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Proceedings: New Technology for Ground Control in Multiple-seam Mining

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Edited by Christopher Mark, Ph.D., P.E., and Robert J. Tuchman

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	m	meter
GPa	gigapascal	min	minute
hr	hour	mm	millimeter
in	inch	MPa	megapascal
ksi	1,000 psi	psi	pound-force per square inch

PROCEEDINGS: NEW TECHNOLOGY FOR GROUND CONTROL IN MULTIPLE-SEAM MINING

Edited by Christopher Mark, Ph.D., P.E.,[1] and Robert J. Tuchman[2]

ABSTRACT

Multiple-seam interactions are a major ground control hazard in many U.S. underground coal mines. In some U.S. coalfields, particularly in central Appalachia and the West, the majority of today's mines are operating above and/or beneath previously mined seams.

The effects of multiple-seam interactions can include roof falls, rib spalling, and floor heave. These can seriously disrupt mining operations and threaten the safety of miners. In early 2006, a West Virginia coal miner was killed by rib roll that occurred in a high-stress zone beneath a remnant structure in an overlying mine.

Fortunately, not every multiple-seam situation results in hazardous conditions. Indeed, the vast majority do not. For the past several years, the National Institute for Occupational Safety and Health has been conducting research to develop better techniques for predicting the location and severity of multiple-seam interactions. During this investigation, more than 50 mines were visited across the U.S. coalfields. Nearly 300 case histories were collected and analyzed using multivariate statistical techniques. The study also employed the numerical model LaM2D to estimate the multiple-seam stress, the Analysis of Longwall Pillar Stability (ALPS) and the Analysis of Retreat Mining Pillar Stability (ARMPS) programs to determine pillar stability factors (SFs), and the Coal Mine Roof Rating to measure roof quality.

The study focused on the two most common types of multiple-seam interactions:

- *Undermining*, where stress concentrations caused by previous full extraction in an overlying seam is the main concern; and
- *Overmining*, where previous full extraction in an underlying seam can result in stress concentrations and rock damage from subsidence.

The study confirmed that overmining is much more difficult than undermining, and isolated remnant pillars cause more problems than gob-solid boundaries. For the first time, however, it was possible to quantify these effects in terms of the equivalent thickness of interburden needed to compensate for them. The study also found that pillar design is a critical component of multiple-seam mine planning. Many of the failed cases involved pillars whose SF seemed inadequate once the multiple-seam stresses were accounted for. Weaker roof was also found to significantly increase the risk of multiple-seam interactions.

The most important result of the study is an equation that predicts the critical thickness of the interburden required to minimize the likelihood of a multiple-seam interaction. This equation was incorporated into a step-by-step methodology that allows mine planners to evaluate each potential interaction and take steps to reduce the risk of ground control failure. Such measures could include installing cable bolts or other supplemental support, increasing the pillar size, or changing the mine layout to avoid the remnant structure entirely.

These Proceedings also contain several previously published papers that cover other facets of multiple-seam mining research. Two papers describe the LaModel family of software developed by Professor Keith A. Heasley of West Virginia University. The LaModel programs were designed for calculating the stresses and displacements in coal mines or other thin, tabular seams in layered media. The original three-dimensional version of LaModel is essential for detailed analyses of complex multiple-seam scenarios. LaM2D, by contrast, implements a simplified two-dimensional model that is suitable for quick approximations of the multiple-seam stresses and strains.

Three additional papers in these Proceedings describe the extensive multiple-seam experience of the Harris Mine, examples of extreme multiple-seam mining from the central Appalachian coalfields, and longwall mine experiences in Pennsylvania, West Virginia, and Utah. The final paper reports on a numerical modeling study that provided some insight into the mechanics of multiple-seam mining.

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MULTIPLE-SEAM MINING IN THE UNITED STATES: BACKGROUND

By Christopher Mark, Ph.D., P.E.[1]

INTRODUCTION

Studies have estimated that 156 billion tons of coal, representing two-thirds of the minable reserves in the United States, are subject to multiple-seam mining [Singh and Dunn 1981]. In some U.S. coalfields, particularly in central Appalachia and the West, the majority of today's mines are operating above and/or beneath previously mined seams.

The effects of multiple-seam interactions can include roof falls, rib spalling, and floor heave, which can seriously disrupt mining operations and threaten the safety of miners. In early 2006, a West Virginia coal miner was killed by rib roll that occurred in a high-stress zone beneath a remnant structure in an overlying mine [MSHA 2006].

Fortunately, not every multiple-seam situation results in hazardous conditions. Indeed, the vast majority do not. Accurate prediction of which interactions are likely to be higher-risk allows mine planners to prepare for them or avoid them.

Over the years, multiple-seam mining has been the subject of much research, both in the United States and abroad. Much advice on how to mitigate the risk has been presented, but unfortunately it is often contradictory. For example, one group of researchers wrote that "stresses from superincumbent workings are not transferred through shale strata for distances of over 110 ft" [Haycocks et al. 1982], while another group indicated that "a stress transfer distance of 760 ft has been recorded between longwalls" [Haycocks et al. 1992].

For the past several years, the National Institute for Occupational Safety and Health has been conducting research to develop better techniques for predicting the location and severity of multiple-seam interactions. During this investigation, more than 50 mines were visited across the U.S. coalfields. The study also made extensive use of numerical models, particularly the LaModel family of software [Heasley and Agioutantis 2007]. This paper presents the background to that study. The results of the study are discussed by Mark et al. [2007].

BACKGROUND

Figure 1 shows the five major underground coal mining regions in the United States. From the standpoint of multiple-seam mining, by far the most significant coalfield is the central Appalachian region of southern West Virginia, eastern Kentucky, and southwestern Virginia. Currently, underground mines in this region produce approximately 123 million tons of coal per year, or about 33% of the total U.S. underground production [EIA 2006]. Mining has been ongoing in central Appalachia for nearly 150 years. Recent studies have indicated that perhaps 70% of the ultimate reserve base in the region has already been mined [Bate and Kvitkovich 2004].

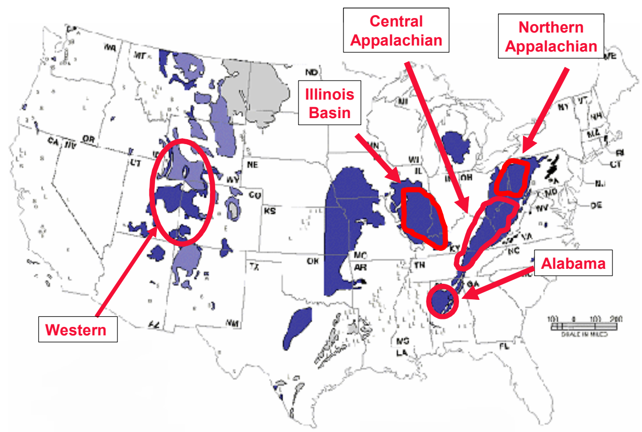

Figure 1.—The five major underground coal mining regions in the United States.

One consequence of the maturity of the central Appalachian coalfields is that nearly every remaining underground reserve has been impacted by past mining activity. The mountains of the central Appalachian coalfields are honeycombed with worked-out mines located above, below, and adjacent to today's and tomorrow's operations. Figure 2 shows a typical geologic column from the central Appalachian region. On this property there are 13 seams in which mining has been or is currently being conducted.

Full extraction is also widely practiced in the central Appalachian coalfields. Although only 8 mines currently use the longwall method [Fiscor 2006], a recent survey indicated that approximately 315 mines, accounting for 58% of the room-and-pillar production in the region, engage in pillar recovery [Mark et al. 2003]. The prevalence of full extraction adds greatly to the potential for multiple-seam interactions.

The Western United States is the next most significant area for multiple-seam mining. In Utah, Colorado, Wyoming, and New Mexico, nearly 95% of underground

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production comes from 13 longwall operations [EIA 2006; Fiscor 2006]. Approximately half of these are operating in multiple-seam configurations. In contrast to central Appalachia, in the West the same mining company is usually responsible for all the mining on a property. As a result, a greater degree of multiple-seam planning is normally possible. On the other hand, when combined with deep cover and strong roof and floor rock, multiple-seam interactions can contribute to deadly bump hazards [Peperakis 1968; Iannacchione and Zelanko 1995].

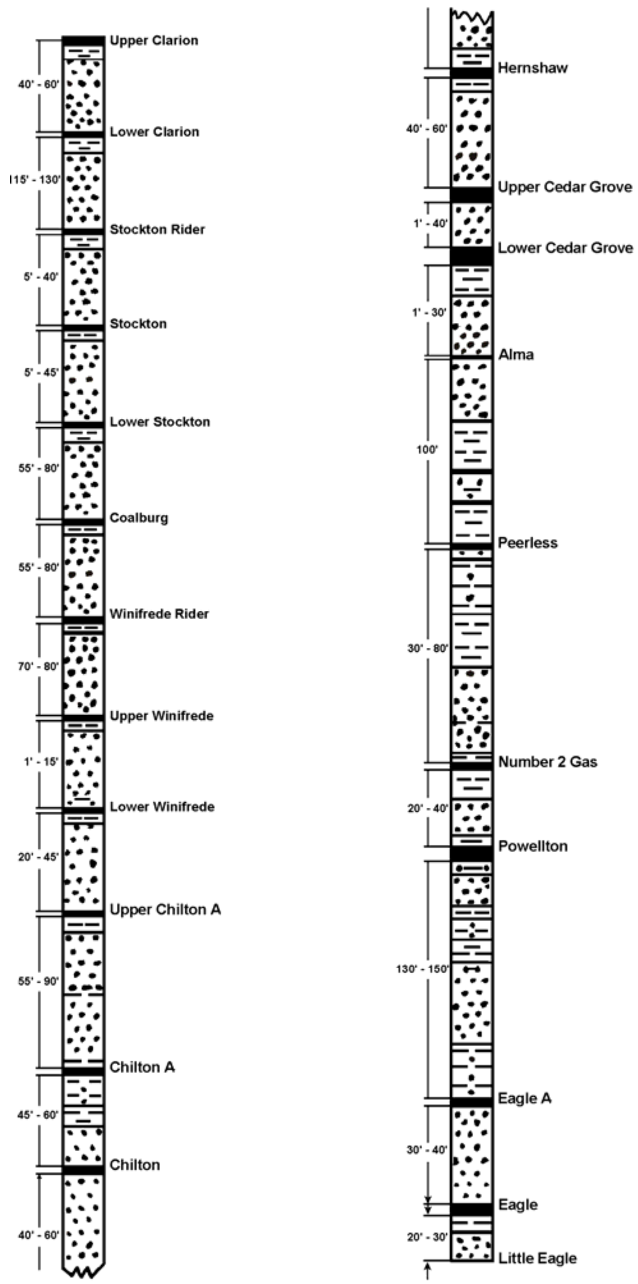

Figure 2.—Typical geologic section for Boone County, WV, showing coal seams.

