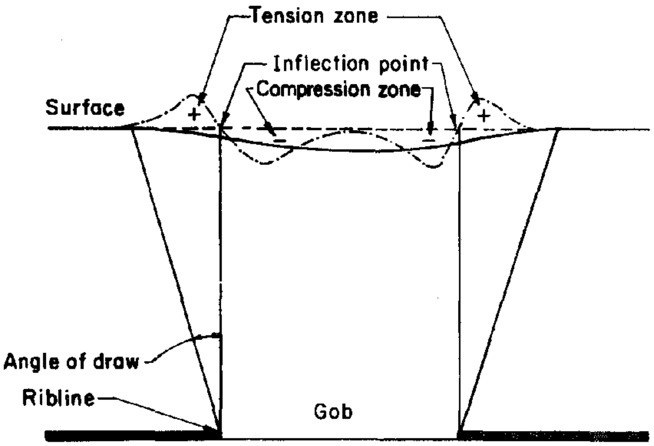

Figure 13.—Formation of subsidence trough above mined-out panel.

pillar instability, mostly rib spalling (*6, 9, 13, 16, 19*). Inside the subsidence trough lies the zone of maximum subsidence. When full-extraction mining is used, the strata in this zone subside uniformly, which usually results in improved ground conditions.

The amount of damage subsidence can cause to an overlying coalbed is largely dependent upon five factors (*9, 13, 18-19, 33*): (1) the lower seam mining height, (2) the distance between the coalbeds, or interburden thickness, (3) the angle of draw and the caving angle, (4) time, or the age of the workings, and (5) the geologic characteristics of the interburden (*6, 8-9, 12*). Some studies have documented the effects of subsidence on overlying operations (*2, 4, 6, 9, 13, 19*), and only recently has meaningful field measurement of subsurface movement and strata response to subsidence been undertaken in the United States. However, the magnitude and extent of subsidence damage that coalbeds will experience can be assessed qualitatively using the factors listed above and other relevant information.

The first two factors are related and can be used to determine if overlying coalbeds are influenced by caving, fracturing, or sagging, as shown in figure 14. Each zone can be identified by the failure characteristics of the strata, but the regions are not well defined and may vary in vertical extent. Studies involving full-extraction mining show that coalbeds lying within 20 times the lower seam mining height are most susceptible to subsidence-related damage, as they usually fall within the caving zone (*13, 33, 35*). The caving zone can actually be further divided into various regions of strata failure. The zone of complete caving is a region of severely disturbed strata, and the failure is best described as highly fragmented to platy blocks. Studies indicate that this zone is generally three to six times the mining height, depending on the expansion ratio or bulking factor of the rock (*35*). Coalbeds located within this distance may not be minable. The region from 6 to 12 times the lower seam mining height is an area of partial caving. The completely caved rock below offers some support to the overlying beds, yet failure may still be severe enough to cause the strata to fracture into large blocks (*35*). The strata within the subsidence trough may have a significant degree of bending, leading to intense fracturing, or may be displaced as a result of shear stresses (*13, 21*). Ground conditions in the zone of maximum subsidence may even be less than ideal, depending on the caving characteristics of the strata. Severe to moderate roof control problems should be anticipated during development in the partial caving zone. A distance of 12 to 20 times the lower seam mining height defines the upper limits of the caving zone. In this region, strata may separate along bedding planes, and fractures or joints may open, but the individual beds tend to remain intact. Also, displacements due to shearing are less likely to occur. These conditions become less intense progressively higher in the zone. Ground control problems may be severe in the subsidence trough, but ground conditions should improve in the zone of maximum subsidence. Coalbeds lying within ranges between 20 and 50 times the lower seam mining height usually fall in the zone of fracturing (*13, 18, 34, 36*). The bending of the strata is not as abrupt, and although fracture zones may

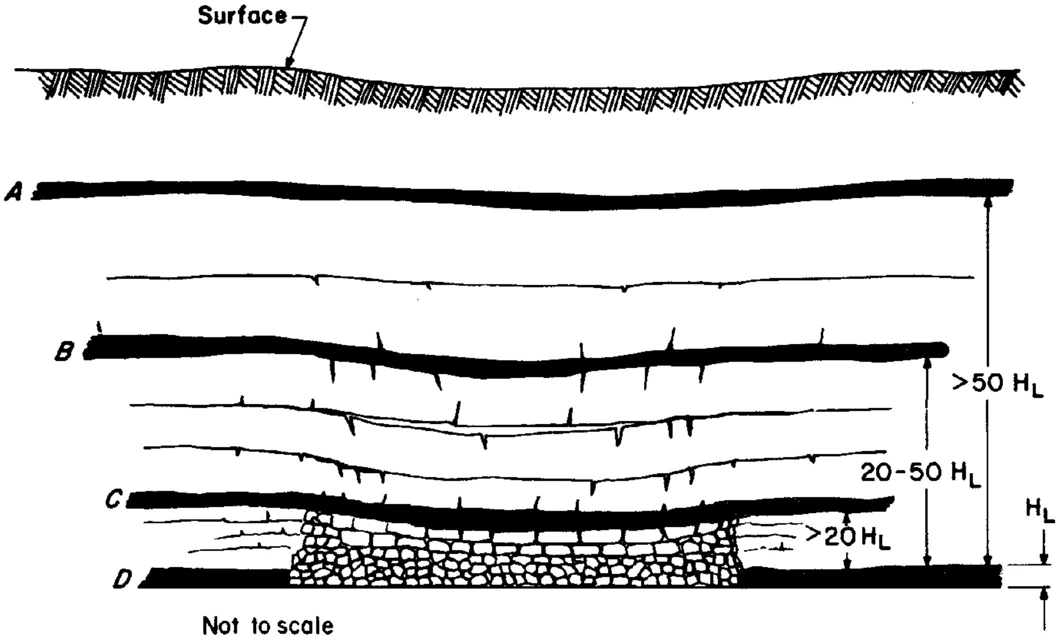

Figure 14.—Failure of overburden due to subsidence. H_L = lower seam mining height.

exist, they are less pronounced. Ground control problems will be encountered mainly in the subsidence trough, but generally the coalbed should be less difficult to mine. Damage to overlying coalbeds is minimal at distances exceeding 50 times the lower seam mining height because this is the zone of sagging (*13, 18, 33, 35*). Bending is gradual and is distributed over a larger horizontal distance. The strata throughout the subsided area tend to sag uniformly, and mining should encounter virtually no problems.

The third factor, the angle of draw and the caving angle, can be used to roughly estimate the extent of the subsidence trough within the overlying coalbed. The angle of draw defines the outer limit of subsidence and projects out over the solid coal from the ribline as shown in figure 15. Accurate calculation of the angle of draw has been the focus of longwall subsidence research over the last decade. Most studies on the subject conclude that the appropriate angle for eastern U.S. applications ranges between 15° and 25° for flat-lying coalbeds (*28-31*). The caving angle is not explicitly defined in rock mechanics literature, but observers have referred to it as a "positive angle of draw." This implies that it projects out over the gob from the ribline as shown in figure 15.

Studies of surface subsidence and caving behavior may provide some insight into a clear definition and value of the caving angle. King (*36*) used this angle to estimate the side abutment load for longwall pillars. He assumed that this angle defined a failure plane where the weight of the overburden was evenly distributed between the pillars and the gob. King referred to this angle as the "shear angle" and he estimated its value at 25°. Choi (*37*) modified King's method and presented data indicating that the angle for the Pittsburgh Coalbed was 18°. Mark (*38*) took a similar approach in developing a method for determining longwall pillar loads; he referred to the angle as the "abutment angle." He estimated it at approximately 10° to 23° based on back-calculation from pillar stress measurements conducted in three coalbeds. Singh (*39*) referred to the angle as the "angle of fracture" and used physical models to study its behavior and formation in different mediums. He noted the shear-tensile failure in its development and estimated its range from 5° to 15°. Peng (*18, 35*) implicitly called it a caving angle and, based on observations, estimated its range from 15° to 35° with an average of 25° applicable for most conditions. Different geological conditions may be the determining factor for this broad range of values. Obviously, caving mechanics warrants further study to better delineate appropriate caving angles based on stratigraphy.

From a purely geometric perspective, the angle of draw and the caving angle can be used to determine the extent Ground control of the subsidence trough. Figure 15 illustrates a simplified example of this zone's influence using an angle of draw of 25° and a caving angle of 25°. Strata bending progresses gradually, beginning at the angle of draw, and becomes more pronounced superjacent to the ribline. On the other side of this boundary, fracturing and poor roof conditions due to tensile stress are most apparent. Farther on, the inflection point denotes the end of the tension zone and the start of the compression zone. Beyond this, the strata begin to settle uniformly in the zone of maximum subsidence. The closer the overlying coalbed is to the mined-out panel, the less the horizontal extent of the subsidence trough, but the greater the bending in the strata. As interburden increases, so does the horizontal extent of the subsidence trough, but the bending is less severe and it is distributed over a larger distance. Since the degree of fracturing is directly related to bending, the potential for ground problems decreases as interburden increases.

The fourth factor, the effects of time, should also be taken into account when assessing potential interactive problems due to subsidence. Sufficient time delay in mining seams damaged by subsidence is an important factor because the delay allows for caving and compaction of the gob, which lessens damage to overlying entries upon development. Studies involving subsidence measurements over longwall panels have shown that additional surface subsidence may occur over a mined-out panel as an adjacent panel is being mined (*30-31*); King (*40*) referred to this as a "triggered subsidence." This concept can also be applied to multiple seams when mining occurs above a mined-out panel. Redistribution of stress may cause additional subsidence and ground problems in the upper mine.

Zhou (*21*) classified subsidence interactions into three possible categories based on a time factor: (1) Lower seam mining is currently active with upper seam mining, an active condition; (2) mining in the lower seam is complete but the ground is still in the process of settling, both an active and passive condition; and (3) subsidence is complete and the ground has settled, reaching a new state of equilibrium, a passive condition. A method to quantify this time variable in terms of upper seam stability was attempted through a rating method, which also considered other factors such as interburden thickness and percent sandstone, lower seam mining height, and percent extraction. This method was empirically developed from room-and-pillar and longwall workings for categories 2 and 3 above. Interestingly, little if any field documentation is available for active conditions, category 1. Since the effects of subsidence on overlying active mines, in terms of time, are almost immediate, the active condition has the potential of being the most damaging of the three.

The fifth factor, stratigraphy, can influence the other four factors that determine subsidence damage (*13, 21*). Factors of primary importance are the number and

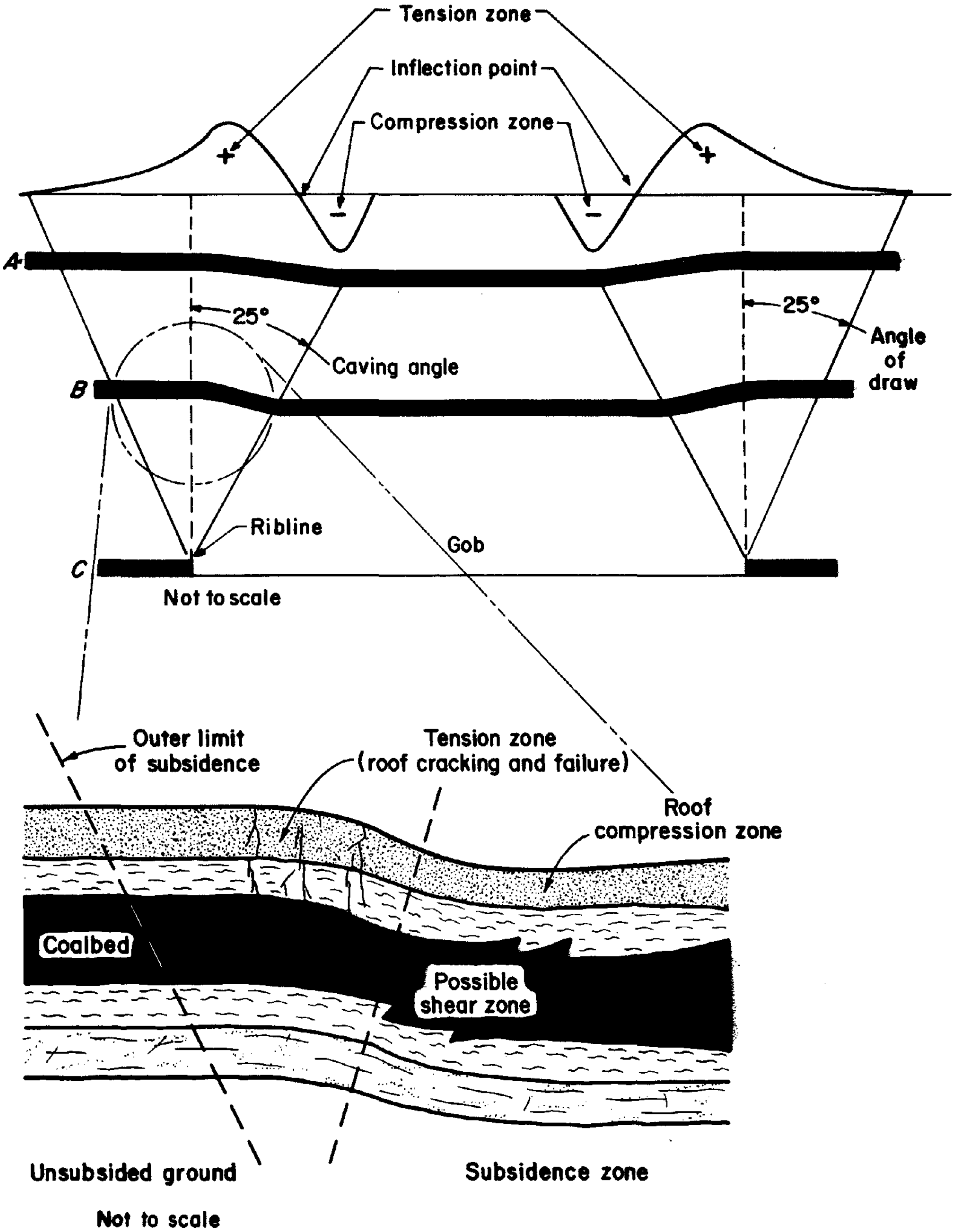

Figure 15.—Angle of draw in subsidence prediction. Adapted from Haycocks (*16*).

thickness of the individual beds, the relative stiffness of each stratum, the presence of natural fractures or joint systems, and the cohesion between individual beds. Strata response to bending stress differs depending on the properties of the individual beds that form the entire rock mass. The elastic modulus indicates the stiffness of the rock and its ability to deform. In general, shales have a low elastic modulus, and the beds tend to bend and fracture as an entire unit. Sandstones, with a high elastic modulus, are stiffer formations, and the beds tend to shear and displace. The degree of fracturing or natural jointing of the rock also affects its elastic modulus. Fractures lower the strength and the elastic modulus of the rock. Shales usually have more pronounced fracture systems than the more competent sandstones. Cohesion between the individual beds is also an important consideration for it determines if slippage will occur along the bed interfaces, leading to differential movement and bed separation. A significant number of field studies that detail subsidence characteristics in relation to stratigraphy are forthcoming. Such information will improve damage assessment and help in the formation of mining plans to control interactive problems.

Interseam Shearing

This type of interaction can be very damaging to overlying coalbeds because the strata tend to shear and displace as shown in figure 16. This interaction is more likely to occur when both operations are "active" as described by Zhou (*21*). Field studies have documented this type of failure in room-and-pillar operations. Holland observed that in 38 cases of coalbeds affected by subsidence, about 75 pct had a shear-tensile failure (*2-3*). The greatest potential for shearing occurs in coalbeds lying within 12 times the lower seam mining height or in the partial caving zone (*13*). Haycocks reports that shearing is most likely to occur when interburden is less than 10 m (33 ft), but opening width is also critical. Under severe circumstances shearing may extend through to the surface, displacing large areas of coal (*15*).

Stratigraphy is the most important factor in defining the shear potential of the overlying strata. Studies indicate that a physical property of the strata, namely high elastic modulus, is a prominent feature in shear failure (*13*). Therefore, shearing occurs more frequently in sandstones and similar rock types. Stemple (*4*) noted in his study that the shear angle differs depending on the strata type. The angle of failure has been observed to range from nearly vertical for thick sandstone units to 25° for highly bedded strata, and it appears to coincide with the shear or caving angle discussed previously. This tendency for hard strata to resist bending, and then shear, can also be observed in retreat sections, as competent sandstone roofs may remain intact, or "hang up," before abruptly fracturing at the pillar line. Fractures and joint systems inherent to the strata are also critical factors in interseam shearing. Vertical joints have few cohesive properties and therefore provide planes for shear failure. Faults, which are offsets in the coalbed, may also complicate or contribute to shear failure.

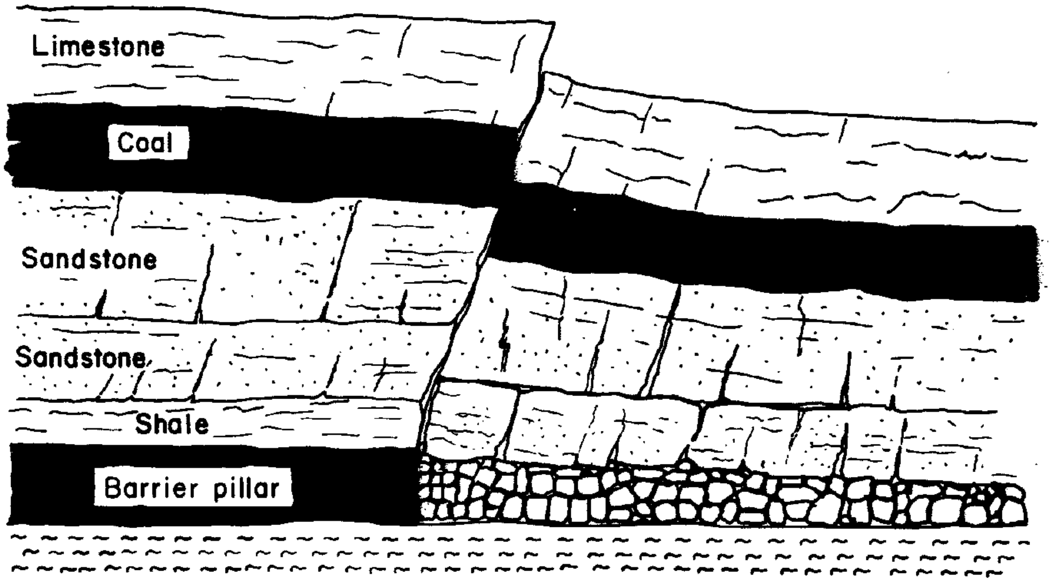

Figure 16.—Interseam shearing. Adapted from Holland (*2*).