In none of the other three underground mining regions are multiple-seam interactions currently a major factor, although all three historically have had problems [Kohli 1992; Paul and Geyer 1932; Zachar 1952], and they may very well have them again in the future. Factors that contribute to the relative lack of multiple-seam interactions in these regions include the following:

- Most longwall production in the northern Appalachian and Alabama coalfields is from a single seam (the Pittsburgh and Blue Creek Seams, respectively), without significant mining in other seams above or below.
- The depth of cover, particularly for room-and-pillar mines, is relatively low in northern Appalachia and the Illinois Basin.
- Very few room-and-pillar mines engage in full-extraction pillar recovery in the Illinois Basin. There is almost no room-and-pillar mining at all in Alabama.

HAZARDS ASSOCIATED WITH MULTIPLE-SEAM MINING

Ground instability is usually the greatest hazard due to multiple-seam interaction. Interactions may be classified into four major categories depending on the mining method, mining sequence, and thickness of the interburden. Other potential hazards are associated with water, gas, and oxygen-deficient air.

Undermining, the first category of interaction, occurs when the upper seam has been mined first and the lower seam is the active seam (Figure 3). In an undermining situation, damage is caused by load transfer from highly stressed remnant structures associated with full-extraction mining in the overlying seam. These remnant structures can generally be classified as either:

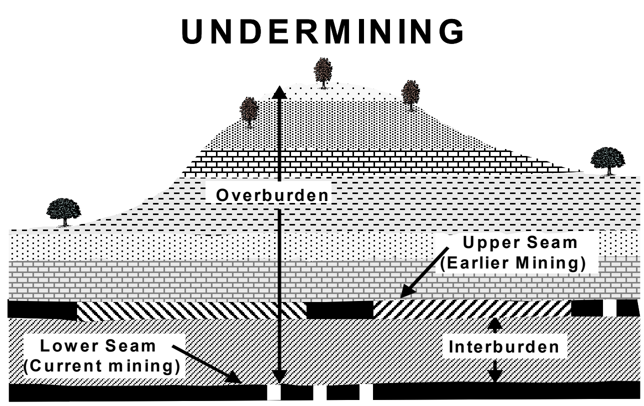

Figure 3.—Undermining interaction.

- *Gob-solid boundaries*, with gob on one side; or
- *Isolated remnant pillars* that are surrounded by gob on two or more sides (Figure 4).

Figure 4 shows that while a gob-solid boundary carries a single, distributed abutment load, an isolated remnant pillar is subjected to two overlapping abutments.

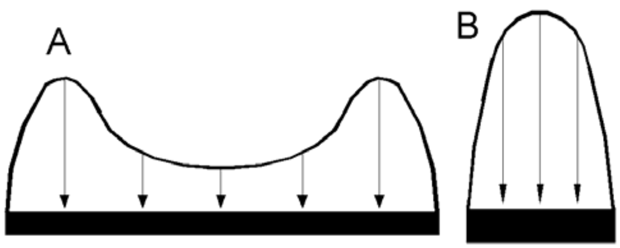

Figure 4.—Stress concentrations in multiple-seam mining: (A) gob-solid boundaries associated with a very large pillar and (B) remnant pillar isolated in the gob.

As a result, the stress concentration on an isolated remnant pillar is usually significantly larger than that on a gob-solid boundary, and its impact on underlying seams is proportionally greater. The interburden thickness is also important because the stress concentration beneath any upper-seam remnant structure becomes less intense the greater the interval between the seams.

Overmining, the second type of interaction, occurs when the upper seam is extracted after mining is complete in the lower seam (Figure 5). Load transfer occurs in this situation just as it does in undermining (in other words, gob-solid boundaries and isolated remnant pillars cause stress concentrations both above and below). In addition, however, full extraction of the lower seam normally results in subsidence of the overlying beds.

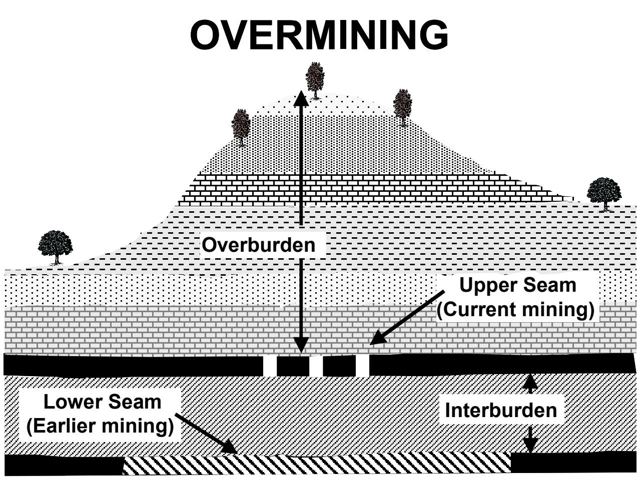

Figure 5.—Overmining interaction.

Figure 6 is a conceptual model that illustrates the type of damage that can be expected within the overburden due to subsidence above a full-extraction panel. Five broad zones can be identified [Singh and Kendorski 1981; Peng and Chiang 1984; Kendorski 1993, 2006]:

1. The *complete caving zone*, in which the roof rock is completely disrupted as it falls into the gob, normally extends two to four times the extracted seam height (h).
2. The *partial caving zone,* in which the beds are completely fractured but never lose contact with one another, extends up to 6–10 h.
3. The *fracture zone,* within which the subsidence strains are great enough to cause new fracturing in the rock and create direct hydraulic connections to the lower seam. The top of this zone can be as high as 24 h above the lower seam.
4. The *dilated zone,* where the permeability is enhanced but little new fracturing is created, extends up to 60 h.
5. The *confined zone,* where subsidence normally causes no change in strata properties other than occasional bed slippage. This zone extends from the top of the dilated zone to about 50 ft below the surface.

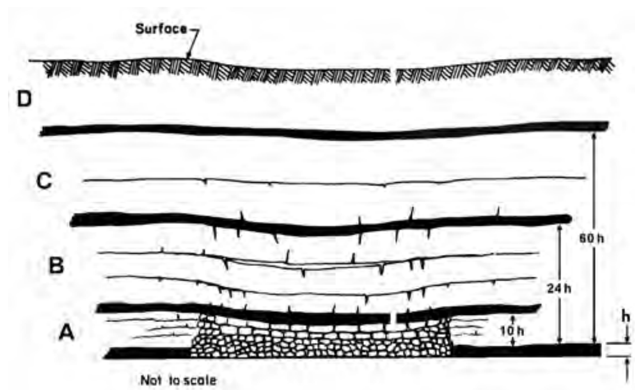

Figure 6.—Overburden response to full-extraction mining: (A) caving zones, (B) fracture zone, (C) dilated zone, and (D) confined zone.

The dimensions of these zones vary from panel to panel because of differences in geology and panel geometry. The implication of this model for multiple-seam mining is that when the interburden thickness exceeds approximately 6–10 times the lower seam thickness, the upper seam should be largely intact, although the roof may be fractured or otherwise damaged.

Dynamic interactions occur whenever active mining occurs above or beneath open entries that are in use. The most severe dynamic interactions occur when a lower seam is longwalled or pillared, resulting in active subsidence of the open overlying workings. However, damage can also be caused by the abutment stresses associated with full extraction in an overlying seam or even, in extreme cases, by development mining above or below.

The conditions associated with dynamic interactions are generally far more difficult than would have been the case if the open workings were developed after the full extraction was completed. Part of the explanation is that a dynamic interaction subjects the preexisting works to a traveling wave of subsidence and/or abutment stress rather than the static situation where the disturbance is concentrated in a single area. In addition, while unmined ground is normally in a confined state when it is overmined or undermined, the presence of a mine opening removes the confinement. The loss of confinement greatly weakens the rock mass and exposes it to tensile bending stresses.

Ultraclose mining is the fourth type of interaction and the only one in which development mining alone is significant. The main concern is failure of the interburden between the two seams. The beam of interburden can fail either through shear caused by pillar punching or by tension caused by the self-weight of the rock plus that of any machinery working on it (Figure 7). Ultraclose interactions are unlikely when the two seams are more than 20–30 ft apart [Haycocks and Zhou 1990; Singh et al. 2002]. Ultraclose scenarios are most likely to occur near where a thick seam splits or where a rider coalbed is of minable thickness.

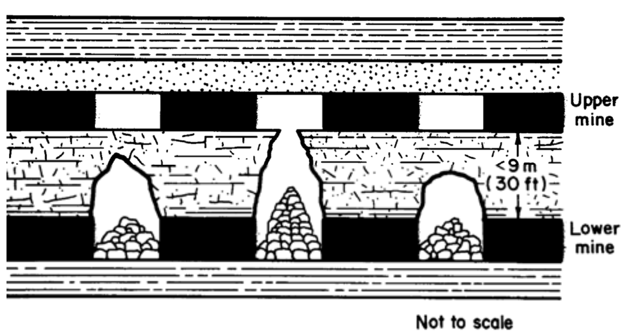

Figure 7.—Ultraclose mining (after Chekan and Listak [1994]).

Other hazards include the potential for inundation from an overlying flooded mine, particularly where full extraction in the lower seam can create a direct pathway between the upper- and lower-seam gobs. Mine Safety and Health Administration (MSHA) regulations require that a permit be obtained prior to mining under a body of water. An evaluation of the potential hazard should consider [Michalek and Wu 2000]:

- Estimates of the potential volume of water in the overlying mine;
- Evaluation of the strata separating the two mines;
- Determination of probable flow paths and identification of critical areas that may become flooded;
- A warning system, water control plan, and evacuation plan in the event of an inundation.

A review of MSHA data indicates that of the 201 inundation incidents that were reported during 1996–2005, only 4 resulted when caving associated with full extraction in a lower seam intersected water-filled overlying workings. Several other water inundations occurred when development in a lower seam inadvertently cut into uncased boreholes that were connected with an upper seam. No injuries were associated with any of these incidents. In one incident, however, the first longwall panel at a Kentucky mine encountered a major inflow from workings 150 ft above. The water posed no hazard to the miners, but the lack of pumping capacity in the lower seam resulted in major mining delays [Mark et al. 1998].

Interestingly, development *above* gob areas has been associated with large, but temporary groundwater inflows in several instances [Stansbury 1981; Bauer et al. 1992; Lazer 1965]. In these cases, the fracture and dilated zones apparently filled with excess groundwater, which was drained when the entries were developed. Fractures in these zones can also fill with methane or oxygen-deficient air, resulting in inflows of methane or blackdamp when they are intersected by overmining.

Overmining

During the hand-loading era, which lasted until about 1950, most underground coal mines operated under shallow cover and emphasized complete recovery, leaving few remnant structures in the gob. Perhaps as a result, early studies of multiple-seam interactions barely mentioned undermining and focused almost exclusively on overmining.