SIMULTANEOUS AND RANDOM ORDERS OF EXTRACTION

Extraction sequences that are simultaneous or random can lead to various interactive problems related to Zhou's (*21*) first two categories described previously. Simultaneous mining implies that both mines will be worked at the same time in the same area so that "active" interactions may occur between the two operations. Probably the most important factor in simultaneous extraction of two seams is coordination. Pillar development and retreat mining in both mines should be planned accordingly to control interactive problems. In most cases, a descending order of extraction is preferable practice to avoid subsidence damage. There are two basic approaches to the layout of room-and-pillar sections for simultaneous extraction of seams: offset and superpositioned. The benefits and disadvantages of both design arrangements are discussed in detail later in the report in the section "Layout of Workings." Simultaneous extraction can also lead to production and scheduling problems. For instance, downtime at the working face in one mine may cause delays in the other mine until these problems are corrected. Since simultaneous mining is such an economically risky endeavor, long-term mine planning and adhering to rigid schedules for pillar development and extraction are essential.

Random seam sequences should be avoided because they only serve to complicate the design process. Unfortunately, in the eastern coalfields random seam mining occurs quite frequently. Operators in many instances encounter old or abandoned workings in overlying or underlying seams. In many instances, interactions are inevitable, but improvements in ground stability can usually be achieved by thorough, careful planning and fundamental ground control methods. An operator should first assess the interactive potential of these workings, then adjust mine plans accordingly. This can include changing pillar design, changing panel orientation and size, or increasing support. Primary factors to consider include the depth, the interburden thickness, and the geometry of the workings. Studies showed that when seams are mined randomly, ground problems are usually encountered during mining over or under gob-solid coal boundaries or large, isolated barrier pillars. Design strategies for laying out workings to avoid problems in these situations are discussed in detail later in the report.

PILLAR LOAD TRANSFER INTERACTION

The transfer of load in multiple seams becomes more critical when a descending or simultaneous extraction sequence is practiced. The transfer of load from overlying to underlying pillars is the major concern, but since the high-stress zones also exist above the pillar, an overlying operation can also be affected. As previously discussed, this interaction mechanism is known as pillar load transfer. Both the pillar and entries can be affected by this load transfer, but if pillars can be properly designed to redistribute or support the transferred stress, the entries may also benefit. Therefore, design criteria will focus mainly on pillar design in the lower mine. There are two fundamental but opposing methodologies for controlling interactions resulting from load transfer. One approach recommends that extraction be increased in lower operations and that small pillars be designed to transfer their load to larger abutment or barrier pillars. The opposite approach recommends that extraction be decreased in lower operations and that lower pillars be designed to accept all the load to which they are subjected.

Safe and effective pillar designs for multiple-seam room-and-pillar developments still remain a pressing problem facing researchers and operators alike. Determining the proper size of pillars to withstand additional loads resulting from multiple-seam mining is a trial-and-error procedure, based mainly on experience. Pillar design for single-seam situations has made considerable progress in recent years because of significant and noteworthy research (*41-48*). It is beyond the scope of this section to detail the findings of this work; however, this research may provide some insight into pillar-loading behavior and design under multiple-seam conditions. There are two basic approaches to pillar design. The yield pillar approach uses small pillars, which are designed to fail in a controlled manner and transfer their load to nearby abutment pillars by means of a pressure arch. The conventional approach uses large pillars, which are designed to carry the entire load to which they are subjected. The principal design concepts and their implications for multiple-seam interaction are discussed in the following sections.

YIELD PILLAR APPROACH

When pillars are designed to transfer their load, a "reactive interaction" results, which is best analyzed through arching concepts (*13*). Holland (*27*) was the first to propose the concept of yielding pillars for ground control purposes. His work focused on yield pillar applications for room-and-pillar developments and the formation of a pressure arch for improved pillar and entry stability. He specifies three fundamental assumptions for yield pillar design. First, the pillars must deform so the main roof bridges, transferring load and creating a pressure arch. Second, there must be a solid abutment nearby of sufficient load-bearing capacity to accept this transferred load. Third, the pillar must fail in a controlled manner but maintain enough strength to support the weight of the rock within the pressure arch. Figure 11 illustrates these three assumptions. Holland proposes a hypothetical panel layout using yield pillars in single-seam mining, and he concludes that more research is necessary for successful application. Mark (*38*) presents some of the most recent advances in yield pillar theory, design, and application for longwall gate roads. He gives some preliminary formulas for determining the width of yield pillars, but also concludes that design is based mostly on experimentation and that no real quantitative guidelines exist.

Although the concept is not yet a reality, yielding pillars may provide some unique solutions in designing stable and profitable multiple-seam developments in the future. In a yield pillar panel, the pillars are designed to yield in a controlled manner and transfer their load to larger abutments or barrier pillars. Applying this concept to multiple-seam operations and practicing pillar columnization, in theory, a larger arch would form and a destressed zone would be created between the upper and lower panel developments. Load transfer would then take place between the barrier pillars, which are designed with large safety factors, rather than the individual support pillars within the panel. Figure 17 illustrates the theoretical distribution of stress in a multiple-seam yield pillar system for workings in close proximity, or less than 33.5 m (110 ft) (*10*).

Haycocks (*13*) provides some insight into the effects of arching in multiple-seam situations and how arching may affect the stability of the lower seam workings. The findings showed that the interaction mechanism responsible for improving stability may closely resemble the concept of yield pillars. This mechanism is illustrated in figure 18, which plots ratios of upper versus lower seam extraction for stable and unstable workings. The graph shows that as upper mine extraction increased, the stability of the lower seam was adversely affected. One would suspect that larger pillars in the lower seam would be more stable than smaller ones, but the data suggest otherwise. Since the number of stable cases increases as extraction increases, it appears that smaller pillars in the lower seam would be more stable than larger ones. Pillar sizes are not given in the data, but since extraction is a reflection of relative pillar size, one can conclude that higher extraction would result in smaller pillars, similar to yield pillars.

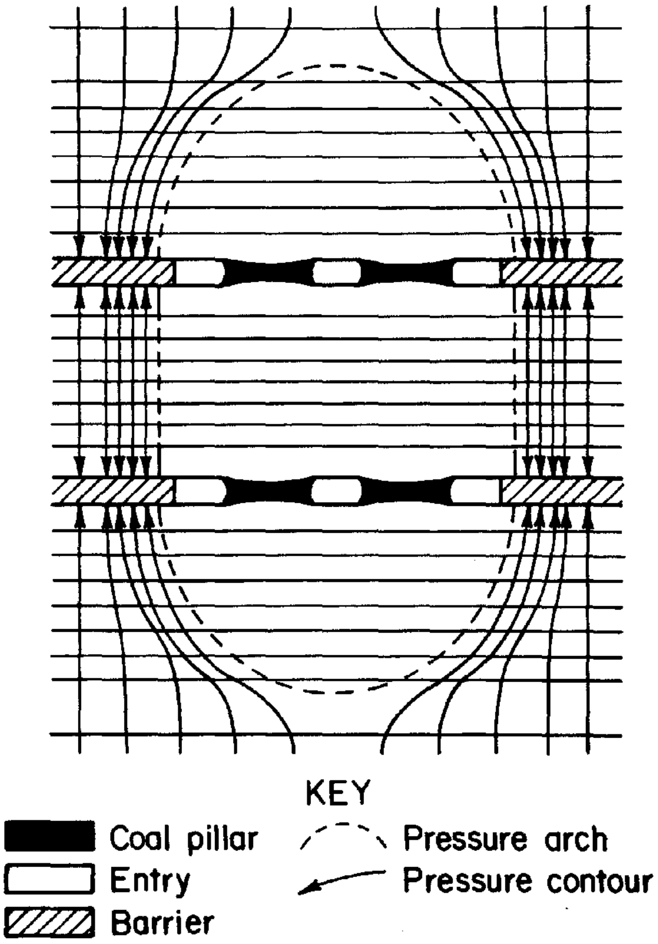

Figure 17.—Conceptualized behavior of yielding pillars for multiple-seam developments.

Haycocks concludes that smaller pillars, which tend to yield, creating major arch formation, best explain why higher extraction mines have more stable workings than low-extraction mines with larger pillars. Figure 19 shows this trend to be consistent over the range of interburden thickness examined. The separation between stable and unstable conditions was a ratio of upper seam to lower seam extraction equal to 1. Haycocks suggests that the data, although not conclusive, indicate that decreasing pillar size in descending extraction orders may be more beneficial to lower mine stability than previously thought.

Although this approach seems to be the optimum method for controlling interactions, designing a pillar system that utilizes all yielding pillars is a complex problem. One major reason is that the postyield and stress-transfer mechanics of yield pillar systems are not yet fully understood.

Until significant advances are made in the field under single-seam conditions, this concept will have limited applications for multiple seams. A more realistic approach utilizes conventional pillars that are designed to accept the transferred load from overlying workings.

CONVENTIONAL APPROACH

When lower mine pillars are designed to accept the transferred load from overlying workings, a "passive" interaction results, which is best analyzed using the pressure bulb concept (*13*). The conventional approach to pillar design uses large pillars, which are of sufficient size to withstand the development and transferred loads to which they are subjected. Proven methods for designing conventional pillars for single-seam situations have been presented by several researchers (*41-48*). Bieniawski is most noted for developing a method for designing pillars specifically for U.S. conditions (*41-43*). Other researchers (*44-48*) have made similar contributions to pillar design based on both theoretical and empirical results. It is beyond the scope of this section to detail the findings of this research. To maintain a multiple-seam perspective, this section will examine the basic loading characteristics or profiles for conventional pillars and pillar design strategies for controlling interaction problems.

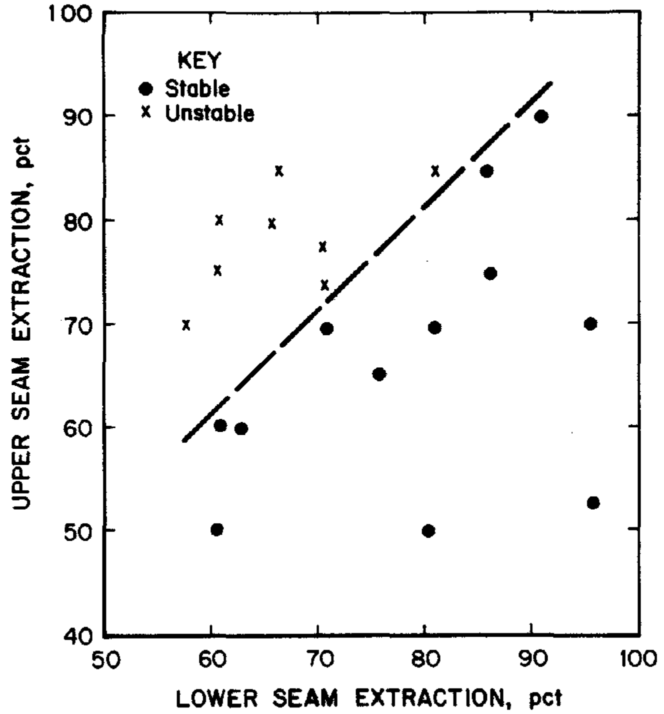

Figure 18.—Percent lower seam extraction versus percent upper seam extraction for stable and unstable lower seam conditions. After Haycocks (*13*).

Hypotheses concerning pillar loading (*47*) have divided the pillar into two distinct zones: the core and the yield zone. The core is the zone in the pillar center, which behaves elastically and is confined by the yield zone surrounding it. Figure 20 shows three basic loading profiles for development or support pillars. Figure 20*A* shows a peak-trough-loaded pillar where the highest pressure occurs toward the pillar yield zone. This loading profile is characteristic of a stable pillar representative of a barrier pillar or properly designed support pillar. A uniform loading on the pillar, as shown in figure 20*B*, rarely occurs in actual underground conditions, although it is used frequently in theoretical design. One such design, known as the "tributary area method," assumes the load is evenly distributed on the pillar. This assumption, although

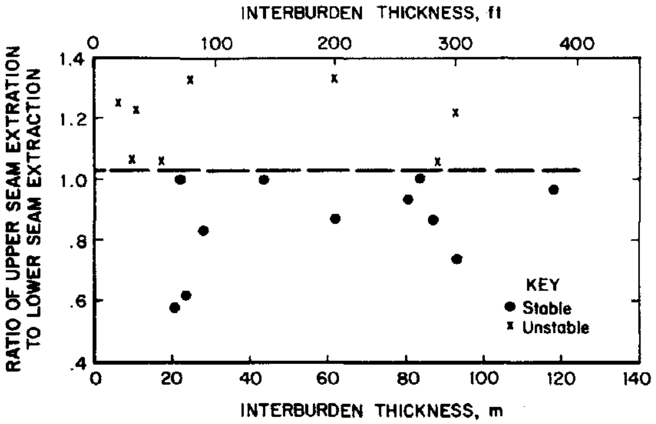

Figure 19.—Interburden thickness versus ratio of upper to lower seam extraction for stable and unstable lower seam conditions. After Haycocks (*13*).

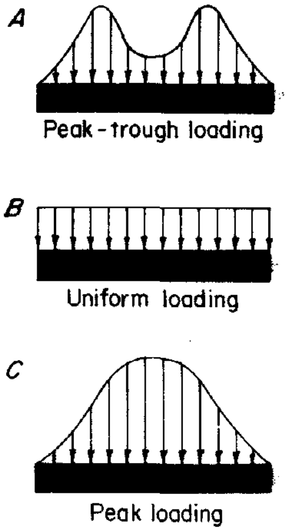

Figure 20.—Loading characteristics of pillars.

simplistic, has an important place in pillar design because it gives a safe limit of pillar load. A pillar that displays a peak loading, as shown in figure 20*C*, where the highest pressure occurs toward the pillar core, is considered an unstable design. This loading profile is characteristic of a small, isolated, remnant pillar or underdesigned support pillar.

Haycocks (*13*) studied these three basic loading profiles and their tendency to transfer load to a lower seam, using photoelastic models. He found that peak-trough-loaded profiles (fig. 20*A*) are stable designs and less likely to transfer load in comparison with the other two profiles. Su (*20*), using finite-element analysis, found that the dimensions of the pillar had a profound effect on the downward transfer of stress. He found that stress transfer was controlled by the least dimension of the pillar. His modeling showed that a rectangular pillar will generally transfer less downward stress a lesser distance than a square pillar of equal load-carrying capacity. This finding indicates that rectangular pillars may be more suitable than square pillars for multiple-seam room-and-pillar design. He also found that a remnant pillar that is core loaded would have a zone of influence that would extend downward at least two to three times the pillar width. In engineering practice, the upper limit of average stress at the pillar core is estimated at four times the overburden load (*47*).

In the application of these pillar-loading concepts to multiple seams, there are three types of structure in an overlying mine that may cause interaction problems in a lower operation (*15, 19, 24*): (1) the development or support pillars within the section or panel, (2) an isolated remnant structure, and (3) a gob-solid coal boundary, which is the interface where gob and solid coal or a pillar line meet.

Mining Beneath Support Pillars

Developing beneath overlying support pillars in a room-and-pillar section can involve two possible design conditions. First, the mines are planned cooperatively and pillars in both mines are designed concurrently to account for the transfer of stress between the operations. This represents the optimum situation, as pillars can be designed with similar size and shape. Second, the upper mine pillars were developed first without coordinated planning with the lower mine. In this situation, pillars in the upper and lower mine may or may not be of the same size, depending on conditions.

When mines are planned cooperatively, the pillars should be designed using the lower seam depth as the design criterion, because this represents the worst loading condition. The pillar safety factors can then be adjusted accordingly to account for the transfer of stress. There are several design formulas available for determining pillar size in relation to depth. Some of the frequently used formulas include the Obert-Duvall, the Holland-Bureau, the Holland-Gaddy, the Salmon-Munro, and the Bieniawski-Pennsylvania State University (PSU) formula (*41-44*).

The Bieniawski-PSU formula, in general, will give higher safety factors for similar pillar sizes in comparison with the other formulas; consequently, it is the least conservative. However, it was developed primarily for conditions in U.S. mines and therefore is the most applicable. The formula is

$$\sigma_p = \sigma_1 \ (0.64 + 0.36 \ w/h), \qquad (1)$$

where σ_p = strength of mine pillar, kPa (psi),

σ_1 = in situ coal strength, kPa (psi),

w = least width of pillar, m (ft),

h = height of pillar, m (ft),

and

$$SF = \sigma_p/TAM, \qquad (2)$$

where SF = pillar safety factor,

σ_p = strength of mine pillar, kPa (psi),

and TAM = estimated pillar load—tributary area method, kPa (psi).

The tributary area method assumes a uniform load on the pillar, as depicted in figure 20*B*. The equation is

$$TAM = c(d)\ (1 + L/b)\ (1 + L/w), \qquad (3)$$

where c = a constant, 24.9 kPa/m (1.1 psi/ft),

d = depth, m (ft),

L = width of mine entry, m (ft),

b = length of pillar, m (ft),

and w = width of pillar, m (ft).

The in situ coal strength (σ_1) is assumed to be 6,205 kPa (900 psi) unless a more accurate strength has been determined from laboratory tests. Mark (*38*), in developing the ALPS method for longwall pillar design, found that this value correlated well with field conditions using the Bieniawski-PSU formula.