One of the first comprehensive studies was reported by Eavenson [1923a]. He concluded that "mining an upper seam after a lower one can almost always be successfully done when the interval between the seams exceeds 19 ft," although he noted several cases where some coal had to be abandoned with interburdens up to 120 ft. Several other individuals, including such notable rock mechanics pioneers as D. Bunting and G. S. Rice, took partial exception to Eavenson's conclusion, pointing out the importance of the nature of the interburden, thickness of lower bed, and uniformity of extraction of the lower bed [Eavenson 1923b]. Taking all the evidence into consideration, the American Institute of Mining and Metallurgical Engineers, Committee on Ground Movement and Subsidence, concluded that Eavenson's figure of 19 ft was appropriate as long as the thickness of the lower seam did not exceed 8–9 ft [AIMME 1926].

The next significant investigations of multiple-seam mining were conducted at Virginia Polytechnic Institute and State University (VPI) in the early 1950s by C. T. Holland and his student D. T. Stemple. Initially, Holland seemed to draw optimistic conclusions similar to those of Eavenson. Citing 38 examples from the literature, he concluded that "all but two or three" were successful, although "success" was defined as extracting as little as 50% of the upper seam [Holland 1951]. Holland found that 20–25 ft of interburden was adequate to provide good mining conditions, although he emphasized that "no remnants should be left in the lower seam" because remnants are "certain to result in considerable disturbance to the overlying strata." Holland also emphasized that at least 3 months, and preferably several years, should elapse after completion of mining in the lower seam to allow settlement of the gob to be complete [Holland 1951].

The study by Stemple [1956] was a landmark. He visited 45 mines throughout the eastern coalfields and ultimately collected a database of 61 actual mining case histories. About one-third of these were overmining cases, and Stemple found that in nearly every one there was some disturbance to the overlying seam, including:

- Cracking or horizontal parting of the roof strata;
- Vertical displacement (subsidence);
- Rarely, but serious when it occurred, "squeezing and crushing of coal, accompanied by falls of top or heaving of the bottom."

Stemple found that the most severe damages occurred directly above isolated remnant pillars abandoned in the underlying seam. Gob-solid boundaries also caused trouble, but the greatest disturbance was typically observed "not directly above the gob edge, but rather 100–300 ft out over the goaf."

Stemple concluded that Eavenson's recommendation of 19 ft of interburden might have been adequate for hand-loading, but that "such conditions would probably be prohibitive to mechanized mining." Indeed, he found that "damage seriously adverse to mining can be done even with a vertical interval greater than 300 ft."

One explanation for the discrepancy between the conclusions of Stemple and Eavenson is that they may have been talking about different things. Eavenson was apparently concerned with mining over gob areas, which were usually quite extensive in hand-loading operations. As mechanized mining became more prevalent, remnants of various shapes and sizes were more often left within the gob areas. In addition, the new mining methods were less flexible, so when working an overlying seam it became much more difficult to avoid the underlying remnants. The result was that even though mining above gob areas might still be feasible, finding enough good mining to make extracting an overlying seam profitable became much more challenging.

One other factor Stemple evaluated was the effect of time. He concluded that mining in an overlying seam should not be conducted until the subsidence process is completed, which could require 5–10 years.

The next major study of multiple-seam mining was conducted by C. Haycocks and his students and colleagues at VPI. This work was conducted over a period of nearly 2 decades, beginning in the early 1980s. Haycock's program included the development of empirical equations based largely on Stemple's data, supplemented by analytic work, photoelastic studies, and numerical modeling. There is little evidence, however, of underground in-mine data collection in Haycock's work. Haycock's research resulted in an extensive published literature, as well as several mine design computer programs.

To evaluate the potential for successful overmining, several equations were proposed [Haycocks and Zhou 1990]:

$$I_{co} = h/t\,[18.84\,X - 2(Z - 50) - 1{,}240] \tag{1}$$

$$I_{co} = h\,(3.5X - 224) \tag{2}$$

$$I_{co} = h/t\,(15X - 973) \tag{3}$$

where I_{co} = critical interburden thickness (ft) for no appreciable damage to upper seam;
h = lower-seam thickness (ft);
t = time since mining the first seam (years);
X = percent extraction in the lower seam;
and Z = percent hard rock in the interburden.

Equation 2 indicates that the critical interburden thickness ranges from zero (for a lower-seam extraction of about 65%) to as much as 700 ft (for 90% extraction in an 8-ft lower seam).

Application of these equations presents several problems. First, it is not made clear where they should be applied—above an isolated remnant pillar, a gob-solid boundary, or anywhere the lower seam has been mined out? Second, where should one determine the percent extraction in the lower seam? Is it an overall percent extraction, or does it vary from place to place? Finally, Equations 1 and 3 are very sensitive to the time factor, but does it make sense that critical interburden thickness is reduced by a factor of 10 if a fully subsided gob is 50 years old rather than 5?

Luo et al. [1997] looked back on the earlier VPI studies and concluded that "although efforts were made to relate the magnitude of upper-seam damage to innerburden thickness, mining height, time, and extraction percentage, the data scatter was too great to achieve this relationship." Further research also showed that "upper-seam damage could not be correlated with subsidence strain at the upper-seam elevation." More success was reportedly achieved when the upper-seam roof conditions were included together with vertical movement in the upper seam.

Several case histories of overmining, successful and unsuccessful, have been reported in the literature during the past 3 decades. In the Gary District of southern West Virginia, U.S. Steel attempted to work the Pocahontas No. 4 and 5 Seams about 60 ft above the worked-out No. 3 Seam [Stansbury 1981]. Conditions were extremely difficult, particularly in the No. 4 Seam where the roof consisted of "3–17 ft of unconsolidated and thinly laminated bands of shale intermixed with thin bands of coal." Particular difficulties occurred "when mining near or directly above gob lines or lost blocks of coal in the No. 3 Seam." Ground control was reportedly achieved by developing 12-ft-wide entries supported by 9-ft bolts and trusses, both on 3-ft centers, but the roof support cost made mining uneconomic. Mining was significantly easier in the No. 5 Seam, typically just 10 ft above the No. 4, and the difference was attributed to a more competent shale roof.

In central Pennsylvania, Bethlehem Mines Corp.'s No. 33 Mine employed longwall methods to extract the B Seam and the overlying C-prime Seam [Bauer et al. 1992]. The B Seam, averaging about 5 ft thick, was extracted first, and the interburden was approximately 105 ft. The depth of cover was typically less than 600 ft, which allowed the upper-seam gates to be stacked above the lower ones. Ground conditions in the upper seam were generally quite good, indeed better than areas where the upper seam was mined over virgin B Seam. The improvement was attributed to subsidence above the lower-seam longwalls that apparently relieved some of the in situ horizontal stress. Some minor areas of poor roof were encountered when crossing into areas above the gob, but these could be handled with some additional support. Water inflows were a more serious impediment to upper-seam mining.

In eastern Kentucky, Black Mountain Resources used room-and-pillar techniques to extract Owl Seam reserves located 200–235 ft above abandoned Harlan Seam longwall panels [Rigsby et al. 2003]. The Harlan Seam was 11 ft thick with up to 1,500 ft of cover. The Owl Seam panels were driven across the longwall stopline pillars and then developed over the longwall gob. Although some roof fractures, rib spalls, and water inflows were observed, the panel was developed and retreated without major incident.

Undermining

Although undermining is more common than overmining and although it is the recommended mining sequence, it has received considerably less attention in the literature than overmining. The explanation may be the apparent simplicity of the load transfer effect. For significant load transfer to occur, two factors must be present:

- The interburden must be relatively thin; and
- The seams must be relatively deep.

Stemple [1956] included 26 cases of undermining in his study, and he documented interactions in about half of them. In those cases where interactions occurred, the depth of cover exceeded 500 ft and the interburden was less than 110 ft. The disturbances all occurred beneath isolated remnant pillars or within 100–200 ft of a gob-solid boundary. Stemple also concluded that the time lag after the mining of the upper seam was not a factor in undermining.

Haycocks et al. [1982] emphasized the role of the interburden geology in determining the extent of load transfer. A softer overburden, either due to a large number of rock layers or a low modulus of the individual layers, results in an elongated pressure bulb that reaches deeper seams below. Using Stemple's data, Haycocks et al. [1982] proposed two relationships for predicting the critical interburden thickness (I_{cu}) in room-and-pillar mining:

$$I_{cu} = 110 - 0.42\,Z \qquad (4)$$

$$I_{cu} = 6.8\,N + 55 \qquad (5)$$

where N = the number of interbeds;
and Z = percent hard rock in the interburden.

Equation 4 is illustrated in Figure 8. Elsewhere, Haycocks and Zhou [1990] emphasized the special role of isolated remnant pillars, including longwall chain pillars, in creating high-pressure zones in seams above or below. Pillars less than 60 ft wide were singled out as allowing the "abutment pressure zones from both sides to superimpose."

In European mines, multiple-seam interactions have been a major concern for many years due to the deep cover and long history of mining. In the 1970s, the U.K. National Coal Board collected detailed data from 18 undermining case histories [Dunham and Stace 1978]. Using multivariate statistical techniques, the study concluded that the two most important factors affecting the condition of the underlying seam during longwall extraction were:

- The type of remnant structure; and
- The initial roadway stability (determined rock strength, roadway width, depth of cover, width of the adjacent pillar, and other factors).

Dunham and Stace cautioned that it is "extremely dangerous to dismiss interaction effects purely on the basis of the thickness of the interval between the seams." In one case in their database, an isolated remnant pillar caused a disturbance 450 ft below, while in another case, a gob-solid boundary had no noticeable effect just 90 ft below.

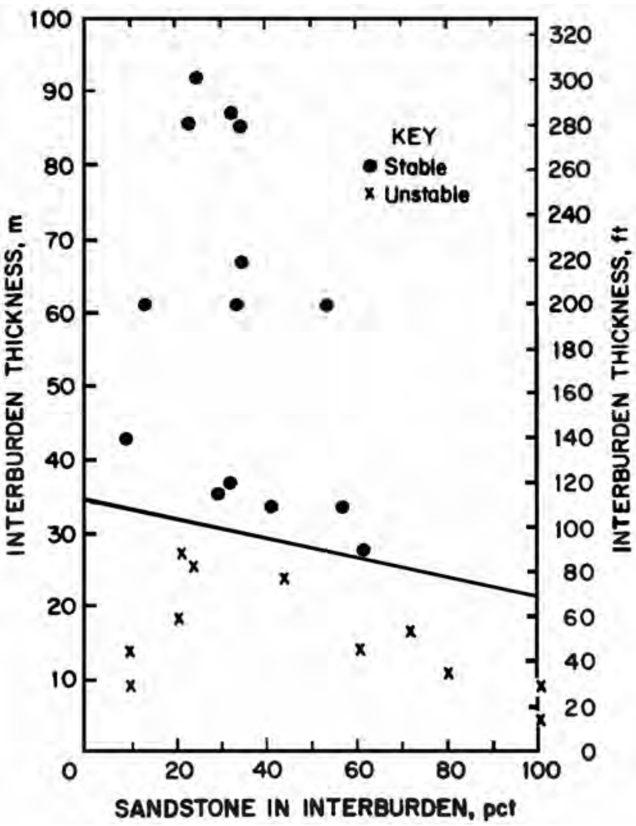

Figure 8.—Percent sandstone in interburden versus interburden thickness (after Haycocks and Zhou [1990]).