Recommended safety factors for pillars designed using the Bieniawski-PSU formula range from 1.5 to 2.2, with adjustments made within this range as ground conditions dictate. USBM researchers (*10*) compared safety factors for pillars in multiple-seam operations and found that safety factors in both mines should be kept toward the upper limit of this range, from 2.0 to 2.2, when pillar columnization is practiced. Pillar columnization is a commonly used method in multiple-seam design that requires the pillars in both mines to be of equal shape and size, and geometrically aligned as shown in figure 21. Laying out pillars in a columnized arrangement is a relatively simple task on paper, but a more difficult undertaking in actual mining practice. Surveying errors, miner operator errors, and inaccurate pillar locations on the mine map of the overlying mine may lead to slight offsets in the pillars. Figure 22 shows a mine layout from a USBM case study (*7*) where columnization was practiced but pillars were slightly offset because of these factors. This offset may generate high shear stresses in the interburden, causing cutter-type roof failures in the lower mine (*15*). When columnization is practiced, extra care and planning are necessary in surveying and while cutting pillars on development.

In the case where the mines are not cooperatively planned, an operator must first evaluate the condition of the overlying pillars and determine if they are sufficiently designed for their depth. The major design concern is that the pillar should have a characteristic loading of a peak-trough profile as shown in figure 20A. This characteristic loading represents the most stable design and is least likely to transfer load to the lower mine. Pillar safety factors should be within the recommended range of 1.5 to 2.2, using the Bieniawski-PSU formula; however, the upper limit from 2.0 to 2.2 is more preferable. If the safety factors fall within the recommended range, then it can be reasonably assumed that the pillars have a peak-trough loading profile and therefore are stable. This evaluation can be supported with visual inspection of the pillars if the mine is accessible.

If upper seam pillar stability is assessed as favorable, then columnization should be practiced. The operator must determine the safety factors of similar-sized pillars for the lower mine using the lower seam depth. If the safety factors fall within the recommended range (2.0 to 2.2), then pillar columnization should provide generally stable conditions.

If the safety factors and stability of upper seam pillars are questionable, then columnization should not be attempted. Columnizing underdesigned pillars may lead to roof control problems, floor heave, and pillar instability in the lower mine. Under such circumstances, the operator has little choice but to use larger pillars with appropriate safety factors to account for the transfer of stress. In such

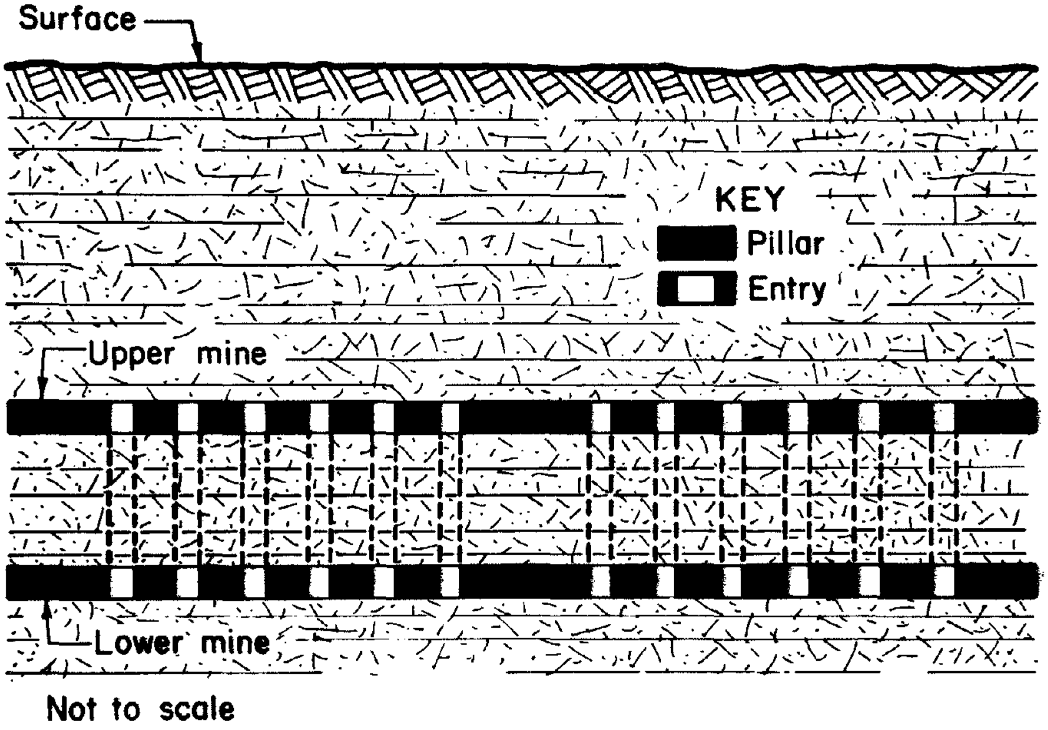

Figure 21.—Columnized pillars in multiple seams.

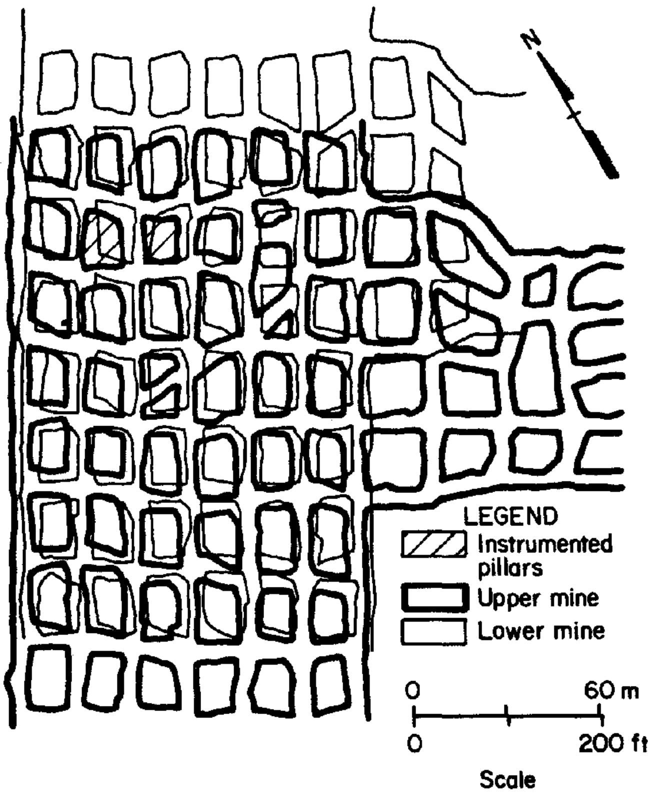

Figure 22.—Pillar offsets at a mine where columnization was attempted.

a case, the pillars will be offset or randomly arranged and the overlying pillars will influence lower mine entries. As mentioned previously, this causes shear stresses to develop in the interburden and may result in roof control problems in the lower mine. The operator must decide if this is a practical undertaking. A systematic trial-and-error approach for adjusting pillar safety factors and arranging the workings may eventually produce tolerable conditions.

The design of the lower seam pillars becomes more critical when depth increases and interburden is less than 15.2 m (50 ft). Since pillar size is proportional to depth, larger pillars required for increasing depth may significantly reduce recovery. Su (*20*), using three-dimensional finite-element modeling, studied the problems inherent in the columnization of pillars at increasing depths and decreasing interburden thicknesses. In general, he showed that as pillar size increases and interburden decreases, the workings become less stable. Using linear regression analysis, he developed a set of equations and nomograms for estimating pillar loading, strength, and safety factors when columnization is practiced for seams in very close proximity (*17, 20*). Haycocks (*15*) and Wu (*22-23*) describe a specific condition in which the coalbeds lie within 9.0 m (30 ft) of each other. In this condition, known as ultra-close seam mining, the stability of the workings is dependent upon the integrity of the interburden and relative location of the upper and lower seam pillars. Design considerations for this particular condition are detailed in a later section, "Ultra-Close Seam Mining."

Finally, barrier pillars that are left between the development sections to separate mined-out and unmined room-and-pillar panels perform a vital function in multiple-seam design. Barrier pillars provide bearing support in the event that load is transferred between operations, and they also provide support for load that may be transferred through pillar yielding as noted by Haycocks (*13*). Several design formulas for determining barrier pillar width are available, and all are empirically based. Briefly, they include the "pressure arch formula," which was developed in England through observation and measurement and is based on the pressure arch concept of stress distribution (*26*). Holland (*49*) developed a formula based on the thickness of the coalbed, and the "Ashley or Mine Inspectors" formula (*50*) uses both depth and coalbed thickness in estimating coal barrier width. Whether the support pillars in the development section are columnized or randomly arranged, barrier pillars in successive seams should be superpositioned, if possible, and should be of consistent width to provide bearing support and to minimize load-transfer effects.

Mining Beneath Remnant Structures

Mining beneath remnant structures occurs frequently when the overlying operation practiced full-extraction mining. These structures are isolated by gob and produce stress concentrations in the lower operation, leading to increased pillar load and entry convergence. These structures include barriers that separate mined-out room-and-pillar sections, remnant pillars left from retreat mining operations, protective barrier pillars for a gas well or surface structures, or isolated gate roads from a longwall operation. Mining in the vicinity of remnant structures can hinder mining because the operator must consider the transfer of stress from these structures and design accordingly. However, mining may also benefit, as the adjacent gob is a destressed area and ground conditions may improve.

Wu (*24*) presents two basic loading profiles to represent the distribution of load on remnant structures. Figure 23 illustrates the loading profile for a wide pillar (>30.5 m). The profile is characterized by peak loads at the pillar edges with a trough at the pillar core. This profile would be representative of a barrier separating two mined-out panels or a large protective barrier. Wilson (*47*) estimates the location of the peak stress at a distance from the edge of the pillar at 0.0015tH, where t is the coalbed thickness in meters, H is the depth of cover in meters, and 0.0015 has the units meters^{-1}. The upper limit of the magnitude

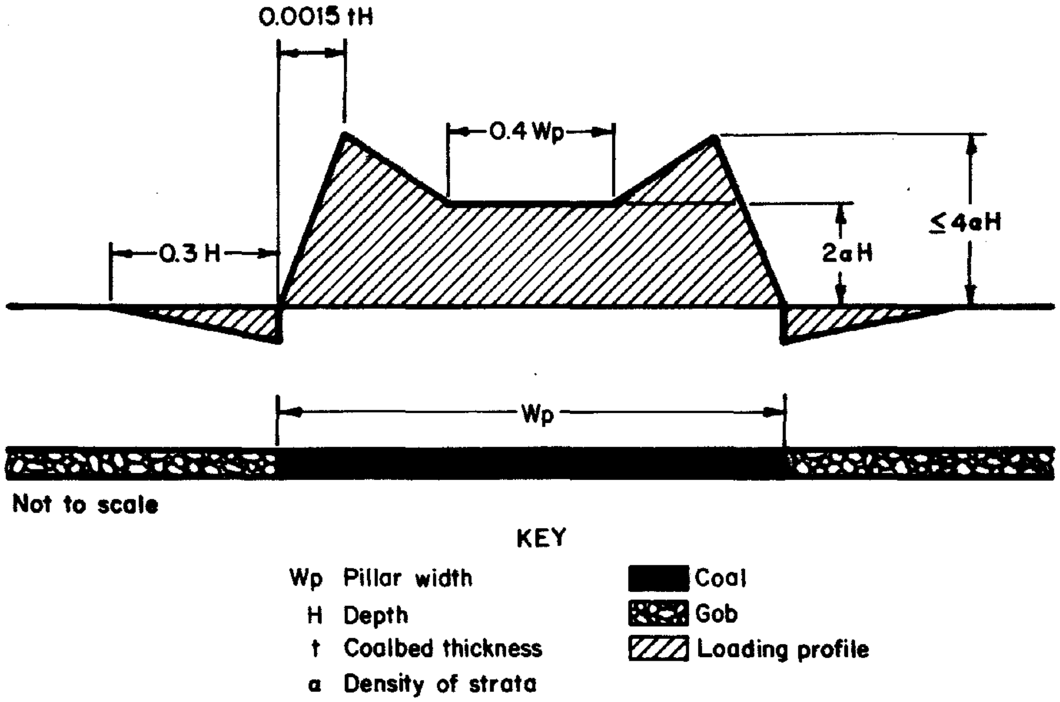

Figure 23.—Loading profile for a wide remnant pillar. After Wu (*24*).

of the peak stress is estimated at four times the cover load (*47*). As shown in the figure, the extent of the core load at the center of the pillar is approximately 0.4 times the pillar width, and the maximum core load is about half the peak load. Figure 24 illustrates the loading profile for a narrow remnant pillar (<30.5 m). This profile is characterized by a core loading with the upper limit estimated at four times the cover load (*47*). This would be representative of an isolated remnant pillar left by retreat mining.

The final loading profile that a remnant structure will eventually carry is dependent upon the caving characteristics of the overlying strata and the distribution of load between the gob and the remnant structure. The caving angle (*18, 35-39*) defines a failure plane where the weight of the overburden is distributed between the gob and the pillar. The age and compaction characteristics of the gob will define the ultimate weight distribution. Therefore, the load on a remnant structure in newly created gob areas may be greater than in older gobs where the strata have had sufficient time to compact, consolidate, and take on load.

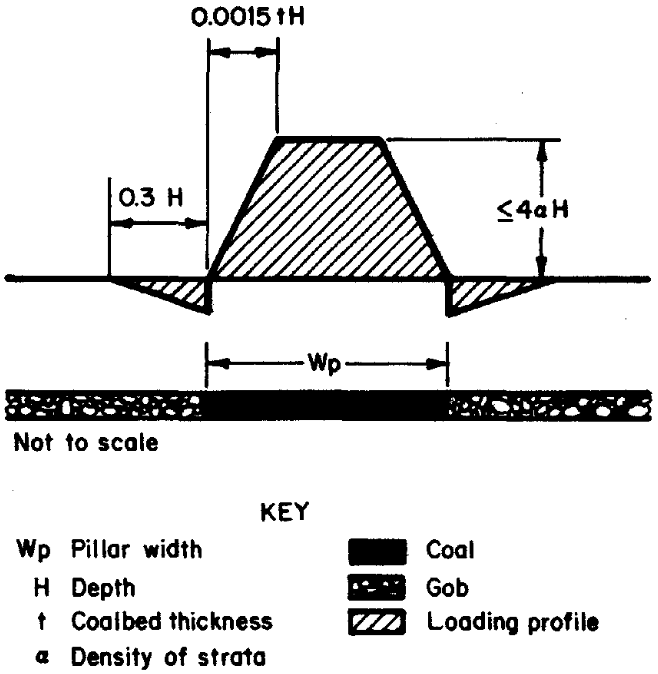

Figure 24.—Loading profile for a narrow remnant pillar. After Wu (*24*).

The magnitude of the load transferred from remnant structures to lower operations is largely dependent upon their size and shape, the depth, and the thickness and composition of the interburden. Using photoelastic and numerical models, several researchers investigated the load-transfer characteristics of remnant structures to approximately determine their influence zones. Hsiung (*19*) determined that the zone of influence for a remnant pillar would extend downward (or upward) two to three times the pillar width. The load would be transferred deeper for a wide pillar; however, the magnitude would be less than that for a narrow pillar. With geologic conditions being equal, a core-loaded narrow pillar would create a greater degree of ground control problems in a lower operation than would a wide pillar. As discussed previously, peak-trough-loaded pillars represent a more stable design and are less likely to influence lower seam mining than core-loaded pillars. Haycocks (*15*) found that remnant pillars whose widths are less than 18.3 m (60 ft) have extremely high core loadings and can create stress concentrations in lower operations twice those created by a normal abutment zone. Pillar design may be more critical if interactions are very intense, such as when overburden is high and seam intervals are small, or where long-term stability is a major concern, such as in a mains development. In this case, it may be necessary to leave larger pillars to support the load. If possible, the operator should lay out the workings to avoid the structure. If this is not feasible, the operator should consider designing pillars with safety factors of between 2.5 and 3.0. In the case where the interaction may be severe, Hsiung (*19*) recommends that a block of coal not smaller than three times the width of the remnant structure be left directly beneath it in the lower mine. Although pillars may be properly designed to distribute the transferred stress, potential failures of the roof and floor should be considered. Poor roof conditions, roof falls, and floor heave may occur if the roof or floor strata are of a particularly weak nature. Under these circumstances, the operator has little option but to increase support as required.

Estimating the magnitude of stress transferred from overlying remnant structures has been attempted by several researchers. Grenoble (*51*) developed a method based on pressure bulb theory and taking into account the effects of interburden layering. The USBM (*52-53*) developed a method for estimating the magnitude of load transferred from isolated gate road pillars in longwall operations and for sizing lower seam pillars when gate road superpositioning is practiced. To better understand the transfer of stress from remnant structures, the MULSIM/NL model was used to study pillar sizing and positioning when mining occurred beneath these features. The findings are detailed under the section "MULSIM/NL Modeling."

Mining Beneath a Gob-Solid Coal Boundary

A gob-solid coal boundary, where gob meets solid coal or a pillar line, is similar to a remnant structure, but a slightly different approach is required in its analysis. As shown in figure 25, the loading profile is characterized by a peak load near the solid coal edge, which gradually diminishes to a cover load over the solid (*24*). The formation of this profile is best explained by caving and arching mechanisms. The caving angle (*18, 35-39*) defines a failure plane where the weight of the overburden is distributed between the gob and the solid coal edge. Depending on depth, an arch may form with the solid coal as the abutment. Wilson (*47*) estimates the location of the peak stress over the solid at a distance from the boundary of 0.0015tH, where t is the coalbed thickness in meters, H is the depth of cover in meters, and 0.0015 has the units meters^{-1} (similar to the estimate for a remnant structure). The upper limit of the magnitude of the peak stress is estimated at four times the cover load (*47*).

The intensity of the interaction in the lower mine will be related to the depth and the interburden thickness and composition. In general, the interaction potential for a gob-solid coal boundary is less than for a remnant structure. In the remnant structure, the load is more concentrated, but in the gob-solid coal case, the solid acts to distribute the load. Hypothetically, the most severe ground conditions in the lower mine will be experienced directly beneath the location of the peak stress. Although increases in pillar load may occur, the operator must decide, based on experience and conditions, if larger pillars are warranted when mining in this area. If so, designing pillars with safety factors toward the upper limit of 2.0 to 2.2 is recommended. In some cases, increasing supplemental support to stabilize entries is all that will be required. Mining in the vicinity of the overlying boundary may also have beneficial effects. The stress beneath the gob of the overlying mine should be equal to or slightly less than that of the normal cover load. Therefore, when the operator is developing in this area, designing pillars with safety factors between 1.5 to 2.0 should be sufficient.