Dynamic Interactions

For nearly a century, the verdict of the experts on dynamic interactions has been unanimous: Don't do it! Some examples follow:

- Eavenson [1923a]: "Working in an upper seam should not be attempted while pillar robbing is going on beneath it."
- Paul and Geyer [1932]: "Pillar recovery should never be commenced under advance work in the overlying seam."
- Stemple [1956]: "The greatest difficulties are caused when pillar falls are made in the lower seam beneath previously developed entry work in the upper seam."
- Lazer [1965]: "If openings are first developed in the upper seam and then undermined, the openings in the upper seam will cave totally and the developed pillars will be lost."

Despite these warnings, this practice is still occasionally tried, with depressing results. Three relatively recent cases have been reported in the literature—one where pillars were extracted beneath previously developed mains 180 ft above [Su et al. 1986] and two where longwalls were extracted as far as 550 ft beneath open main entries [Ellenberger et al. 2003; Mark 2006]. In each case, the overlying main entries were lost or severely damaged.

Less predictable are instances in which delayed subsidence of underlying works has the same destructive effect on overlying entries. In one instance, a set of mains was developed 180 ft above pillared works, and conditions were excellent for 2 years [Mark 2006]. Then the roof began to deteriorate dramatically, and heavy supplemental support was required to prevent major roof collapses. In another instance, dewatering of 20-year-old works caused marginally stable support pillars to fail, causing a pillar collapse in an overlying seam and subsidence at the surface [Kohli 1992]. In yet a third case, extensive floor heave developed in a lower seam 2 years after it was developed. A year later, the 5-year-old workings in the upper seam were severely damaged [Matetic et al. 1987].

Although subsidence associated with full extraction in a lower seam has the most dramatic effects, dynamic interactions have also been attributed to full extraction in an upper seam [Hill 1995]. In this situation, because the stress abutments are applied to the unconfined strata around preexisting openings in the lower seam, their effects are more severe than would be the case if the upper-seam mining was complete before the lower seam was developed.

Ultraclose Mining

Haycocks and Zhou [1990] stated that "when the interburden thickness is less than two times the room width, interburden failure cannot be ruled out." Typically, however, ultraclose interactions are only a concern when the interburden is less than 25 ft. Zhou and Haycocks [1989] determined that the minimum safe working thickness for a massive, unstratified sandstone was just 6 ft, whereas for shale it was 20 ft. They also determined that tensile failure is unlikely when the interburden thickness exceeds about 4 ft, so shear failure is the main concern.

Columnization of the pillars is considered the standard design practice when ultraclose interactions are a concern. Columnization minimizes the shear stress in the interburden and also provides a more uniform stress on the pillars, minimizing the risk of pillar failure. In Indian coal mines, columnization is required if the interburden is less than 30 ft [Singh et al. 2002]. In South Africa, columnization is recommended where the parting distance is less than 0.6–0.75 times the pillar center-to-center distance. Barrier pillars should be columnized for interburdens up to 100 ft thick [Munsamy et al. 2004].

NUMERICAL MODELING FOR MULTIPLE-SEAM MINING

Analysis of multiple-seam mining interactions is complex because of the many geologic and mine design variables, as well as the complicated three-dimensional (3–D) geometries that occur. This complexity makes empirical analysis difficult and lends attractiveness to numerical approaches. Two main types of numerical model have been employed for multiple-seam analysis:

- *Displacement-discontinuity* models, including MULSIM and LaModel, in which only the seams of interest are discretized; and
- *Finite-element* models, in which the entire rock mass must be discretized.

Displacement-discontinuity models provide a pseudo-three-dimensional simulation of tabular deposits such as coal. They have undergone continuous development and improvement over the past 2 decades. The original MULSIM and MULSIM–PC codes were limited to purely elastic analyses [Donato 1992]. MULSIM–NL allowed yielding of elements within the coal seams and nonlinear gob elements [Zipf 1992], but the overburden was still simulated as one solid material. LaModel introduced a formulation that simulates the overburden as a stack of layers with frictionless interfaces, thereby providing a more realistic suppleness to the strata response [Heasley and Chekan 1999]. LaModel can also consider topographic relief and subsidence, and LaModel grids can be generated directly from AutoCAD mine maps [Heasley and Agioutantis 2007]. The most recent development is a simplified two-dimensional (2–D) version of LaModel called LaM2D, which is much easier to grid and which runs in a fraction of the time required for the full 3–D model [Akinkugbe and Heasley 2007].

Chekan and Listak [1993, 1994] employed MULSIM–NL in an extensive series of parametric studies evaluating the effects of mining sequence and orientation on multiple-seam interactions. Their most significant findings were:

- Peak multiple-seam stresses are greater when retreating from solid toward the gob than when retreating from the gob to the solid (Figure 9);
- Stresses on the longwall face are greatest when the face is being retreated in a direction directly perpendicular to a remnant structure in the other seam; and
- Orientation relative to other seam remnant structures is not a major factor for development workings.

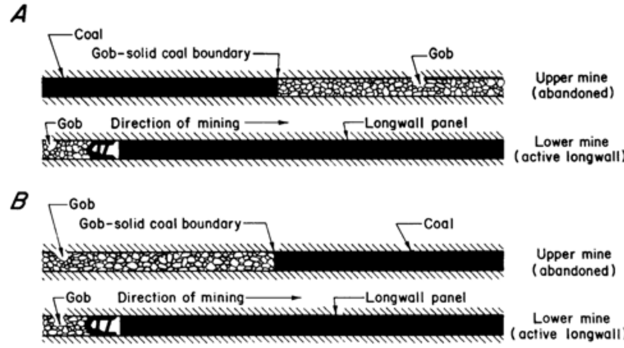

Figure 9.—Influence of retreat direction on multiple-seam interaction: (A) retreating from solid to gob creates an unfavorable "stress window," while (B) retreating from gob to solid results in lower stress concentrations (after Chekan and Listak [1993]).

Heasley and Chekan [1999] report two case histories in which LaModel was used to evaluate multiple-seam interactions. In both cases, the model results were calibrated against extensive stress mapping that was conducted underground. In the first instance, an undermining example from eastern Kentucky, a 60-ft-wide isolated remnant pillar in the upper seam resulted in a multiple-seam stress of 2,200 psi, which, when added to the 3,000-psi single-seam pillar stress, was enough to cause significant roof and rib failure (Figure 10). In the other case, a set of longwall gates encountered multiple-seam stresses of 1,300 psi above a barrier adjacent to high-extraction room-and-pillar mining. A significant feature of this study was that it was necessary to simulate the yielding of the lower-seam production pillars in order to realistically model the interaction.

Su et al. [1986] report an early example of the use of finite-element modeling to investigate multiple-seam interactions. Both 2–D and 3–D models were employed, and some allowed bedding plane slip. One significant conclusion was that caving of the lower-seam roof strata forced the horizontal stresses upward, potentially creating stress concentrations around openings in the upper seam. The models also showed that highly bedded rock, where sliding takes place along individual layers, results in a narrower and deeper zone of interaction.

Hsiung and Peng [1987a] used numerical modeling to develop some rules of thumb for undermining. They concluded that if the interburden thickness is two to three times the width of the upper-seam isolated remnant pillar, no interaction is likely to occur. On the other hand, when the interburden is less than 10 times the mining height of the upper seam, the models indicated that the lower seam is likely to be fractured as well as highly stressed. Hsiung and Peng [1987b] also indicated that it is best to retreat from the gob toward the solid and that the best situation occurs when a longwall face maintains an approach angle of about 30° to remnant structure.

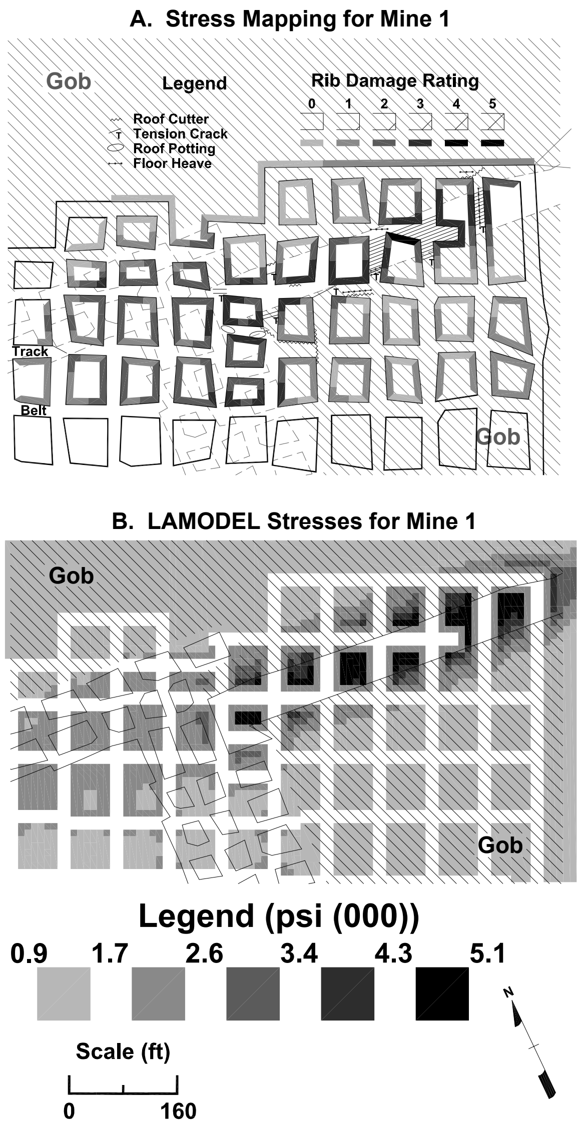

Figure 10.—Comparison between (A) in-mine stress mapping and (B) LaModel-calculated stresses for eastern Kentucky (after Heasley and Chekan [1999]).

Some recent examples of finite-element modeling applications to multiple-seam mining include 2–D and 3–D analyses of pillar and roof stability in overmining cases from northern West Virginia [Zhang et al. 2004; Morsy et al. 2006]. Zipf [2007] focused on the effects of vertical stress, horizontal stress, stress reorientation, and bedding slip on failure mechanics during multiple-seam mining. Gale [2004] evaluated different stacked longwall chain pillar layouts in the Australian context and concluded (as have many others) that the offset arrangement is far superior to vertical stacking. His models also predicted that stress transfer might be observed up to four pillar widths above and below a chain pillar, which would be approximately 400 ft for a typical Australian longwall design.

SUMMARY AND CONCLUSIONS

Hazards resulting from multiple-seam interactions are a serious issue at many U.S. coal mines, particularly in the central Appalachian and western mining regions. The four types of interaction are:

- *Undermining*, where stress concentrations caused by previous full extraction in an overlying seam is the main concern;
- *Overmining*, where previous full extraction in an underlying seam can result in stress concentrations and rock damage from subsidence;
- *Dynamic interactions*, caused when full extraction takes place above or below open entries that are in use (the most extreme dynamic interactions involve mining beneath open entries in an upper seam); and
- *Ultraclose mining*, where room-and-pillar development of two seams within 25–30 ft of each other can result in interburden failure.