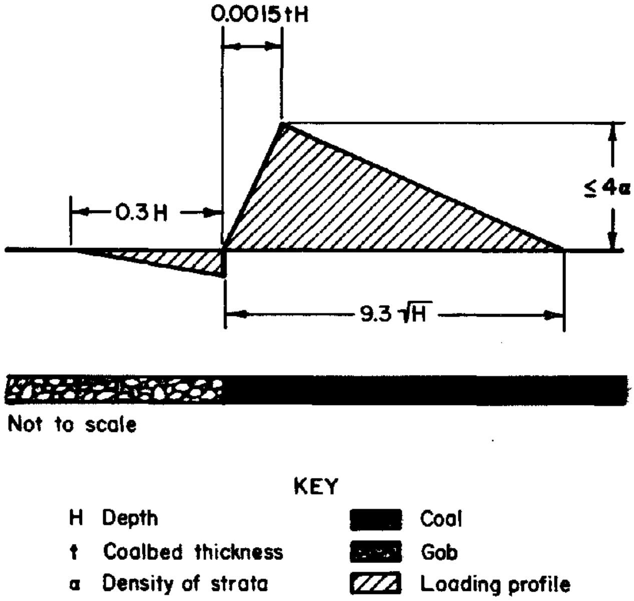

Figure 25.—Loading profile for a gob-solid coal boundary. After Wu (*24*).

Research into multiple-seam longwall mining has found that mining the longwall panel from the gob to the solid coal side of the boundary can greatly reduce the stress across the longwall face (*19-20, 53-54*). Although empirical studies have yet to document similar experiences with room-and-pillar mining in the United States, insight can be sought through numerical models. The MULSIM/NL model was used to assess the direction of mining in relation to an overlying gob-solid boundary both for development and retreat mining. These findings are detailed under the section "MULSIM/NL Modeling."

SUBSIDENCE INTERACTION

Coalbeds sequenced in ascending order will be affected by subsidence if full-extraction room-and-pillar or longwall mining was used in the lower mine. The magnitude of damage an overlying coalbed will experience is dependent upon the caving characteristics of the strata. Ground control problems will be experienced mainly in the zone of the subsidence trough if extraction in the lower mine was uniform and complete. Although the pillars may be influenced by this zone, it is in the entries that most problems will occur, and maintaining roof stability will be the major design consideration.

The subsidence trough will form superjacent to the gob-solid coal boundary or remnant structures left in the lower mine. As previously discussed, the trough is characterized by distinct zones of tension and compression as shown in figure 15. The stability of the entries when the subsidence trough is mined will be affected mostly by the tension zone. Since most rocks are weak in tension, this zone is associated with the formation of fractures and opening of joints, which lead to poor roof conditions. Increased flows of methane and water are frequently encountered as fractures provide pathways for their migration. The compression zone has been observed to cause only minor ground problems related to pillar instability, characterized by rib spalling (*6, 9, 13, 16*). Increases in pillar loads may be experienced when mining proceeds from the gob to the solid side of the lower seam, but increases are usually not significant enough to cause any pillar problems (*9*). Pillars may also experience problems when mining occurs above remnant pillars in a lower mine if they are of sufficient size to transfer stress through the interburden as depicted by Zhou (*21*) in figure 26. Beyond the subsidence trough lies the zone of maximum subsidence. When full-extraction mining is used in the lower mine, the strata in this zone subside uniformly, which usually results in a destressed area and improved ground conditions.

Case study documentation of subsidence problems (*2-4, 6, 9, 12, 19, 21, 33-34*) has found that roof stability in the upper mine is primarily dependent upon the type of strata in the immediate roof and floor. Roof falls resulting from bed separation and failure along roof joints are a common occurrence in the subsidence trough. Bed separation may occur if the beds are competent and able to withstand a certain amount of bending in the roof. Roof joints have few cohesive properties and therefore provide natural planes for tension failure. Weak shale roofs that are highly bedded, are jointed, or have many geologic discontinuities are most susceptible to the effects of subsidence. Geologic discontinuities, such as clay veins and slickensides, disrupt the continuity of the roof beam, and failure may occur along these features under the bending stresses produced in the trough. Competent sandstone roofs that resist bending may provide better roof conditions, but because sandstone is a high-modulus rock they are more prone to shear failure. Floor heave can also occur in an overlying operation when mining is over remnant pillars or small groups of pillars (*21*). Stress transferred through the interburden to the upper mine may affect soft floor strata, such as rocks with a high clay content. The next three sections focus on practices and strategies for improving and maintaining entry stability for operations affected by subsidence.

ASSESSING THE MAGNITUDE OF DAMAGE

When mining in subsidence-affected coalbeds, the operator should first determine the location and extent of the subsidence trough. The general location of the trough can be determined by using maps of the lower mine. Once this location is known, the horizontal extent of the subsidence trough in an overlying coalbed can be estimated using both the angle of draw and the caving angle as depicted in figure 15. From a purely geometric perspective, the

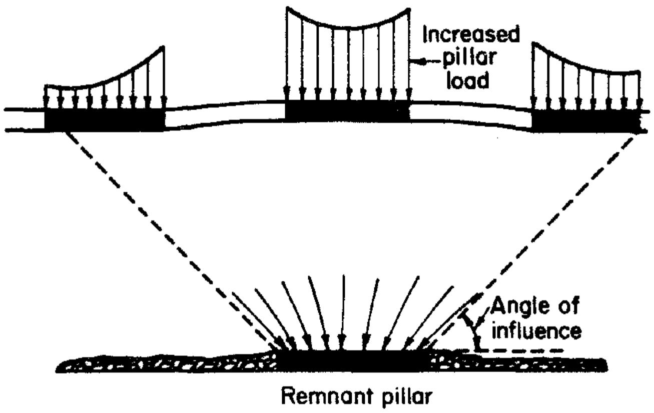

Figure 26.—Remnant pillar in lower mine causing increased pillar load in upper mine. After Zhou (21).

horizontal extent of the trough can be expressed by the following equation:

$$d = h(\tan\theta), \tag{4}$$

where d = horizontal extent of trough, m (ft),

θ = angle of draw and/or caving angle, deg,

and h = interburden thickness, m (ft).

Because of the geometry of the figure, d must be calculated for both the angle of draw and the caving angle and the two products added together to determine the total extent of the trough. An appropriate value for θ for U.S. applications will range from 15° to 25°. Although this exercise may give a good approximation of the trough's horizontal extent on the surface, for subsurface subsidence the trough's influence may differ depending on the caving characteristics of the strata. Case study documentation of subsidence problems in overlying operations shows that most ground problems occur as mining crosses over the gob of the lower seam or within the caving zone (*6, 9, 55*). Therefore, the caving angle may have more of an effect on ground conditions than the angle of draw.

Next, the operator should assess the condition of the strata that surround the coalbed and the magnitude of potential damage. Using the ratio of interburden to lower seam mining height as a basis, an operator can make an assessment of the condition of the coalbed and surrounding strata. Coalbeds within 20 times the lower seam mining height will experience the most damage because they lie within the lower mine caving zone.

Zhou (*21*) and Webster (*34*) developed a predictive method called the Damage Factor Method for quantitatively estimating the mining conditions for coalbeds affected by subsidence. The method generates a rating number that represents the degree of damage to the coalbed. The damage factor rating number is represented by the following equation:

$$DF = 620 + 0.5Y - 9.2X + (Z - 50), \tag{5}$$

where DF = damage factor rating number for upper coalbed,

Y = [interburden thickness, m (ft), divided by lower seam mining height, m (ft)] multiplied by [time lapse after mining lower coalbed, years],

X = percent extraction in lower coalbed,

and Z = percent sandstone in interburden.

A positive number indicates that no appreciable damage is anticipated in the upper coalbed. A negative number indicates that damage is possible, and the higher the negative number the greater the damage. This method was applied in a USBM case study (*55*), and a good correlation was shown between the rating number and the actual underground conditions.

DEVELOPING ENTRIES OVER GOB

When the location and extent of the subsidence trough have been determined and a damage assessment has been made, the operator must develop strategies for mining in this zone. Improved ground conditions can usually be achieved by modifying the mining plan with emphasis on minimizing total roof exposure while balancing mining strategies with profitable extraction ratios. Modifications to the mining plan can include reducing entry width and decreasing percent extraction on advance, developing three-way T-intersections by staggering crosscuts, changing the heading of entries, planning shorter panels, and changing roof support requirements.

Reducing entry width should be the first consideration, for obvious reasons. Since the potential for roof problems is directly related to the condition of the strata, narrower entries lessen the influence of structural anomalies in the roof. Entry width should be reduced as much as possible to allow for the safe passage of equipment and workers. As depicted in figure 27, the entry width is reduced and the pillar width increased before development proceeds over the subsided area. However, depending on ground conditions, the operator may need to implement the development of narrower entries in the upper mine farther over the solid coal in the underlying mine. Although this is an easy solution, the disadvantage is that pillars are overdesigned and percent extraction may decrease to an unacceptable level to maintain profitability. If the effects of the trough are minimal and conditions are expected to improve in the zone of maximum subsidence, entries can be widened back to the original mining plan once mining is past the influence of the trough. The operator must determine if this is practical based on local ground conditions.

Another method to reduce the amount of exposed roof in the zone of the trough is to develop three-way T-intersections as shown in figure 28. The traditional four-way intersection is an area where roof exposure is at a maximum and where problems commonly may occur. The T-intersection is more time consuming to develop and makes it more difficult for machinery to maneuver, but does meet the objective of reducing the entry width and roof spans. Again, the operator must determine if the development of T-intersections is warranted based on local roof conditions.

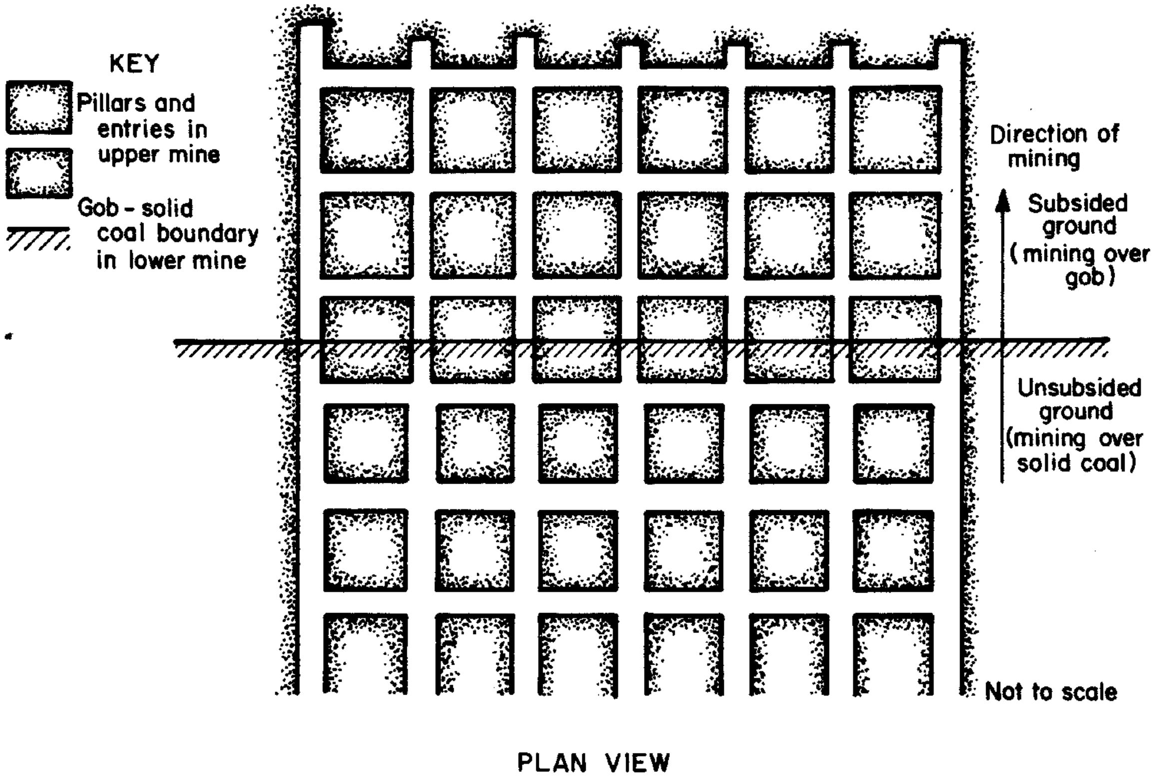

Figure 27.—Reducing entry width in upper mine when developing over subsided ground.

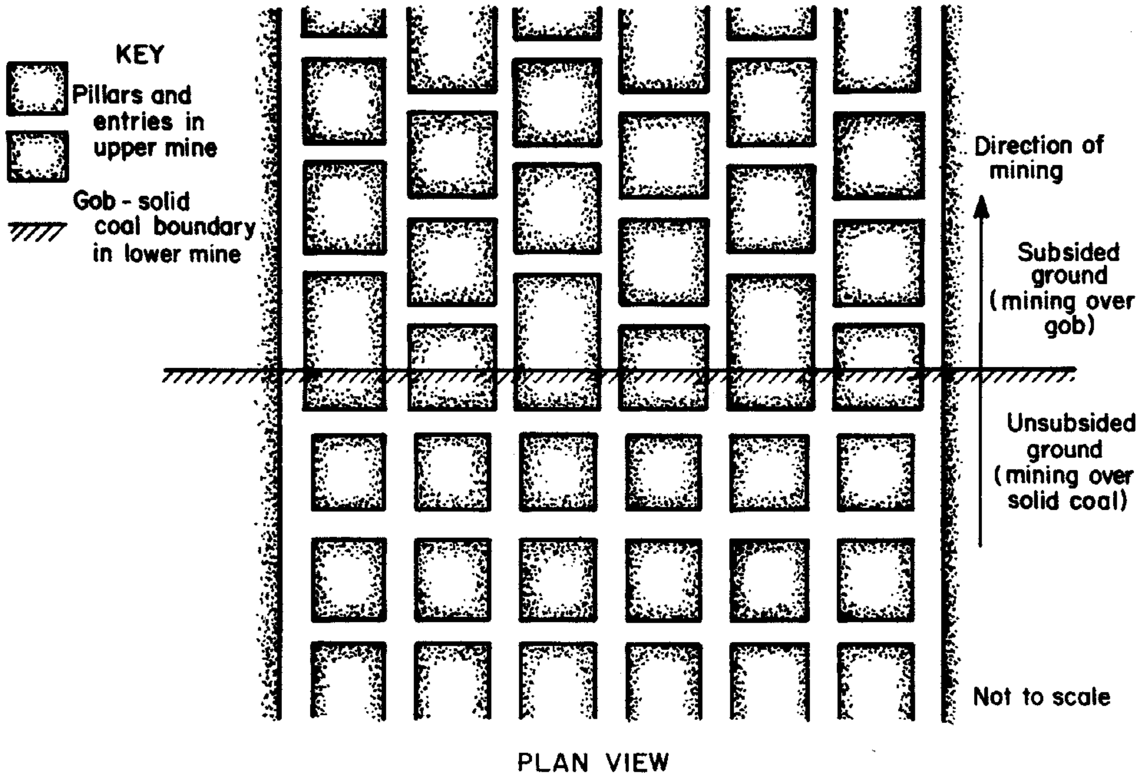

Figure 28.—Reducing entry width and staggering crosscuts in upper mine when developing over subsided ground.

The heading or direction of mining in relation to the lower seam pillar line or joint sets in the upper mine roof is another consideration. The area of influence for the trough can be minimized by crossing the lower seam pillar line at a right angle as shown in figures 27 and 28. This method works best when the geometry of the pillar line in the lower mine is straight and not irregular or jagged. If a joint system is present in the upper mine roof and is a major contributor to roof problems, its presence may dictate the orientation of entries. Roof joints have few cohesive properties and therefore provide natural planes for tension failure. Joint sets that run parallel or almost parallel to entries or crosscuts are more likely to cause roof problems than joints with other orientations. For joint sets oriented parallel to crosscuts, changing crosscut development from 90° to 45° (also known as herringbone pattern) may provide better conditions. When joints are oriented parallel to entries, the heading or the direction of mining must be changed. If this is not feasible, the only other option is to heavily support the entries.

Sufficient time delay in mining seams damaged by subsidence is an important factor as this allows for adequate caving and compaction of the gob. There are two possible strata movements that may occur when mining is over gob. First, if sufficient time has not been allowed for caving and compaction, mining will be in an area where the underlying gob is still in the process of settling. As the entries are developed, they will be affected by the continued settlement of the ground. Second, the ground may be completely settled, but the stress concentrations from overlying pillars as they are developed reactivate the gob, which induces additional movement and causes ground problems in the upper mine. This movement can occur in the subsidence trough as well as in the zone of maximum subsidence. Developing shorter panels in subsided ground may eliminate problems associated with gob settlement. This movement and its effects on overlying workings are time dependent. Therefore, the less time spent developing over the gob, the less the influence of gob settlement on overlying entries. Developing and retreating workings as quickly as possible when mining over gob will help to reduce the effects of gob settlement.

When mining in subsided ground, the operator should be aware of the roof conditions and modify the roof support plan accordingly. For the most part, this will be a trial-and-error procedure as roof conditions will vary based on roof type, local geology, and the degree of interaction. Supplementary support such as timbers and cribs may be all that is required. If the roof conditions are particularly poor, this may require altering the roof support plan. Changing bolt length or bolt type and increasing the bolting density should be considered under these circumstances. More comprehensive support can be provided with steel straps or wire mesh. Intersections and entries along the track and belt, where long-term stability is essential, may require steel sets on timbers or cribbing. A more cost-effective approach may include the application of truss support. Tensile stresses producing failure along roof joints or subsidence-induced fractures are the primary cause of roof falls. Truss support would generate an upward, compressive force at midspan, thereby reducing tensile stress. Anchorage is provided by angle holes over the pillar, which may reduce failures over the ribline. Whatever support system is used, the operator should anticipate these problems in advance, and for optimum results, supports should be installed when interactions are first suspected and before ground problems develop.