Undermining and overmining are by far the most common types of interaction. Nearly a century of research has identified a number of factors that can affect the intensity of a multiple-seam interaction. These include:

- *Depth of cover:* The deeper the overburden, the greater the potential stress concentration caused by multiple-seam mining.
- *Mining sequence:* Overmining is more difficult than undermining because of the potential for rock damage caused by subsidence. Dynamic interactions (particularly retreating beneath open works) should be avoided at all costs.
- *Interburden thickness:* The smaller the distance between the seams, the greater the intensity of the potential interaction.
- *Type of remnant structure:* Isolated remnant pillars that are surrounded by gob cause more intense interactions than gob-solid boundaries. First workings are generally not a concern unless the seams are ultraclose.
- *Interburden geology:* Stronger, less bedded interburden tend to distribute multiple-seam stress concentrations more rapidly, resulting in less intense interactions.
- *Immediate roof geology:* Weak roof (and floor) are more likely to be damaged by multiple-seam interactions.
- *Angle of approach to remnant structure:* Retreat mining should proceed from the gob toward the solid side of a gob-solid boundary, and a longwall should not be brought broadside into long remnant structure.

The large number of geologic and mining variables involved in multiple-seam interactions has made them very difficult to analyze. Empirical studies have foundered because the databases were too small for the number of variables and because bivariate analyses are inappropriate when there are so many variables involved. Numerical models have been helpful, but to be most useful they have required site-specific calibration to underground conditions. A hybrid approach, employing multivariate statistical analysis of a large database combined with numerical modeling, could provide the mining community with a valuable tool for predicting, avoiding, or controlling multiple-seam hazards.

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MULTIPLE-SEAM MINING IN THE UNITED STATES: DESIGN BASED ON CASE HISTORIES

By Christopher Mark, Ph.D., P.E.,[1] Frank E. Chase,[2] and Deno M. Pappas[3]

INTRODUCTION

Multiple-seam interactions are a major ground control hazard in many U.S. underground coal mines. The two most common types are:

- *Undermining*, where stress concentrations caused by previous full extraction in an overlying seam is the main concern; and
- *Overmining,* where previous full extraction in an underlying seam can result in stress concentrations and rock damage from subsidence.

The goal of the study described in this paper is to help identify the location and likely severity of these interactions. Mine planners can use this information to adjust the ground support, pillar design, or mine layout to minimize the hazard.

In conducting the study, the National Institute for Occupational Safety and Health (NIOSH) relied mainly on an empirical approach. Empirical methods in ground control start with the concept that real-world mining experience, in the form of case histories, can provide valuable insight into the performance of very complex rock mechanics systems. In recent years, statistical analysis of large ground control case history databases has led to the development of methods for longwall pillar design [Mark et al. 1994; Colwell et al. 1999], roof bolt selection [Mark et al. 2001], retreat mine pillar design [Mark and Chase 1997], and design of rib support [Colwell and Mark 2005]. Although fairly uncommon in mining, modern empirical research methods based on quantitative data analysis using statistics are the foundation of econometrics, epidemiology, and many other scientific disciplines.

DATA COLLECTION

The multiple-seam case history database was developed over the course of several years through a program of mine visits. The mines included in the study were identified through discussions with mining company personnel and Mine Safety and Health Administration (MSHA) roof control specialists in each MSHA district. The study focused on those mines that had experienced the most difficulties with multiple-seam interactions. At each operation, however, care was taken to collect both successful and unsuccessful case histories. In general, only those case histories where problems might reasonably have been expected were documented. The many cases where the seams were clearly too far apart for interaction to occur were ignored.

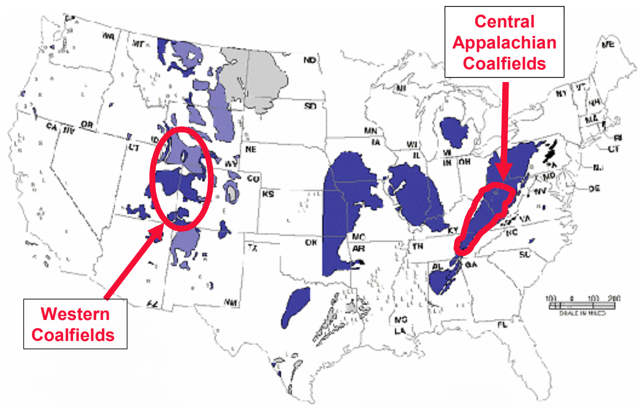

Figure 1.—Location of mines included in the NIOSH multiple-seam database.

A total of 44 mines were investigated during the study, nearly all from the central Appalachian and western coalfields (Figure 1). Several mines were visited in the northern Appalachian coalfields, but none of the case histories collected met the criteria for inclusion in the final database.

The key goal of each mine visit was to develop a history of multiple-seam interactions (and noninteractions) for the operation. Overlay mine maps, showing both the active mine and past workings above and/or below, were reviewed with experienced mine officials who had first-hand experience of the conditions encountered. Every instance where the active mine had crossed a gob-solid boundary or a remnant pillar was discussed. The officials also provided their best recollection of the support used and other relevant information. These discussions resulted in a preliminary list of case histories for the operation.

Underground investigations were also conducted at nearly every mine. It was seldom possible to access more than a few of the historic interaction sites because many were in sealed or otherwise inaccessible areas. However,

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underground observations provided a sample of the ground conditions associated with interactions at that mine. Mapping of the conditions was only conducted in some instances. The underground visits also provided raw data on roof geology and strength for determination of the Coal Mine Roof Rating (CMRR).

The mine officials were also asked to provide AutoCAD files with mine maps for all of the seams on the property, together with exploratory bore logs. These data were subsequently analyzed by NIOSH to complete the database.

PARAMETERS IN THE DATABASE

In any empirical study, the most important parameter is the outcome for each case history. A nonsubjective measure of the outcome, one that does not rely solely on the opinions of different observers, is highly desirable. For example, in the NIOSH study that led to the development of the Analysis of Roof Bolt Stability (ARBS), the outcome variable was the number of MSHA-reportable roof falls per 10,000 ft of drivage [Mark et al. 2001].

In this multiple-seam study, there was no such clear, unbiased measure of the outcome. Complete reliance on the observations of the miners themselves, however, was not an option. As Stemple [1956] noted while he was collecting his multiple-seam database:

> Bad roof conditions are present in many cases where there is no vertically adjacent mining, and so it is not always possible to state definitely that mining in another seam is responsible for the conditions. The coal miner is usually anxious to identify the cause of any difficulty which arises, and certainly the previous mining of a contiguous seam provides a convenient scapegoat.

Therefore, a combination of reported conditions and evidence from the mine map were used to rate the conditions for each case history. For example, where a roof fall occurred above or beneath a remnant structure, but the map showed that nearby noninteraction areas encountered a similar density of roof falls, the case would be eliminated from the database.

A four-level outcome rating scale was used:

- *No interaction* was assigned where undermining or overmining had occurred, but no effect was reported in the target seam (i.e., the conditions were the same in the affected and the unaffected areas).
- *Minimal interaction* was assigned where the presence of past mining was noticed underground (e.g., there was slightly more rib spall or an occasional roof crack), but this did not have any effect on mining operations.
- *Moderate interactions* were those where mining was completed, but with significant difficulties attributed to multiple-seam interactions, including such evidence on the mine map as roof falls, entry segments or crosscuts that were not developed, or pillars that were left unmined during retreat operations.
- *Severe interactions* were those where mining operations were abandoned.

In the statistical analyses, these four levels were collapsed into two. The "no interaction" and "minimal interaction" cases were combined as "successes," while the "moderate" and "severe" interactions became the unsuccessful cases (or "failures"). A handful of cases were rated "borderline" where the interaction seemed to fall between "minimal" and "moderate."

The "explanatory" or "independent" variables are those that are thought to possibly contribute to the outcome. Values for some of the variables were readily available, including whether the case was:

- Overmining or undermining
- Development or retreat
- Longwall or room-and-pillar

Other variable values could be obtained from the mine maps or drill logs:

- Depth to the target seam
- Thickness of the interburden
- Seam heights for both seams
- Time lag between the mining of the two seams (obtained by comparing the dates of mining for each seam)
- Angle of mining at which the active section intercepted the remnant structure

The level of roof support was determined during the discussion with the mine staff. Originally, the plan was to use ARBS to measure the amount of support installed. However, it was found that in almost every instance the primary support consisted of 4- or 5-ft fully grouted resin bolts. With so little variation, it did not make sense to include primary support as an independent variable. Similarly, supplemental support was almost always a pattern of 8- to 12-ft-long cable bolts or resin-assisted mechanical bolts. Therefore, supplemental support was included as a "yes/no" variable.

Some variables required some intermediate calculations. These included:

- *Pillar stability factors (SFs)* were calculated for the target seam using the Analysis of Longwall Pillar Stability (ALPS) or the Analysis of Retreat Mining Pillar Stability (ARMPS) programs. In some cases, SFs were also determined for remnant structures in the previously mined seam to determine whether they were likely to be yielded or intact.

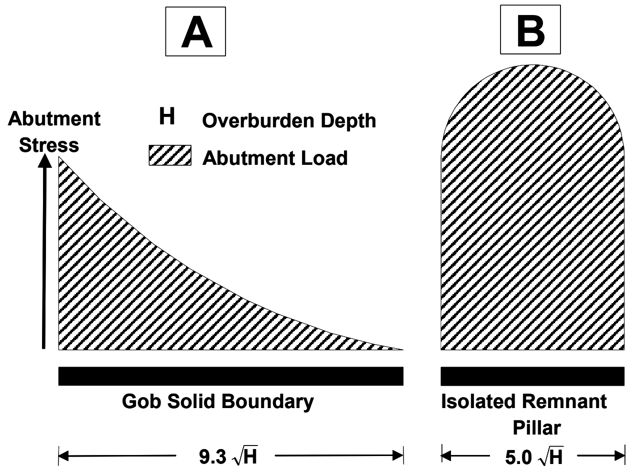

Figure 2.—Stress distribution on isolated remnant pillars and gob-solid boundaries.

- *Type of remnant structure* (gob-solid boundary or isolated remnant pillar). A remnant structure was judged to be an isolated remnant pillar if its SF indicated that it was large enough to be intact, but small enough that it concentrated the abutment stress, as shown in Figure 2. Equation 1 was used to determine whether a pillar was considered an isolated remnant or a gob-solid boundary:

$$W_p = 5\sqrt{H} \tag{1}$$

  where W_p is the maximum allowable width (ft) for a remnant structure to be considered an isolated remnant pillar, and H is the depth of cover (ft). Equation 1 indicates that the maximum width of an isolated remnant pillar is 100 ft at 400 ft of cover and 200 ft at 1,600 ft of cover. Larger remnant structures were considered gob-solid boundaries.
- The *CMRR* was normally determined underground, but the core logs often showed that the geology varied from hole to hole. Using the underground unit ratings for individual rock layers, CMRR values were calculated for each borehole. Each case history was then assigned the CMRR determined for the nearest borehole. However, since geostatistical studies have shown that immediate roof geology is seldom consistent between holes [Mark et al. 2004], an average CMRR value was also determined for each mine.
- The *percentage of competent rock* in the interburden was calculated at each borehole by summing the total sandstone plus limestone, and then dividing by the total interburden thickness.
- The *number of beds* in the interburden.