PRACTICES WHEN MINING THE LOWER SEAM FIRST

If an operator has control over several coalbeds on a property, sequencing in a downward order is most preferable. However, there will be instances when a lower coalbed must be mined first because of coal quality, market conditions, or other reasons. Under these circumstances, it is important that several design factors be considered to minimize damage to the overlying coalbed(s) and improve their minability. The operator should develop an overall mining strategy based on the stress-relief effects created by the lower mine gob. Mains, submains, and panels should be planned so the overlying mine can take advantage of the underlying gob as best as possible.

The major consideration should be to maximize the gob as much as possible so that ground problems in the upper mine will be limited to the perimeter of underlying gob areas. In full-extraction panels, the operator should take extra precautions against leaving remnant pillars or large pillar stumps. As shown in figure 29, this leads to a nonuniform subsidence profile in the overlying mine and formation of tension zones above the remnant pillars throughout the subsided area. There will be instances when remnant pillars will be left, usually because of safety-related caving problems near the pillar line. If possible, operators should leave small remnants and stumps, which tend to crush out, resulting in a more uniform subsidence. Operators should avoid leaving large remnant pillars at regular spacings, for this may jeopardize the minability of the overlying coalbed. If remnant pillars are left in the gob, they should be clearly marked on the mine map so potential problem zones can be located in the overlying coalbed.

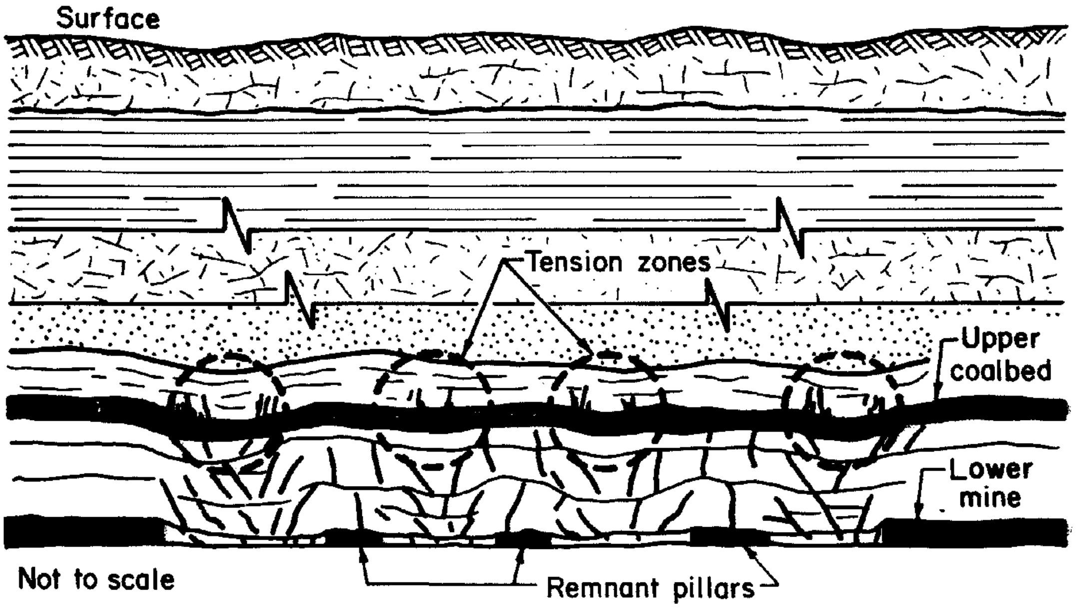

Figure 29.—Remnant pillars left in lower mine causing a nonuniform subsidence profile and formation of tension zones in overlying seam.

ULTRA-CLOSE SEAM MINING (*15, 56-58*)

When coalbeds lie within 9 m (30 ft) of each other, special consideration needs to be given to the behavior of the interburden. Haycocks and Zhou described this as an ultra-close seam interaction, and they presented significant research regarding design considerations for this unique case (*15, 56-58*). The interburden is the primary structural element in stability considerations. The failure potential of the interburden is determined by the relative positions of the upper and lower seam pillars. Haycocks and Zhou identified three basic pillar layouts that contribute to interburden failures: (1) columnized pillars, (2) partially offset pillars, and (3) totally offset pillars.

Columnized pillars are commonly used, but this practice results in a high concentration of load on the pillars. Columnization produces a symmetrical loading condition in the interburden strata, which at high overburdens creates a stress gradient that may cause shear failure at the lower seam pillar edge. Haycocks states (*15*) that even at shallow overburdens, shear failure may still be a problem if the ratio of opening width to interburden thickness is less than 5. Tensile failure of the interburden is possible as the interburden fails under its own weight and may lead to roof falls that extend into the overlying operation, as illustrated in figure 30. The potential for this type of failure becomes critical when the interburden thickness is less than twice the opening width. To maintain pillar stability, the required safety factor should be applied to the combined pillar height of both seams (*58*).

Partially offset pillars can occur because of surveying errors, miner operator errors, or unknown pillar locations in the overlying mine. As in the case of columnization, shear failure of the interburden is the predominant failure mechanism. Totally offset pillars represent the most unstable interburden loading condition and usually occur when planning between mines is not coordinated. Large pillars in the upper seam generally will provide for more stable conditions, compared with small pillars, as they distribute lower seam stress more evenly. Haycocks and Zhou recommend that careful columnization of pillars be practiced for optimum stability in ultra-close seam situations.

In addition to relative pillar positions, Zhou describes some other factors to consider in ultra-close seam situations (*56-58*). The seams should be sequenced in a descending order to avoid the damaging effect of subsidence because the overlying seam will usually be in the

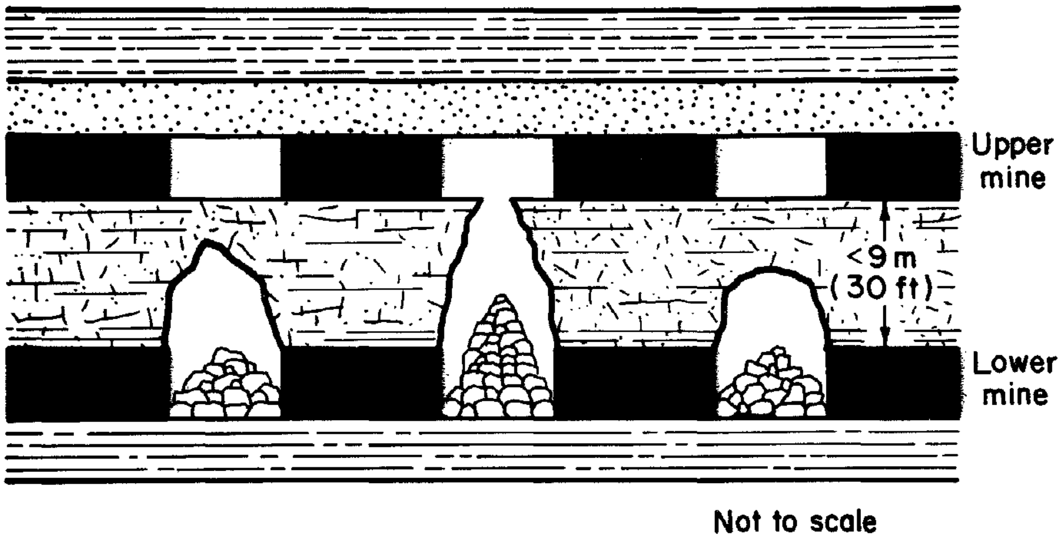

Figure 30.—Ultra-close seam interaction where roof fall extends to overlying mine.

complete caving zone. Lithology is a primary factor in defining the stability of the interburden. Strata type, degree of jointing, and geologic discontinuities that characterize the interburden will influence its failure potential. Hard-rock types, such as sandstones and limestones, will generally result in more stable interburden conditions than will soft shales or fireclays. Finally, for very thin interburdens, the tramming of heavy mining equipment can subject the interburden to dynamic loading and possibly aggravate or initiate interburden failure.

LAYOUT OF WORKINGS

Developing mine layout strategies for improving stability in multiple-seam room-and-pillar workings will depend primarily upon the extraction sequence. For optimum results, these strategies need to be developed in the initial planning stages of mine development before mining in any coalbed is implemented. There are two basic approaches to laying out room-and-pillar panels in successive seams: the use of superpositioned panels or offset panels. Superpositioned panel arrangements are used in most instances for all extraction sequences. Offset arrangements are used to avoid interactions when geologic conditions are not favorable.

SUPERPOSITIONED PANELS

Superpositioned arrangements work best when the upper seam is mined first and full-extraction retreat mining is practiced in the panels. The lower seam panel pillars can be developed beneath the upper seam gob and designed for single-seam conditions. In most cases, lower seam workings will be stable when the panels are the same overall width and the barrier pillars are columnized in both mines, as shown in figure 31. In extreme cases (i.e., deep workings and thin interburden), transfer of load from the overlying barrier may influence the outer entries and pillars of the underlying section. In this case, the width of the barrier in the lower mine may need to be increased to support the transferred load. Also, the outer entries and pillars should be positioned farther away from the high-stress zone, as shown in figure 32. A disadvantage of this arrangement is that overall extraction in the panels decreases as the number of entries is reduced because of the wider barrier. If the room-and-pillar sections in the upper mine are not retreated, lower mine panels can be superpositioned, with barriers and pillars columnized as depicted in figure 21. Pillars should be designed with appropriate safety factors using the lower seam depth as the design criterion.

Coalbeds sequenced in ascending order will experience interactions resulting from subsidence. Although ascending order is not the optimum sequence, successful extraction of the upper seam can result if mining strategies are planned in advance and the geologic conditions are favorable. Superpositioned panels require that the barriers be

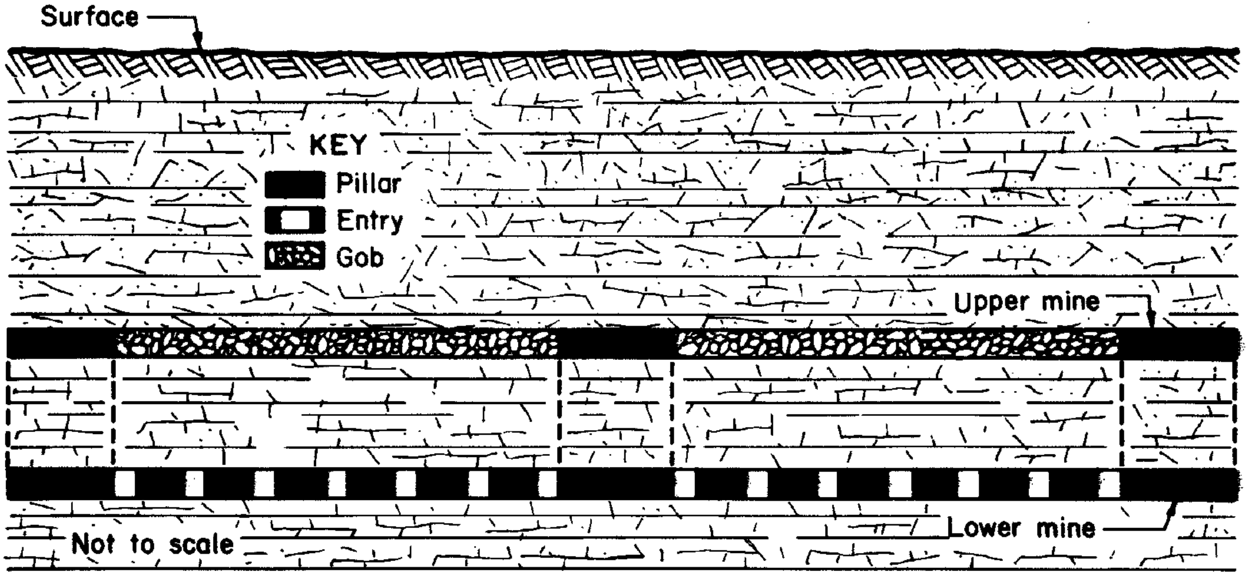

Figure 31.—Superpositioned panels with upper seam mined first and barrier pillars columnized.

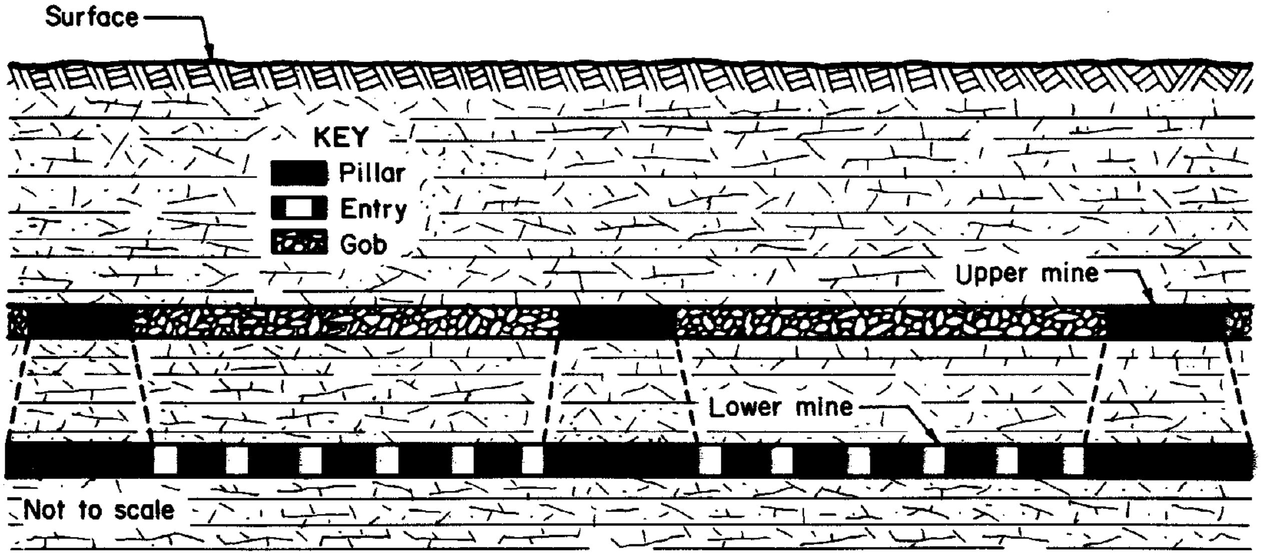

Figure 32.—Superpositioned panels with upper seam mined first and wider barrier pillars in lower mine to protect outer entries from pillar load transfer.

columnized. Since most ground problems will occur in the subsidence trough, it may be necessary to leave slightly larger barriers in the upper mine so that the outer entries are developed within the zone of maximum subsidence, as shown in figure 33. Pillars in the panel can be designed at depth for a single-seam situation. Design considerations for entries developed over gob, discussed previously, may need to be incorporated into the mining plan.

OFFSET PANELS

Offset panels are used primarily to avoid interaction and are most applicable when geologic conditions are less than favorable, as in very deep workings and thin interburdens. As shown in figure 34, the panels are offset and large barriers are positioned above and below the developments to protect them from interaction. Offset

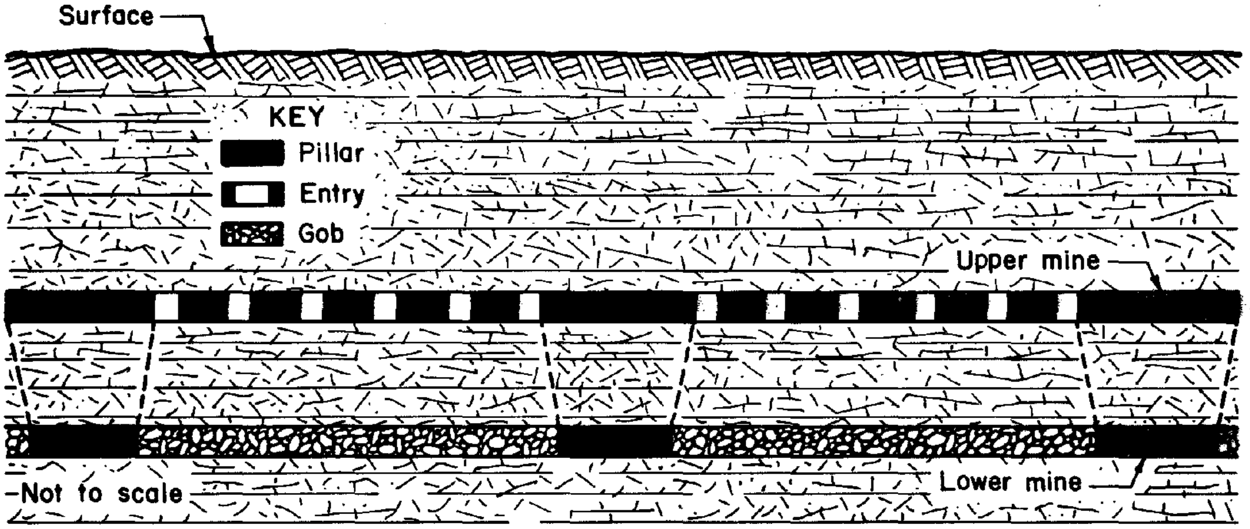

Figure 33.—Superpositioned panels with lower seam mined first and wider barrier pillars in upper mine to protect outer entries from subsidence trough.