A key difficulty in multiple-seam analysis is obtaining estimates of the multiple-seam stresses. The complex three-dimensional (3–D) geometries of most multiple-seam situations have so far defied attempts at empirical estimation. In the early phases of this study, 3–D LaModel analyses were conducted of several case histories using LaModel's capability to import pillar grids directly from AutoCAD mine maps [Ellenberger et al. 2003; Heasley and Agioutantis 2007]. However, the sheer volume of case histories was too great to contemplate conducting full-scale 3–D analyses on the entire database. Fortunately, it was possible to analyze every case using LaM2D [Akinkugbe and Heasley 2007]. Some simplifications were necessary in order to create two-dimensional (2–D) grids of the case histories:

- *Gob widths* were defined by the least dimension of the gob (in plan view);
- *Entry widths* in the previously mined seam were adjusted so that the model 2–D extraction ratio approximated the true 3–D extraction ratio in order to more accurately simulate pillar yielding;
- *Standard LaM2D defaults* for the rock and coal moduli, lamination thickness, gob stiffness, and yielding properties of the previously mined seam were employed;
- Coal elements in the target seam were modeled as elastic (nonyielding) to better estimate the loads that the ground was attempting to apply to the critical pillars; and
- *An out-of-plane extraction ratio* multiplier was applied to the target seam to account for the crosscuts that could not be modeled in 2–D.

Each model was run for the development case and, where appropriate, the retreat mining case. Figure 3 shows a portion of a typical LaM2D model grid. The variable values that were derived from the model results included:

- *Average total vertical stress* applied to the critical pillar (most heavily loaded pillar above or beneath the remnant structure);
- *Average multiple-seam stress* on the critical pillar;
- *Maximum convergence* in the entry adjacent to the critical pillar; and
- *Maximum differential convergence*, defined as the difference between the convergence at the edge of the critical pillar and the convergence at the rib on the other side of the entry.

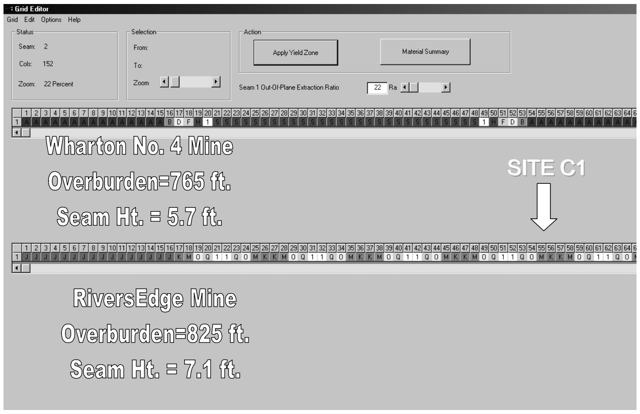

Figure 3.—Portion of a typical LaM2D model grid used to determine the multiple-seam stress and total vertical stress.

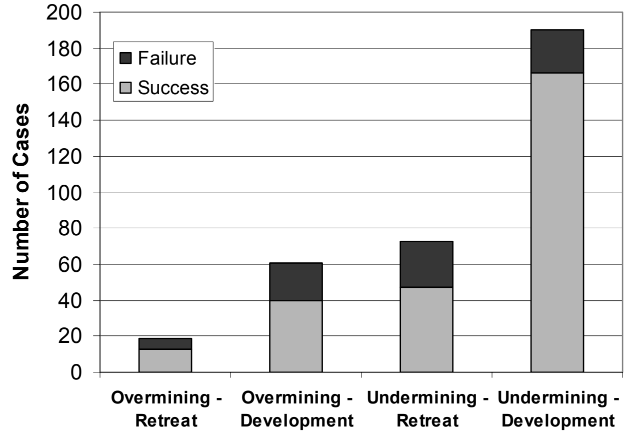

Figure 4.—Histogram showing the case history database by type of mining (development or retreat) and type of interaction (overmining or undermining).

The results from the LaM2D analyses were then used to determine the multiple-seam stability factor (ARMPS SF_{MS}) determined for the target seam using the following formula (using either ARMPS or ALPS, as appropriate):

ARMPS SF_{MS} =

$$\text{ARMPS SF}\left[\frac{\text{single seam load}}{(\text{single seam load} + \text{multiple seam load})}\right] \tag{2}$$

Finally, an SF rating was calculated by comparing the ARMPS SF_{MS} to the recommended ARMPS SF, which depends on the depth of cover [Chase et al. 2002]. Those cases where the ARMPS SF_{MS} exceeded the recommended SF were given a rating of 1; the others were rated 0.

DESCRIPTION OF THE DATABASE

The final database includes 344 case histories from 36 different coal mines. The cases include 252 development cases and 92 retreat mining cases. Since retreat mining cannot be conducted unless development mining was successful, every retreat mining case is also included in the development mining database.

Figure 4 shows that more than half of the cases in the database involved undermining during development (n=190). Only about 13% of these undermining development cases were judged to be failures. Retreat mining was later attempted in about 40% of the undermining cases and was successful about 65% of the time. There are about one-third as many overmining development cases in the database as undermining (n=61), and their failure rate is almost three times as great. Retreat mining was only attempted in 19 of the overmining cases in the database, with a 68% success rate.

Figure 5 shows the type of remnant structure encountered for the development cases only. It indicates that when undermining encountered a gob-solid boundary, the crossing was successful 90% of the time. The failure rate almost doubled for undermining isolated remnant pillars, however, from 10% to 19%. Overmining developments were successful 73% of the time when crossing gob-solid boundaries, but that rate dropped to only 59% for remnants.

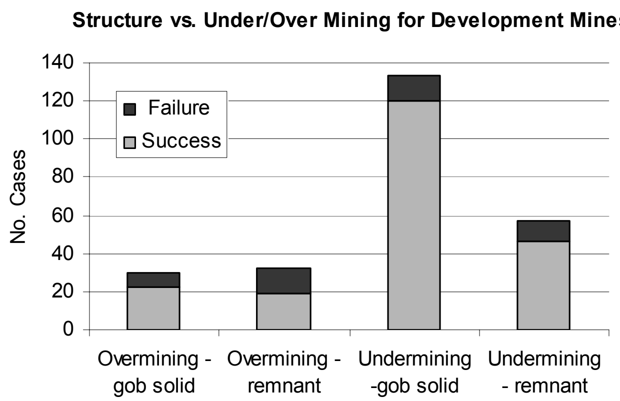

Figure 5.—Histogram showing the case history database by type of remnant structure and type of interaction.

Figure 6 shows the depth of cover and interburden thickness for the undermining cases. In about 90% of the cases, the depth of cover ranges between 400 and 1,200 ft. The interburden is less than 220 ft in all but 20 cases (and these are all successes). Figure 6 also shows that there are few cases in which the interburden falls between 90 and 150 ft. The fact that the data fall into two main groupings (interburdens of 40–90 ft and 150–240 ft) is less than ideal from a statistical point of view. However, when the sample pool is dictated by geology, it is impossible to conduct perfect “random sampling.”

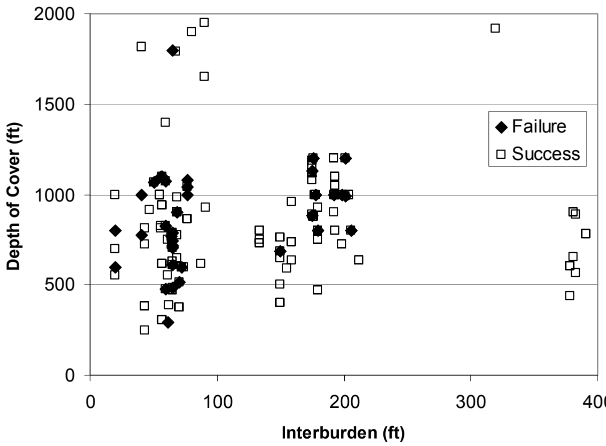

Figure 6.—Plot showing depth of cover and interburden thickness for the undermining cases in the database.

Depth of cover and interburden thickness for the 81 overmining cases are shown in Figure 7. Both Figures 6 and 7 show that the likelihood of success increases as the interburden thickness increases.

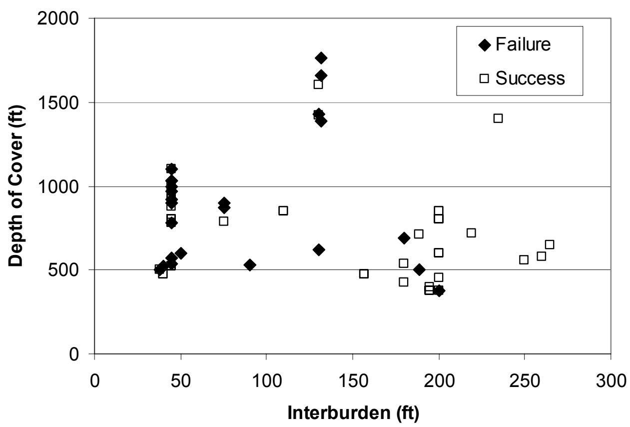

Figure 7.—Plot showing depth of cover and interburden thickness for the overmining cases in the database.

Figure 8 shows the TVS and multiple-seam stress determined for the critical pillar. The TVS is determined as:

$$\text{TVS} = \text{Tributary area stress} + \text{multiple-seam stress} + \text{abutment stress (if applicable)} \quad (3)$$

where the tributary area and abutment stresses were calculated with ALPS or ARMPS and the multiple-seam stress was determined using LaM2D.

The range of the TVS is from approximately 1,000 to 4,000 psi, while the multiple-seam stress varies from near zero to about 2,000 psi. Failures are more likely to occur at higher levels of both types of stress.

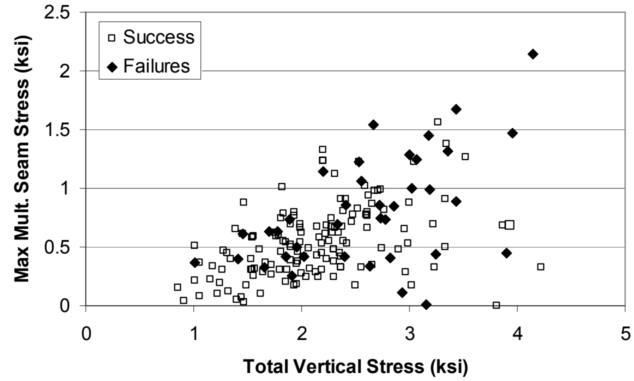

Figure 8.—Plot comparing the total vertical stress and multiple-seam stress in the database.