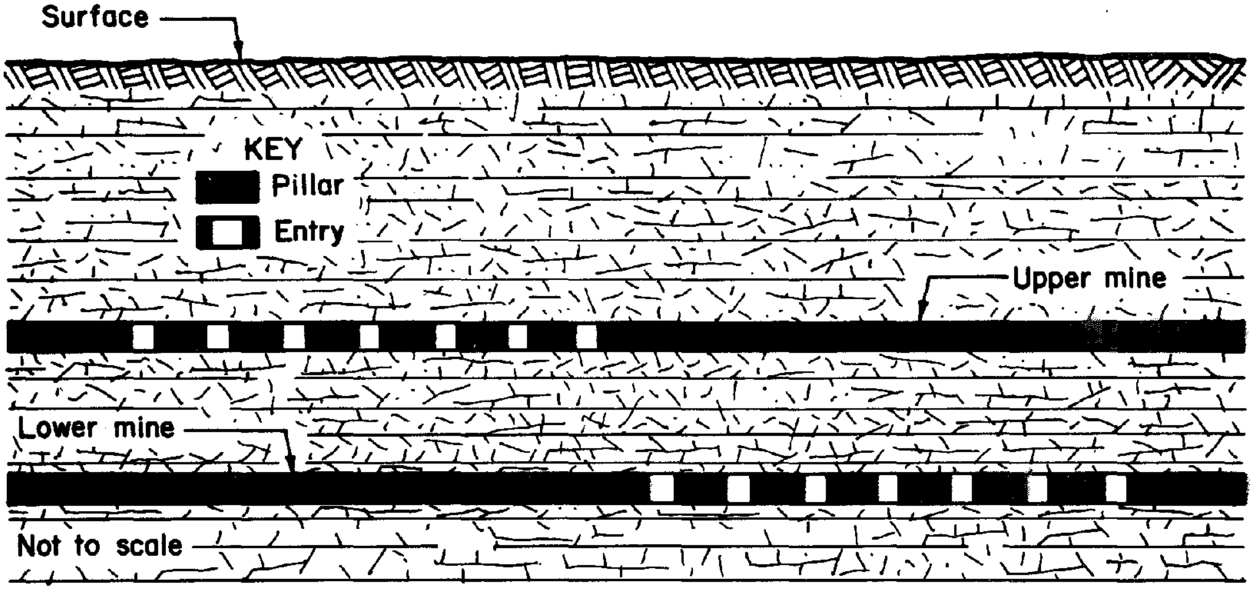

Figure 34.—Offset panels protecting both upper and lower mine from interaction.

arrangements are useful mainly in ultra-close seam mining where excessive pillar loading, interburden failure, and roof falls in the lower mine are potential problems. This arrangement should also be considered where long-term pillar stability is the primary consideration, such as in mains and submains developments. The offset ensures the protection of most of the developments from interaction because potential pillar problems will be confined to areas where developments leading to high-extraction panels cross one another as shown in figure 35. Avoiding interactions is the major advantage to offsetting. The major disadvantage is a decrease in recoverable coal that becomes locked up in barriers that protect the developments.

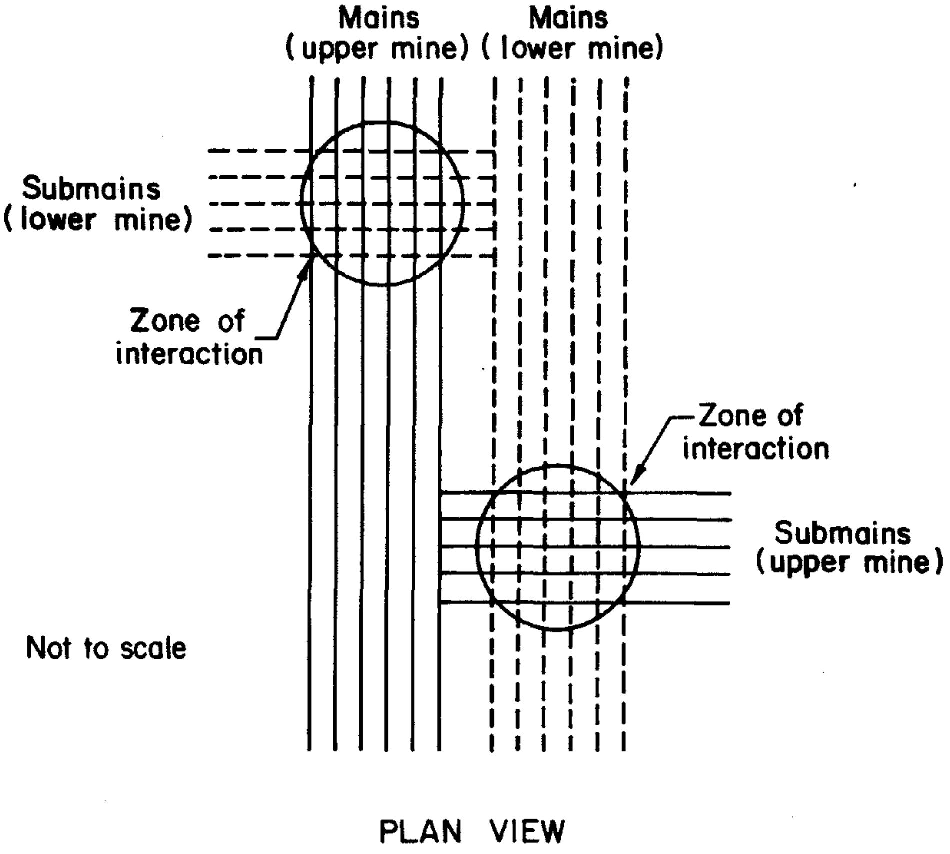

Figure 35.—Locations of interaction in upper and lower mines when panels are offset.

MULSIM/NL MODELING

MULSIM/NL is a boundary-element computer model, developed by the USBM, for calculating stresses and displacements in tabular deposits (*59*). The model provides the capability to analyze many coal mining situations and to determine the effects of the three-dimensional stress redistribution caused by mining in either single or multiple seams. In this case, the model was used to evaluate different design layouts when mining occurs beneath overlying workings and to determine which layouts produce the most favorable loading condition in the lower mine. The three types of structure in an overlying mine that can create interaction problems in a lower operation were investigated: (1) a gob-solid coal boundary, which is the interface where gob and solid coal or a pillar line meet, (2) an isolated remnant structure such as a barrier pillar, and (3) the development or support pillars within the section or panel.

To establish stress trends related to the above design arrangements, certain design and geologic criteria were fixed to limit the number of influence variables and narrow the extent of the investigation. The mine design criteria fixed in the study included the pillar size, the entry width, and the number of entries. The values of these three design criteria were selected to generally represent those commonly used in room-and-pillar sections. An eight-entry room-and-pillar section using 15.2- by 21.3-m (50- by 70-ft) pillars and 6.1-m (20-ft) wide entries was selected for study.

The fixed geologic criteria included the depth, interburden thickness and physical characteristics, coalbed thickness and physical characteristics, in situ stresses, and geologic discontinuities. Of these, depth and interburden thickness are the critical factors influencing stress transfer. Statistical analysis of case study information and photoelastic model results show that interaction probability is most sensitive to the relationship between these two parameters (*13*). For this analysis, the Bieniawski-PSU formula was used to determine the depth range that

15.2- by 21.3-m (50- by 70-ft) pillars can withstand for safety factors ranging from 1.5 to 2.2. With an in situ coal strength of 6,205 kPa (900 psi) and a seam thickness of 1.83 m (6 ft), the depth range was determined to be from 213.4 to 335.3 m (700 to 1,100 ft). Interburden thickness was kept constant at 15.2 m (50 ft) in most of the model investigations, which represents a close-seam interaction. Under this condition, the magnitude of stress transfer to the lower mine room-and-pillar section would be maximum, thereby making it easier to distinguish stress trends.

The next most important parameters are those of the coalbeds, which include thickness, strength, and dip. In situ stresses, such as a high horizontal stress, may affect overall stress magnitude, but the transfer of stress is more directly related to the normal cover load, which is a function of depth. Geologic discontinuities, such as clay veins, are more likely to cause localized instability in the workings, rather than having an effect on the overall transfer of stress.

In relation to this study, the MULSIM/NL model has two geologic shortcomings. First, geologic discontinuities cannot be represented in the model. Secondly, individual strata that characterize the overburden and interburden cannot be represented, so a generic modulus is chosen that depicts the overall lithology. Assuming the overburden and interburden are one homogeneous, isotopic material makes the strata reactions stiffer than reality. Therefore, the elastic modulus of the material is lowered in order to more closely approximate a stratified rock mass. Physical properties of strata in the MULSIM/NL model are represented by the elastic modulus and Poisson's ratio. The following linear elastic modulus values for the overburden and interburden, coal, and gob are given below. A Poisson's ratio of 0.25 was assumed for all cases.

Overburden and interburden . .	5,516,000 kPa (800,000 psi)
Coal	2,068,500 kPa (300,000 psi)
Gob	10,345 kPa (1,500 psi)

The coalbeds in the upper and lower mine were fixed at 1.83 m (6 ft) thick and were assumed to be flat-lying deposits with no dip. The assumed density of the overburden was 2,603 kg/m^3 (162.5 lb/ft^3).

CROSSING A GOB-SOLID COAL BOUNDARY

Developing and retreating a room-and-pillar section beneath a gob-solid coal boundary occurs frequently in the eastern coalfields when abandoned workings are encountered in overlying seams. The loading profile for this type of structure is shown in figure 25. The MULSIM/NL model was used to evaluate two fundamental design considerations regarding the magnitude of the vertical stress transferred from the boundary to the lower mine pillars. The first consideration is the magnitude of the stress as it relates to the direction of mining across the boundary. Two mining directions are proposed: (1) the room-and-pillar section is developed from the solid to the gob side of the boundary and then retreated from the gob to the solid side, and (2) the opposite situation: the section is developed from the gob to the solid side of boundary and then retreated from the solid to the gob side. The second consideration is the magnitude of stress as it relates to the positioning of pillars. Two designs are proposed: (1) the boundary edge is supported with a row of pillars, and (2) the pillars are positioned on either side of the boundary with the crosscut directly beneath the boundary. The combination of these two design considerations produced four possible arrangements, as illustrated in figures 36 and 37. The model was used to determine which of these four design arrangements would produce the least amount of stress in the lower seam pillars as mining developed and retreated beneath the boundary.

The results of the model analysis for these four situations is shown in figures 38 and 39. To produce results that were comparable, the analysis was conducted in the following manner. The room-and-pillar section was developed and retreated in 27.4-m (90-ft) increments (pillar centers), and the average stress was calculated across the last row of pillars at the face where the abutment stress is located. These average stress values were then normalized to a single-seam situation for both development and retreat mining. The single-seam model runs used the same input parameters as mentioned above, but without the gob-solid coal boundary in the upper mine. The average stresses for development and retreat mining for a single-seam situation were 10,135 kPa (1,470 psi) and 16,200 kPa (2,350 psi), respectively. Normalizing the data in this manner simplified the analysis and comparison of trends without using actual stress values. The angle of approach or the angle at which the room-and-pillar section crosses the overlying boundary was kept constant at 90°. The interburden between the two mines was also kept constant at 15.2 m (50 ft).

The stress trends for the four situations were very similar, with variations in the minimum and maximum stress values produced. A summary of the four design arrangements is as follows:

Figure 38A: The room-and-pillar section is developed from the solid to the gob side of the boundary and then retreated from the gob to the solid side, with a row of pillars supporting the boundary edge as depicted in figure 36A. As shown in the graph, the normalized average stress across the last row of pillars at the face was above the single-seam datum when the face was located beneath the solid coal and below the single-seam datum when the face was beneath the gob. The minimum normalized average stress for both development and retreat mining occurred under the gob, 61 m (200 ft) past the boundary edge, and was approximately 0.40 times the single-seam stress. The maximum normalized average stresses for both development and retreat mining occurred under the solid coal in the first inby row of pillars approximately 27.4 m (90 ft) from the boundary edge. The values were 1.45 and 1.23 times the single-seam stress, respectively.

Figure 38*B*: The room-and-pillar section is developed from the gob to the solid side of the boundary and then retreated from the solid to the gob side, with a row of pillars supporting the boundary edge as depicted in figure 36*B*. Similar to the data in figure 38*A*, the minimum normalized average stress for development and retreat mining occurred beneath the gob, approximately 76 m (200 ft) from the boundary and was 0.40 times the single-seam stress. The maximum normalized average stresses occurred under the solid coal, in the first inby row of pillars approximately 27.4 m (90 ft) past the boundary edge, and were 1.50 times the single-seam stress for development and 1.40 for retreat mining.

Figure 39*A*: The room-and-pillar section is developed from the solid to the gob side of the boundary and then retreated from the gob to the solid side, with the crosscut positioned directly beneath the boundary as depicted in figure 37*A*. The minimum normalized average stress for development and retreat mining occurred under the gob, approximately 30.5 m (125 ft) from the boundary, and had a value of 0.40 times the single-seam stress. The maximum normalized average stresses for development and retreat mining occurred under the solid coal in the row of pillars located just beyond the boundary edge and were 1.62 and 1.25 times the single-seam stress, respectively.

Figure 39*B*: The room-and-pillar section is developed from the gob to the solid side of the boundary and retreated from the solid to the gob side, with the crosscut positioned directly beneath the boundary as depicted in figure 37*B*. The minimum normalized average stress for development and retreat mining occurred under the gob and had a value of 0.40 times the single-seam stress. The maximum normalized average stresses occurred under the solid coal in the row of pillars located just beyond the boundary edge and were 1.58 for development and 1.48 for retreat mining.

To address the first design consideration, the data suggest that developing from the solid to the gob, thereby retreating from the gob to the solid side of the boundary, produces the most favorable stress condition. This relationship is best shown by comparing figures 38*A* and 38*B*. In figure 38*A*, the maximum normalized average stresses for both development and retreat mining are experienced under the solid coal approximately 27.4 m (90 ft) from the boundary edge and are 1.45 and 1.23 times the single-seam stress, respectively. In comparison, figure 38*B* shows that the maximum stresses also occur under the solid coal but are slightly higher for both development and retreat mining, 1.50 and 1.40 times the single-seam stress, respectively. A similar trend of minimum and peak stress applies for figures 39*A* and 39*B*.

Field studies indicate that when full-extraction mining is practiced it is best to retreat from the gob to the solid side of the boundary to minimize stress. Researchers from the United Kingdom (*54*) have documented ground conditions during retreat longwall mining beneath gob-solid coal boundaries in their coalfields. In one case, a longwall face approached the boundary from the solid side. As the face advanced closer to the overlying boundary, the ground conditions deteriorated as a high vertical stress was being supported by a diminishing area of the panel and pillars. Once the face was past the boundary and under the gob, face conditions improved. When the same face encountered the next boundary, and advanced from the gob to the solid, the vertical stress encountered was lessened.

The second design consideration concerns the positioning of pillars in relation to the overlying boundary. In figures 38*A* and 38*B*, the boundary edge is supported with a row of pillars. In figures 39*A* and 39*B*, the pillars are positioned on either side of the boundary, with the crosscut directly beneath the boundary. Comparison of these figures generally shows that the maximum normalized average stress is less when a row of pillars is positioned beneath the boundary edge. This is particularly noticeable for the development stress, as figures 38*A* and 38*B* display a lower normalized average stress in comparison with figures 39*A* and 39*B* regardless of the direction of mining. One must also consider that this analysis does not take into account the condition of the roof strata in the lower mine. If the mine roof is of a particularly weak nature, positioning a row of pillars, rather than a crosscut, beneath the boundary may be a better arrangement because this will limit the amount of roof exposed to the high stress under the boundary edge. Finally, the four graphs also show some similar trends that are worth noting. The minimum normalized average stress when mining is beneath the gob is approximately the same for all four cases, 0.40 times the single-seam stress. The graphs also show that the stress, when mining is under the solid coal, returns to a normal cover load (single-seam datum) at approximately 106.6 m (350 ft) to 122 m (400 ft) past the boundary edge for all four cases.

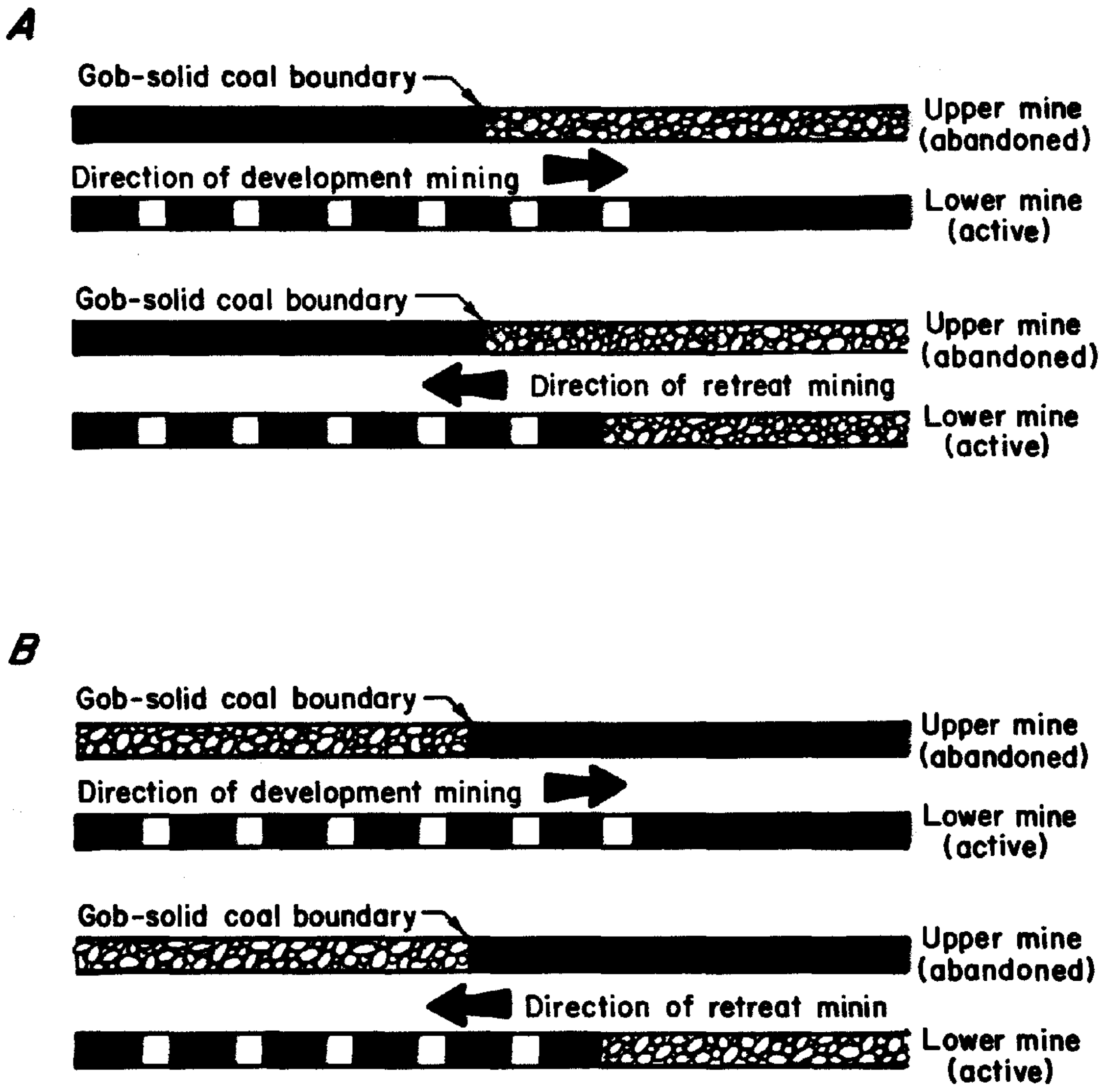

Figure 36.—Various arrangements of room-and-pillar panel being developed and retreated above and below a gob-solid coal boundary—pillar supports boundary edge. *A*, Panel developed from the solid to the gob and then retreated from the gob to the solid side of the boundary; *B*, panel developed from the gob to the solid and then retreated from the solid to the gob side of the boundary.