The range of CMRR values in the database is shown in Figure 9. None of the cases had a CMRR of less than 44, which means that truly weak roof conditions are not represented in the database.

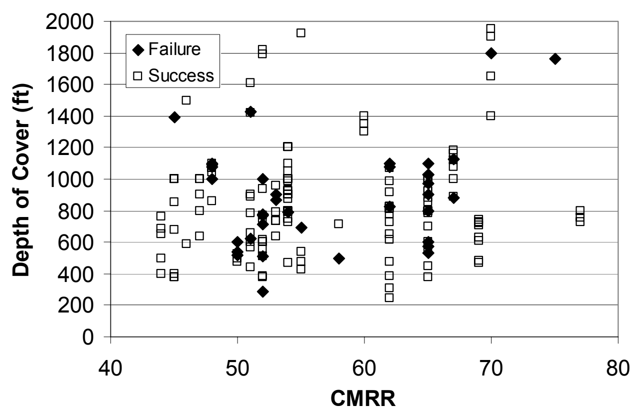

Figure 9.—Plot showing the range of CMRR values in the database.

Figure 10 shows the ARMPS SF adjusted for the multiple-seam stress plotted against the depth of cover. Of the failed cases, about one-third had ARMPS SFs that were below the recommended values. These included nearly half of the retreat cases. In contrast, more than 87% of the successful cases (including two-thirds of the retreat successes) had ARMPS SFs that exceeded the recommended values. The clear implication is that many multiple-seam interactions could be avoided simply by adjusting the pillar design to account for the additional multiple-seam stresses. On the other hand, there are still many unsuccessful cases in the database that cannot be explained by improper pillar design.

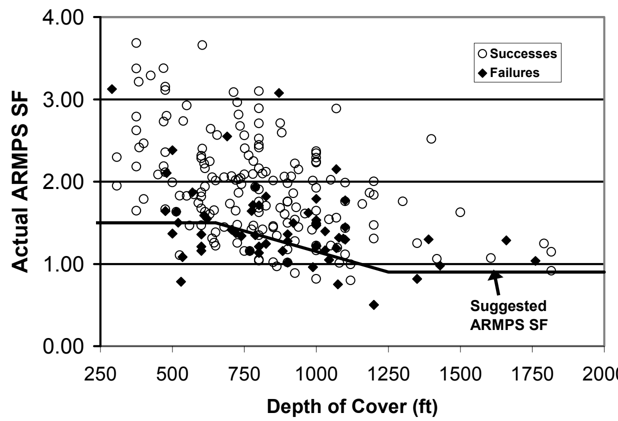

Figure 10.—ARMPS SF for the case histories compared with the suggested values of the ARMPS SF.

LOGISTIC REGRESSION

Logistic regression is the most common multivariate statistical technique used when the outcome variable is binary (i.e., there are two possible outcomes). In the NIOSH multiple-seam study, the two possible outcomes are either "successful" or "unsuccessful."

Logistic regression has much in common with linear regression. In both cases, the goal is to predict the outcome as a linear combination of the predictive variables. With linear regression, the method of least squares is used to estimate the unknown parameters (or coefficients, or slopes). The analogous function in logistic regression is called the method of maximum likelihood. According to Hosmer and Lemeshow [2000], "in a very general sense, the method of maximum likelihood yields values for the unknown parameters which maximize the probability of obtaining the observed set of data." The method of maximum likelihood solves for the "logit" g(x) of the logistic regression model as:

$$g(x) = B_0 + B_1x_1 + B_2x_2 + \ldots + B_nx_n \qquad (4)$$

where a "B" represents a coefficient and an "x" represents a value of a variable in the data set. The more positive the value of g(x) is for an individual case, the greater the likelihood of a positive (successful) outcome; the more negative, the greater the likelihood of a negative (unsuccessful) outcome.

The process of model-building with logistic regression is also similar to that with linear regression. In general, the goal is to obtain the model that best explains the data with the fewest variables. Logistic regression software provides standard deviations and significance levels for each individual coefficient, which allows their contribution to the overall outcome to be assessed. Variables with little significance can be eliminated from the model.

It is important that the effect of any continuous variables be "linear in the logit." When the relationship between a variable and the logit is nonlinear (i.e., quadratic, logarithmic, binary, or something else), then the variables can be transformed so that the transformed variable does have a linear effect. It is, of course, essential that the transformed variable make scientific sense.

When logistic regression is used to classify cases into two groups, a plot of sensitivity versus specificity is used. Sensitivity is the probability of correctly identifying a positive (or successful) case, while specificity is the probability of correctly identifying a negative (or unsuccessful) case. Where the two curves cross, the likelihood of detecting a false positive (1-sensitivity) equals that of detecting a false negative (1-specificity). This is considered the optimal "cut-point" [Hosmer and Lemeshow 2000]. Mathematically, the selection of the cut-point affects the value of the B_0 term in Equation 4.

One disadvantage of logistic regression is that there is no universally accepted measure of the overall model goodness-of-fit analogous to the r-squared used in linear regression. One of the most recommended measures is the "area under the ROC curve." The ROC, or receiver operating characteristic, is a concept borrowed from signal detection theory. It plots the sensitivity against 1-specificity for an entire range of possible cut-points [Hosmer and Lemeshow 2000]. As a general rule:

- If ROC = 0.5, there is no discrimination (same as flipping a coin);
- If 0.7 < ROC < 0.8, discrimination is considered acceptable;
- If 0.8 < ROC < 0.9, discrimination is considered excellent; and
- If ROC > 0.9, discrimination is outstanding.

All of the statistical analyses conducted for the NIOSH multiple-seam study were performed using the Stata statistical package [StataCorp 2005].

STATISTICAL ANALYSIS

With such a large database and so many variables, the statistical analysis was a complex iterative process. Numerous logistic regression models were tested and evaluated. As more refined models were developed with new combinations of variables, it was often necessary to test parameters that had previously been excluded to ensure that they were still nonsignificant. Eventually, the process arrived at a single design equation.

The first step in the analysis was to weight the cases. Weighting was necessary because some mines provided a large number of case histories, whereas others provided only a few. To fairly represent all of these cases without allowing the database to be overwhelmed by a few mines that contributed many cases, the following weighting equation was used:

$$\text{case weight} = \frac{1}{\sqrt{N_m}} \quad (5)$$

where N_m = the total number of cases from this mine.

In other words, the more cases there were from an individual mine, the smaller the weight of each individual case, but the greater the weight of the mine's total experience.

Another important issue is that of correlations between variables within the database. In general, it does not make sense to include two variables that are highly correlated with each other in the same analysis. In the NIOSH database, for example, the TVS, multiple-seam stress, and depth of cover are all highly correlated with each other. Logistic regression trials indicated that of these three, the TVS gave the best overall results.

Several continuous variables were tested for the linearity of their effects on the outcome. Ultimately, logarithmic transformations were applied to the thickness of the interburden and the CMRR, although linear versions of the variables were also retained. Using the natural log of the interburden thickness eliminates the possibility that in some low-stress undermining cases the logistic equation might predict a negative value for the critical interburden thickness. On the other hand, when the log of the interburden is used, the assessment of extreme high-stress overmining scenarios can result in unreasonably large values for the critical interburden thickness.

In the case of the CMRR, the evidence in the data was not clearly in favor of a logarithmic transformation, perhaps because of the relatively narrow range of CMRRs in the database. However, the scientific logic is that increasing the CMRR from 40 to 50 has a greater effect on stability than an increase from 80 to 90. In effect, a logarithmic transformation implies that it is the percent change in the value of a variable that matters, not the absolute value of the change. The transformed variable that was used in the multiple-seam analysis was:

$$\text{lnCMRR20} = \ln(\text{CMRR-20}) \quad (6)$$

Another reason for using the transformed CMRR variable in the analysis is that there were so few cases where the CMRR was less than 45. Since the transformed variable implies that the effect of multiple-seam interactions is amplified when the roof is weak, using it means that the ultimate design equation is more conservative for the low range of CMRR values.

One other transformation that was applied was to the angle at which the active mining intercepted the remnant structure. The transformed variable was binary, with angles greater than 20° given a value of "perpendicular" while the others were "parallel." This variable was not significant in the final model, however.

In designing the analysis, a key issue was whether the undermining, overmining, development, and retreat cases should be analyzed separately or together. There are good scientific arguments for separating them, since the mechanics of the interactions may be different in the different groups. The disadvantage is that the four databases would each be much smaller. As discussed in the next section, the analyses showed that all four groups could be combined and analyzed together.

When the values for both the CMRR and the interburden competence (expressed as the percent of strong rock in the interburden) were obtained from the borehole nearest the case history, the analysis showed that neither variable was statistically significant. When mine-wide averages were employed instead, the CMRR was highly significant, and it is included in the final design equation.

Interburden competence was still not significant, however. Two related factors may have contributed to this:

- The percent of competent rock was based entirely on the geologic descriptions included with the core logs. In many cases, the description was little more than the rock type (shale, sandstone, etc.). In the central Appalachian coalfields, however, some siltstones and even shales can be very strong [Rusnak and Mark 2000]. Without an actual geotechnical description, some weak rocks may have been labeled strong and vice versa.
- Because the case histories are all from two coalfields where the rocks tend to be strong, there may not be sufficient variability in the database to capture the effect of interburden competence.

Two other variables that were expected to be significant for the overmining cases were the time lag since mining the bottom seam and the lower coalbed-to-interburden thickness ratio. However, the analysis did not find that either was significant. In the case of the time lag, the database contained a total of 12 overmining cases in which the time lag was less than 10 years. Of these, all but two were successes, indicating that time lag by itself is unlikely to be a major factor. However, one of the two failures proved to be a major outlier when compared with the rest of the database. It seems quite likely, in this instance at least, that the settling time was important.

The lack of influence of the lower coalbed-to-interburden thickness ratio may also be due to the sample size. There are 30 cases (21 development and 9 retreat) in which the interburden thickness was 7.5–10 times the lower coalbed thickness. Of these, 13, or 44%, are failures, which is a relatively high failure rate. However, the effect may be captured by other variables, particularly the interburden

Table 1.—Logistic regression table for final model (Equation 7)

Variable	Coef.	Std. err.	z	P > z	95% confidence interval	
TVS..........................	–0.80655	0.125674	–6.42	0.000	–1.05287	–0.56023
UO..........................	1.79438	0.21375	8.39	0.000	1.37543	2.21333
INT..........................	0.02331	0.00229	10.16	0.000	0.01881	0.02780
EX..........................	2.02037	0.27899	7.24	0.000	1.47356	2.56719
REMPIL....................	–1.79952	0.23288	–7.73	0.000	–2.25596	–1.34307
lnCMRR20..................	1.95214	0.47521	4.11	0.000	1.02074	2.88354
Constant....................	–6.467325	1.805228	–3.58	0.117	–10.0055	–2.92914

thickness, which was less than 50 ft in all but one of these cases. It seems likely that the upper-seam mining in these 30 cases probably took place in the fracture zone, above the top of the caving zone, which is normally 6–10 seam heights above the lower bed [Kendorski 2006]. It may be that once the upper seam is above the caving zone, the lower coalbed-to-interburden thickness ratio may not be significant. However, since all of these cases (except one) come from just two mines in Virginia, it is possible that more trouble might be encountered in other geologic environments.