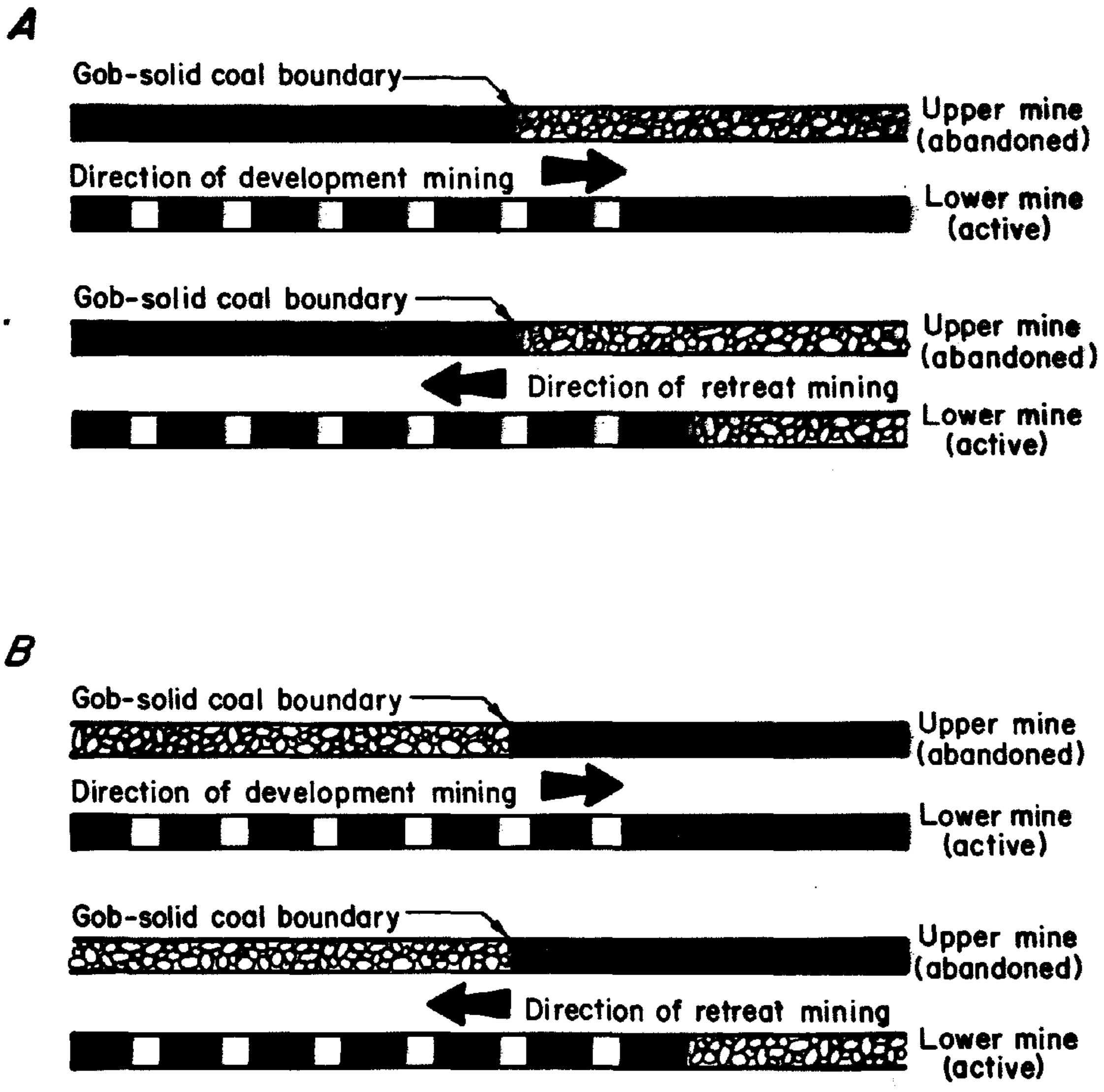

Figure 37.—Various arrangements of room-and-pillar panel being developed and retreated beneath a gob-solid coal boundary—entry supports boundary edge. *A*, Panel developed from the solid to the gob and then retreated from the gob to the solid side of the boundary; *B*, panel developed from the gob to the solid and then retreated from the solid to the gob side of the boundary.

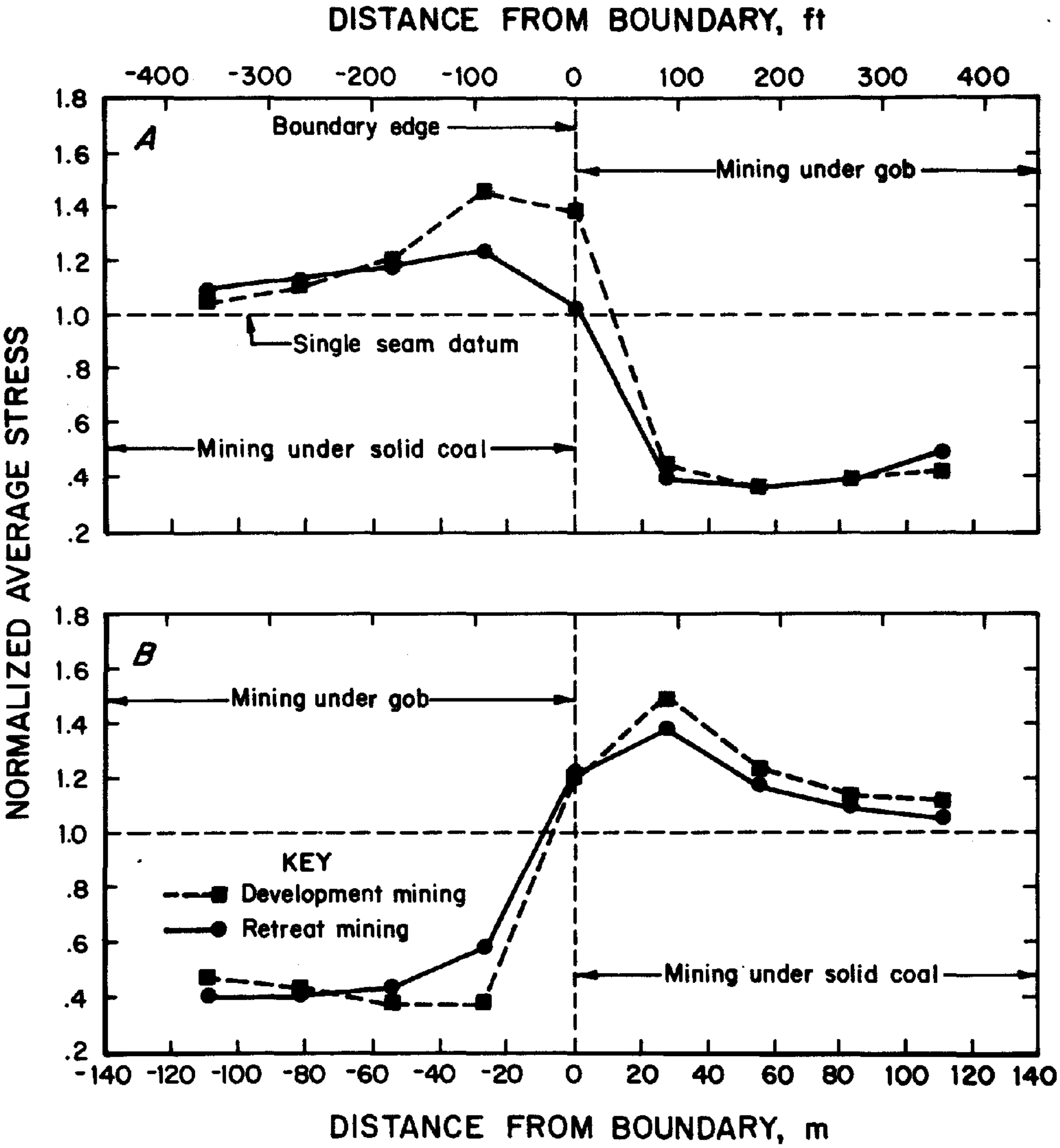

Figure 38.—Normalized average stress when developing and retreating beneath a gob-solid coal boundary-pillar supports boundary edge. *A*, Panel developed from the solid to the gob and then retreated from the gob to the solid side of the boundary; *B*, panel developed from the gob to the solid and then retreated from the solid to the gob side of the boundary.

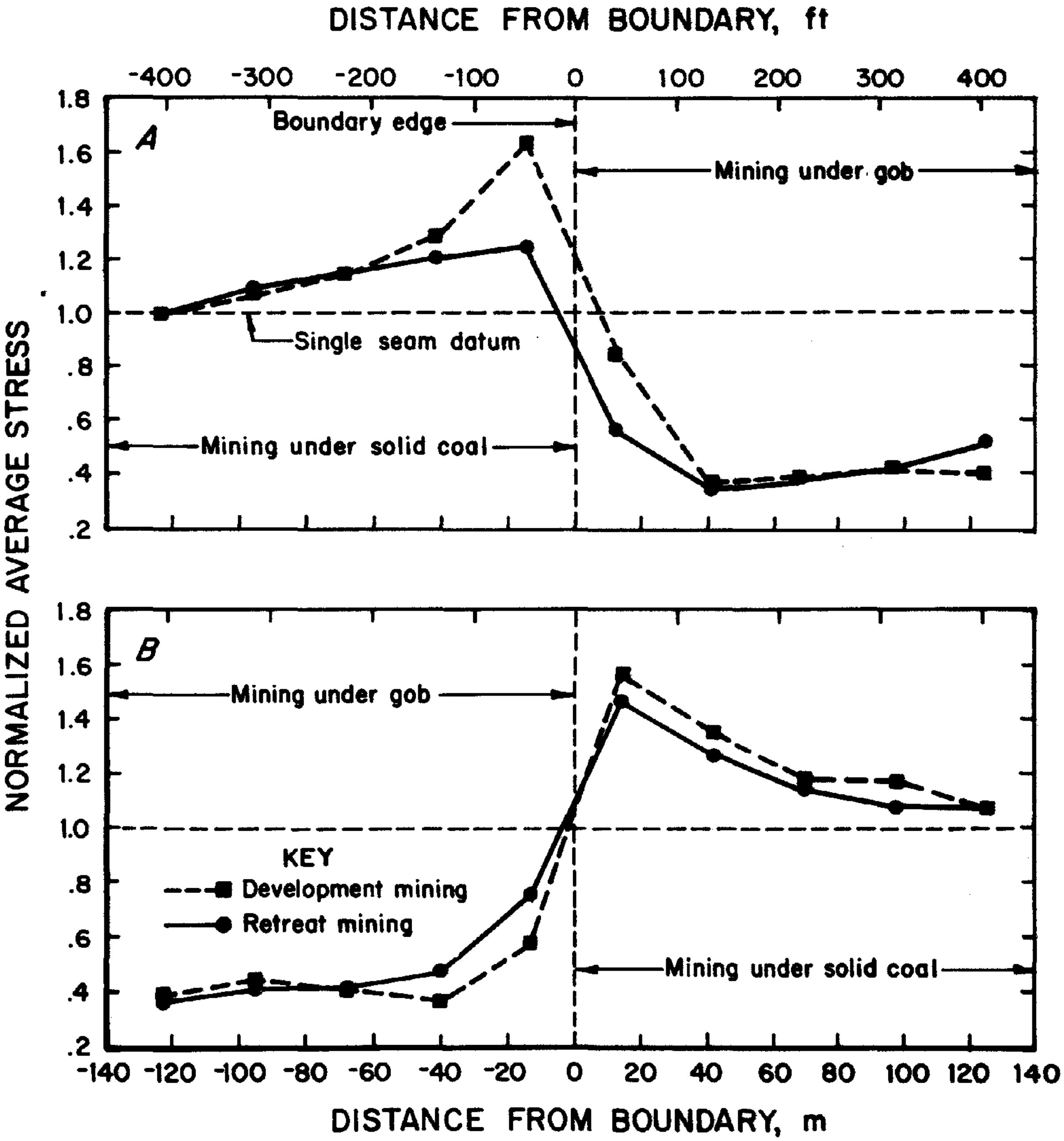

Figure 39.—Normalized average stress when developing and retreating beneath a gob-solid coal boundary—entry supports boundary edge. *A*, Panel developed from the solid to the gob and then retreated from the gob to the solid side of the boundary; *B*, panel developed from the gob to the solid and then retreated from the solid to the gob side of the boundary.

MINING BENEATH A BARRIER PILLAR

An isolated barrier pillar has a symmetric loading profile as shown in figure 23 for a wide pillar. Since the structure is surrounded by gob, there is no advantage in approaching the barrier from a particular direction as in the case of a gob-solid boundary. High-stress zones in the lower mine will occur near the barrier pillar edges where the peak load is located. Therefore, the primary design consideration is sizing and positioning the pillars beneath the barrier to reduce the lower seam loading. Two design arrangements are proposed: (1) the pillars are positioned so that the entries are located beneath the barrier edges as shown in figure 40*A*, and (2) the pillars are positioned so that they support the barrier edges as shown in figure 40*B*. The MULSIM/NL model was used to determine which of these two design arrangements would produce the least amount of stress in the lower seam pillars as mining developed and retreated beneath the barrier.

To produce results that were comparable, the analysis was conducted in the same manner as in the case when mining crosses a gob-solid coal boundary. The room-and-pillar section was developed and retreated in 27.4-m (90-ft) increments (pillar centers), and the average stress was calculated across the last row of pillars at the face where the abutment stress is located. These average stress values were then normalized to a single-seam situation for both development and retreat mining, which were 10,135 kPa (1,470 psi) and 16,200 kPa (2,350 psi), respectively. The single-seam model runs used the same input parameters as mentioned above, but without the isolated barrier pillar in the upper seam. Normalizing the data in this manner simplified the analysis and comparison of trends without using actual stress values. The angle of approach or the angle at which the room-and-pillar section crosses the isolated barrier was kept constant at 90°. The width of the barrier pillar was 110 m (360 ft), and the interburden between the two mines was kept constant at 15.2 m (50 ft).

The results of the model analysis for these two situations are shown in figures 41*A* and 41*B*. A summary of the two design arrangements is as follows:

Figure 41*A*: The pillars are positioned so that the entries are located beneath the barrier edges as illustrated in figure 40*A*. As shown in the graph, the peaks and trough of the stress profile for both development and retreat mining are very similar to those of a barrier pillar, depicted in figure 23. The maximum normalized average stress occurs in the row of pillars located just beyond the barrier edge, indicating that these pillars are supporting most of the transferred load. The maximum average normalized stresses are approximately 1.90 times the single-seam stress for development mining and 1.80 for retreat mining.

Figure 41*B*: The pillars are positioned so that they support the barrier edge as illustrated in figure 40*B*. As shown in the graph, the peaks and troughs of the stress profile are less severe than those in figure 41*A*, indicating that the stress is more evenly distributed between the pillars beneath the barrier. The row of pillars that support the boundary has normalized average stresses of approximately 1.56 times the single-seam stress for development and 1.58 for retreat mining. The maximum normalized average stresses actually occur in the next inby row of pillars and are 1.80 and 1.70 for development and retreat mining, respectively.

The data suggest that when mining is planned beneath an isolated barrier pillar, the best design layout would be to support the barrier edges with a row of pillars. This arrangement tends to distribute the transferred load from the barrier more evenly to the underlying pillars, resulting in a slight reduction in stress. Another consideration would be to resize the pillars beneath the barrier since the average development stress is rather high, approximately 1.65 times the single-seam stress, and this condition reduces the pillar safety factors. First, use equations 1 and 2 to determine the safety factors for the pillars beneath the barrier. Equation 1, $\sigma_p = \sigma_1$ (0.64 + 0.36 w/h), is used to determine the pillar strength. A 15.2- by 21.3-m (50- by 70-ft) pillar in a 1.83-m (6-ft) seam, assuming an in situ coal strength of 6,205 kPa (900 psi), has a strength of 22,410 kPa (3,280 psi). The average development stress for the pillars beneath the barrier is approximately 1.65 times the single-seam stress of 10,135 kPa (1,470 psi), or 16,750 kPa (2,430 psi). Substituting 16,750 kPa (2,430 psi) as the tributary area method value in equation 2, SF = σ_p/TAM, the safety factor is calculated at 1.24. In a single-seam situation, this same pillar has a safety factor of 2.23 (22,410/10,135 kPa).

To resize the pillars, assume a similar safety factor as for single-seam conditions, 2.23, and back-calculate. The required pillar strength from equation 2 becomes 37,360 kPa (5,420 psi). Using this as the pillar strength in equation 1 and solving for the pillar width (w), the required pillar width is approximately 27.4 m (90 ft). A 27.4- by 27.4-m (90- by 90-ft) pillar under single-seam conditions has a development stress, from equation 3, TAM = c(d) (1 + L/b) (1 + L/w), of 8,480 kPa (1,230 psi) and a safety factor of 4.4. A similar-sized pillar positioned under the barrier with the pillar supporting the barrier edges would meet the necessary design criteria.

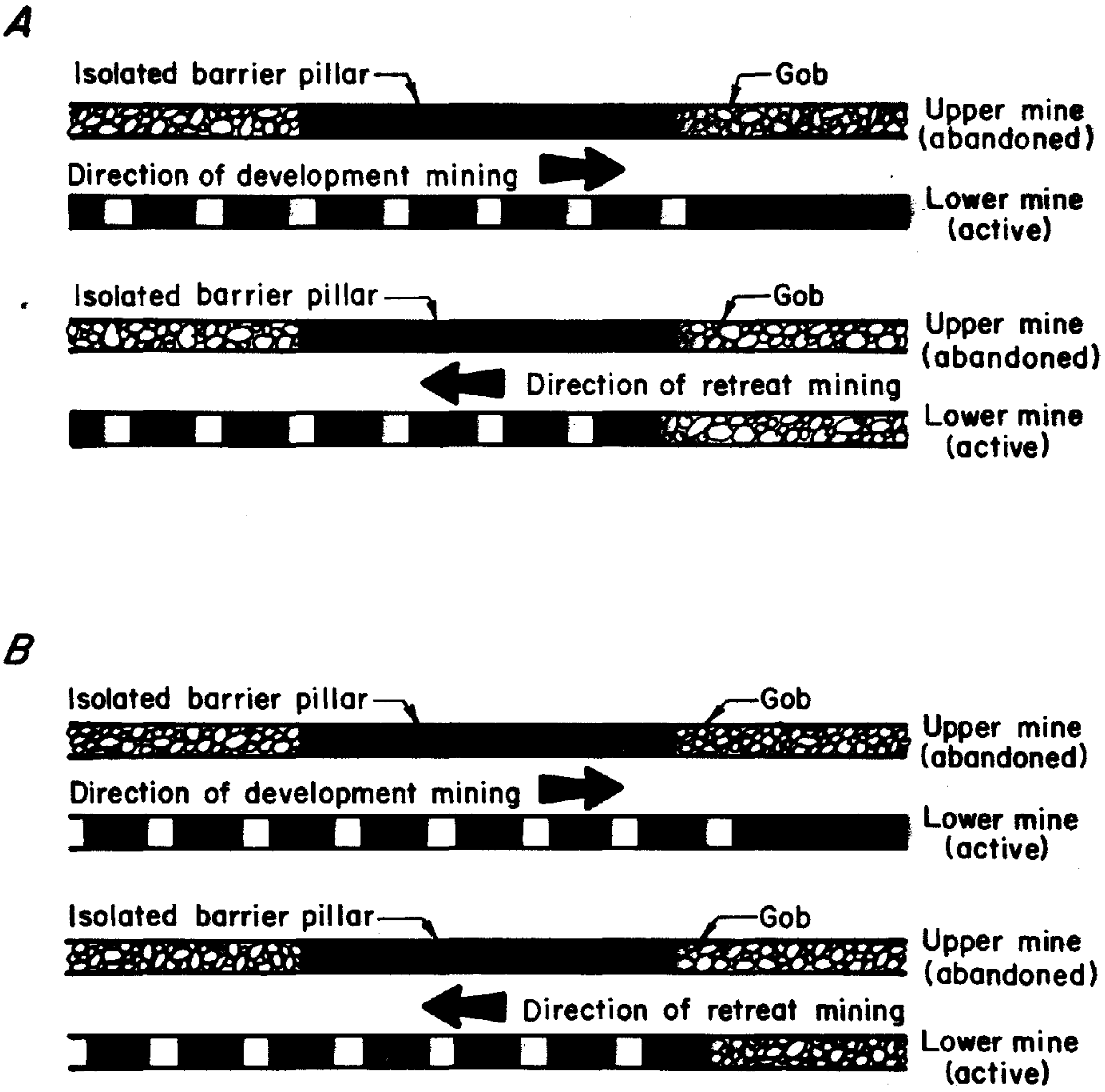

Figure 40.—Various arrangements of room-and-pillar panel being developed and retreated beneath a wide isolated barrier pillar. *A*, Entry positioned beneath barrier edge; *B*, pillar supports barrier edge.

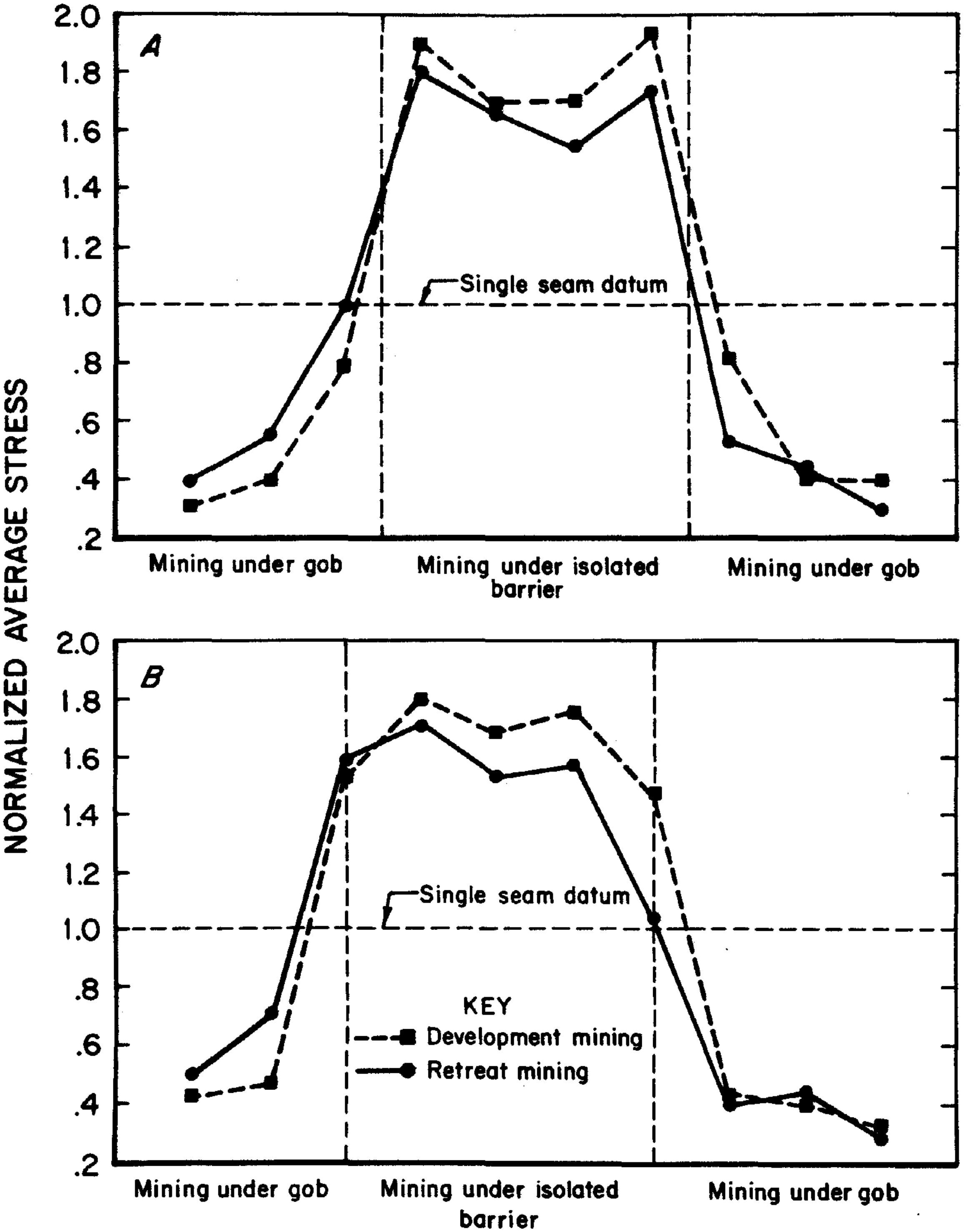

Figure 41.—Normalized average stress when developing and retreating beneath a wide isolated barrier pillar. *A*, Entry positioned beneath barrier edge; *B*, pillar supports barrier edge.

MINING BENEATH SUPPORT PILLARS

Developing beneath overlying support pillars in a room-and-pillar section can involve two possible design conditions. First, the mines are planned cooperatively and the pillars in both mines are designed for the lower seam depth. Second, the upper mine pillars are developed first without coordinated planning with the lower mine. In either case, the pillars should be columnized and designed using the lower seam depth as the design criterion because this represents the worst loading condition. To study the effects of pillar columnization on lower seam loading, a parametric study was conducted using the MULSIM/NL model. The two parameters examined were overburden and interburden. Statistical analysis of case study information and photoelastic model results show that interaction probability is most sensitive to the relationship between these two parameters (*13*). The values of these two parameters were varied to gain insight into the effects the overburden-interburden relationship has on safety factors for lower seam pillars.

For this analysis, the Bieniawski-PSU formula was used to determine the safety factors for 15.2- by 21.3-m (50- by 70-ft) pillars for a depth range from 122 to 335.3 m (400 to 1,100 ft) in 30.5-m (100-ft) increments. The in situ coal strength and seam thickness were assumed to be 6,207 kPa (900 psi) and 1.8 m (6 ft), respectively. Through a systematic procedure, MULSIM/NL model input data were gradually modified to match the pillar loadings calculated through this depth range. Once the model was calibrated to this single-seam situation, the lower mine workings were introduced into the model mesh and the interburden between the two mines was set at 7.6, 15.2, 30.5, and 61 m (25, 50, 100, and 200 ft). Figure 42 shows the columnized arrangement of the pillars and the depth and interburden ranges used in the model.

The results of the parametric study are shown in the graph in figure 43. The graph shows the effects of various interburden thicknesses on lower seam pillar safety factors as a function of depth. The relationship shows that as interburden decreases so does the lower seam design depth. To illustrate, assume the 15.2- by 21.3-m (50- by 70-ft) pillars in the lower mine are designed with a safety factor of 2.2. For a single-seam situation, the maximum design depth is approximately 221 m (725 ft). For columnized pillars in a multiple-seam situation and 7.6 m (25 ft) of interburden, the maximum design depth to the lower mine is approximately 160 m (525 ft). At 15.2 m (50 ft) of interburden, the maximum design depth is approximately 167.6 m (550 ft) and so forth, up to 61 m (200 ft) of interburden. The model predicts that lower seam loading and corresponding pillar safety factors will return to a single-seam situation at about 91.4 m (300 ft) of interburden.

Although this parametric study was conducted on only one pillar size, it demonstrates the need to use a more

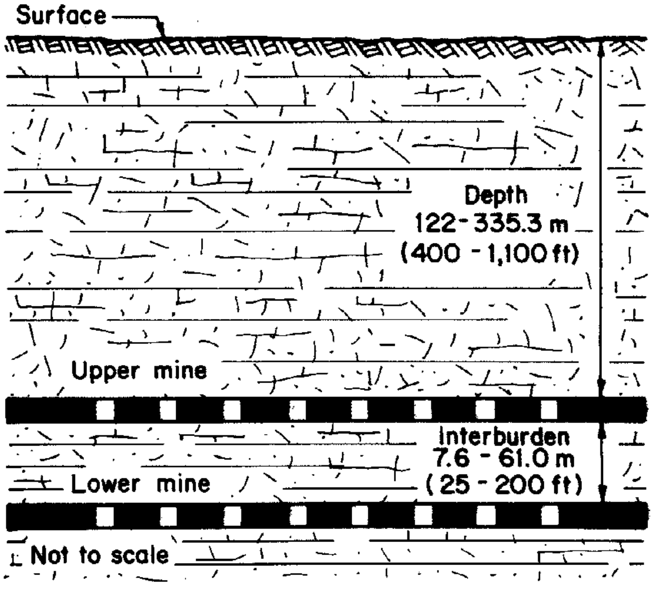

Figure 42.—Columnized pillars with depth and interburden values used in parametric study.

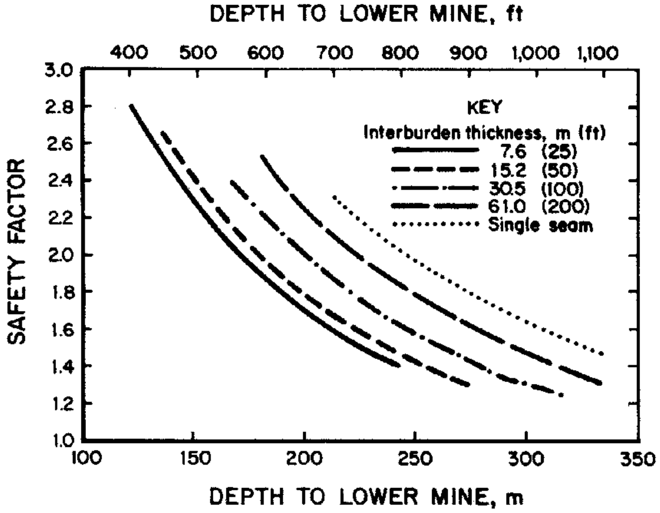

Figure 43.—Safety factors for columnized pillars at various interburdens and depths.

conservative design approach in a multiple-seam situation. The design of lower seam pillars becomes more critical under increasing depths and when the interburden is less than 33.5 m (110 ft). For instance, if the 15.2- by 21.3-m (50- by 70-ft) pillars were used under 228.6 m (750 ft) of cover and 7.6 m (25 ft) of interburden, the lower seam pillar safety factor would be 1.5. Although this may be sufficient for a single-seam situation, for multiple seams the pillars may be underdesigned. Designing with an upper limit safety factor of 2.2 will ensure that the lower seam pillars remain stable during both development and retreat mining activities.

SUMMARY

Experience has shown that mining one seam can affect subsequent operations in seams both above and below the one being mined. In the past, coal seams were mined in no particular order with regard to controlling interactions between operations and reducing associated ground control problems. The primary factors influencing seam sequencing were related to economics, availability, and ownership. Unfortunately, this practice still continues today in many instances. Ground problems associated with multiple-seam mining can cause significant damage to the mine structure, resulting in escalated mine costs, reduced safety for employees, and the loss of minable reserves. Ground problems are usually compounded by poor mine planning and a lack of knowledge of the factors that contribute to multiple-seam interactions. Improvements in mine planning and design that would control or eliminate multiple-seam interactions present a major challenge to the mining industry.

Multiple-seam mining research, for the most part, has concentrated in two areas. The first area constitutes the bulk of the research to date and involves the analysis of field data. These empirical studies involve observation or the use of geomechanical instrumentation to gather data leading to descriptive conclusions of ground problems and design recommendations for improving operation stability. Empirical studies based on case study documentation have established the factors under which interactions are most likely to occur. These studies have found that both geology and mine design influence interactive distance, magnitude, and location.

The second area involves the use of numerical methods for predicting interactive problems. These methods combine case study results with theoretical and statistical analysis in an attempt to develop optimum mining plans for different multiple-seam conditions. Photoelastic and numerical models have provided further understanding of mining-induced stress and interactions with other workings. This work has led to the development of several predictive models by government and university researchers. Numerical models can expedite the design process and provide insight into the relative stress distribution and transfer that occur under various design conditions. Numerical models have considerable potential in helping operators find solutions to complex multiple-seam interactive problems.

The purpose of this report is to provide mine operators with practical information for planning and designing multiple-seam room-and-pillar mines. It provides design strategies that should be useful when workings in overlying or underlying seams are encountered. However, the successful practice of designing multiple-seam room-and-pillar layouts depends primarily on the operator's intrinsic knowledge of local geology and strata behavior. The report has focused on three fundamental design principles for planning safe and productive multiple-seam mines: (1) the sequencing of seams, (2) the design of pillar and entries, and (3) the geometric layout of the workings.

A descending order of extraction is preferable, because the severe ground problems associated with subsidence should be avoided in most cases. When descending extraction is practiced, the operator's major concern will be the proper design of lower seam pillars beneath high-stress zones such as gob-solid coal boundaries and isolated barrier pillars. The overlying gob is a stress-relief zone and should be taken advantage of when possible. When ascending extraction is practiced, the major concern is the condition of the overlying strata that have been subjected to caving-induced stresses. Most ground control problems will occur in the zone of the subsidence trough where tensile and shear stresses are present. The operator should first assess the magnitude of potential damage in the overlying coalbed, then change mining plans accordingly when developing in this zone.

Pillar design in multiple-seam room-and-pillar developments has taken two basic approaches, yield pillars and conventional pillars. For the most part, yield pillars require further study to assess their performance under multiple-seam conditions. Although the concept is not yet a reality, yielding pillars may provide some unique solutions in designing stable and profitable multiple-seam developments in the future. The conventional approach to pillar design uses large pillars of sufficient size to withstand the development and transferred loads to which they are subjected. Proven methods for designing conventional pillars for single-seam situations have been presented by several researchers. There are several conventional pillar design approaches available to the operator that have demonstrated their success in the field under multiple-seam conditions. When laying out room-and-pillar panels, the operator can use either a superpositioned or offset arrangement, depending on mining conditions. Superpositioned panel arrangements will be used in most instances for all extraction sequences. Offset arrangements are used to avoid interactions when geologic conditions are not favorable.

In this report, the MULSIM/NL model was used to evaluate different design layouts when mining is beneath overlying workings and to determine which layouts produce the most favorable loading condition in the lower mine. The three types of upper seam structure investigated with the model were (1) a gob-solid coal boundary, which is the interface where gob and solid coal or a pillar line meet, (2) an isolated remnant structure such as a barrier pillar, and (3) the development or support pillars within the section or panel. The model showed that it is best to approach a gob-solid coal boundary by developing from the solid to the gob and retreating from the gob to the solid side of the boundary. The boundary edge should be supported with a row of pillars. Similarly, when mining is beneath an isolated structure, such as a barrier pillar, the barrier edge should be supported with a row of pillars to more evenly distribute the load to the underlying pillars. Finally, when columnizing pillars in multiple-seam, an operator should consider the relationship between depth and interburden thickness when determining pillar safety factors. A conservative design approach is needed to ensure stable lower seam workings.

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