Retreat mining was another factor that was not significant in the final analysis. However, the effect of retreat mining is indirectly included in the TVS variable. On average, the vertical stress was 20% greater in the retreat cases than in the development cases.

FINAL MODEL AND DESIGN EQUATION

Of the 344 cases in the database, the outcomes in 9 of them were considered "borderline," and these were excluded. An additional 26 failed cases were excluded because their ARMPS SF_{MS} were less than the recommended values. It was believed that the poor mining conditions in these cases were likely attributable to inadequate pillar design rather than multiple-seam interaction per se. As a result, the final database included 309 case histories.

The final, best model is given below:

$$g(x) = -0.81*TVS + 1.79*UO + 0.0233*INT + 2.02*EX - 1.80*REMPIL + 1.95*\ln CMRR20 - 6.47 \quad (7)$$

where TVS = total vertical stress on the critical pillar (thousands of psi);
UO = 1 for undermining, 0 for overmining;
INT = interburden (ft);
EX = 1 for extra support, 0 for none;
REMPIL = 1 for isolated remnant pillar, 0 for gob-solid boundary;
and lnCMRR20 = ln (CMRR-20).

The logistic regression table for this model is shown in Table 1. It indicates that all of the parameters are statistically significant at well above the 99% confidence level.

Figure 11 shows that the ROC = 0.883 for this model. The model's optimal cut-point is approximately p=0.86, as shown in Figure 12. The classification table (Table 2) indicates that this model correctly classifies approximately 80% of the cases overall, including 81% of the failures, when this cut-point is used.

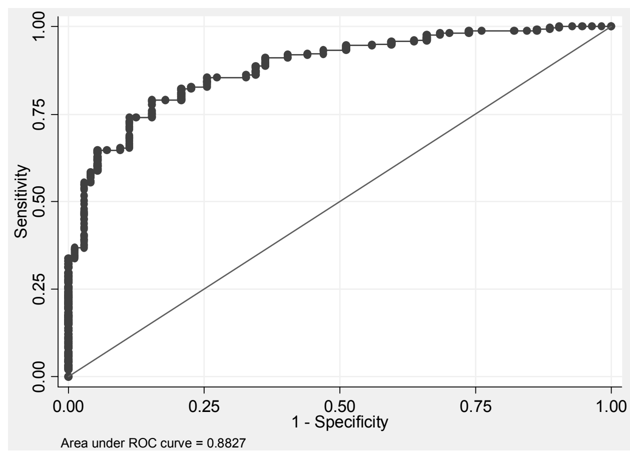

Figure 11.—Receiver operating characteristic (ROC) curve for Equation 7.

Table 2.—Performance of the design equation against the NIOSH database

Model predictions	No. of cases	% of total cases
Successes correctly predicted	212.2	68.7
Failures correctly predicted	36.2	11.7
Total cases correctly predicted	248.4	80.4
Failures predicted as successes	9.6	3.1
Successes predicted as failures....................	51.0	16.5
Total cases incorrectly predicted...................	60.6	19.6
Total cases	309	100

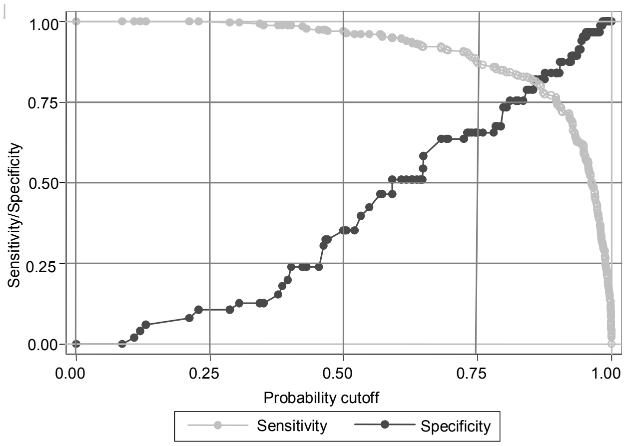

Figure 12.—Plot of specificity versus sensitivity for Equation 7, showing that the optimal cut-point is approximately p=0.86.

A version of Equation 7 using the log transformation of the interburden was also determined. The lnINT model was very similar to Equation 7, but its ROC was slightly less at 0.873.

Table 3 compares the model derived from the overall data set (Equation 7, shown as "Linear-all" in Table 3) with the lnINT model ("Log-all" in Table 3) and models using subsets consisting of just the undermining, overmining, development, or retreat cases. It is remarkable that there is so little variation in the coefficients (b) among these different models. The influence of the interburden thickness, for instance, varies by no more than ±10%. The effects of EX, REMPIL, and lnCMRR20 are also very stable. The ROC values for all four of these models are also excellent. Overall, these results support the use of a single universal equation to predict the severity of multiple-seam interactions.

For use in design, Equation 7 was adjusted to correspond to the cut-point of 0.86 and transformed to predict the critical interburden thickness (INT_{crit}, ft):

$$INT_{crit} = 35*TVS - 77*UO - 87*EX + 77*REMPIL - 83*(\ln CMRR20) + 359 \quad (8)$$

One disadvantage of Equation 8 is that in some extreme cases it can predict a negative value of the critical interburden thickness. Therefore, the lnINT model was used to derive a second equation for the critical interburden thickness INT_{critLN} :

$$INT_{critLN} = EXP[0.35*TVS - 0.74*UO - 0.99*EX + 0.74*REMPIL - 0.91*(\ln CMRR20) + 7.23] \quad (9)$$

Figure 13 shows that, in general, $INT_{critLN} > INT_{crit}$ when the interburden is less than about 50 ft or greater than about 170 ft. Since the linear interburden model fits the data slightly better and since it provides more conservative answers where the data are sparse (when the interburden falls between 90 and 150 ft), Equation 8 was preferred for most situations. The log interburden model is preferred only for the thinnest interburdens, where Equation 9 provides the most conservative value for the critical interburden.

When the actual interburden thickness exceeds the INT_{crit} determined by Equation 8, there is a very good likelihood that conditions will be satisfactory. The data in Table 2 and Figure 14 indicate that within the NIOSH database only 4% of the cases (9.6 of 221.8 weighted cases) where the interburden exceeded the critical value defined by Equation 8 were failures. Of the cases where the actual interburden was less than the critical value, the multiple-seam interaction resulted in unsatisfactory conditions 43% of the time.

Table 3.—Comparison between logistic regression models

Variable	Linear-all coef. (b)	Log-all coef. (b)	Undermining coef. (b)	Overmining coef. (b)	Development coef. (b)	Retreat coef. (b)
TVS………………………..	–0.81	–0.80	–0.61	–1.14	–1.13	–0.43
UO………………………….	1.79	1.69	NA	NA	2.48	0.40
INT………………………….	0.0233	NA	0.024	0.024	0.024	0.026
EX………………………….	2.02	2.26	1.64	2.45	1.83	2.56
REMPIL…………………….	–1.80	–1.68	–1.74	–2.05	–1.82	–1.98
lnCMRR20………………..	1.95	2.07	1.72	2.59	2.71	0.61
Constant…………………..	–6.47	–14.72	–0.91	–3.82	–10.07	1.13
No. of cases………………	309	309	234	75	237	72

NA Not applicable.

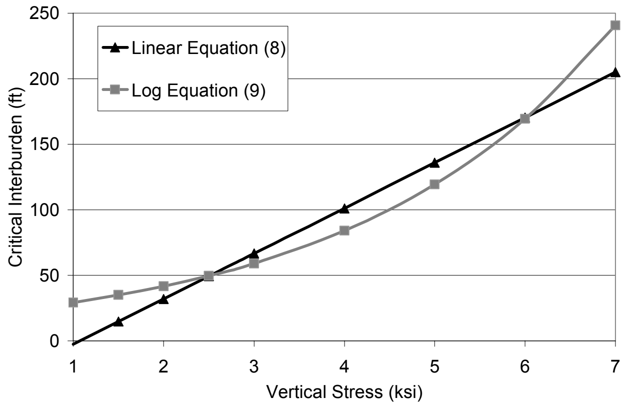

Figure 13.—Comparison of Equations 8 and 9, showing that the logarithmic version (Equation 9) can yield the most conservative value of the critical interburden when the calculated interburden is less than about 50 ft.

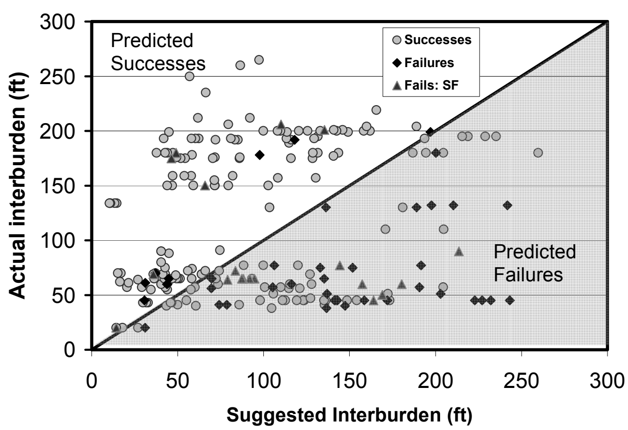

Figure 14.—Performance of the design equation, comparing the suggested critical interburdens with the actual interburdens in the case histories.

Equation 8 also indicates that:

- Each additional 1,000 psi of vertical stress is equivalent to subtracting 35 ft of interburden.
- All other factors being the same, overmining requires 77 more feet of interburden than undermining.
- All other factors being the same, an isolated remnant pillar requires 77 more feet of interburden than a gob-solid boundary.
- All else being equal, a CMRR = 45 roof requires approximately 50 more feet of interburden than a CMRR = 65 roof.

The analysis indicates that installing a pattern of cable bolts or other heavy supplemental support is equivalent to adding as much as 87 ft of interburden. However, while supplemental support may make mining possible, the likelihood of encountering rib spalling, floor heave, or hazardous roof also increases when the analysis suggests that supplemental support is necessary.

In Figure 15 the case histories are plotted again, but this time each point is plotted with its suggested overburden for the "no extra support" (EX=0) condition. Three regions are defined on the graph. The uppermost region, where the actual interburden exceeds the critical interburden when EX=0, is labeled "Predicted Successes." Within this region, 97% of the case histories that maintained an adequate pillar SF were successful. In the middle region, success is predicted only if a pattern of supplemental support is installed. In this region, 93% of the cases that did install supplemental support were successful, whereas only 63% of those that did not were successful. In the bottom region, where failure is predicted, only 52% of the cases were successful.

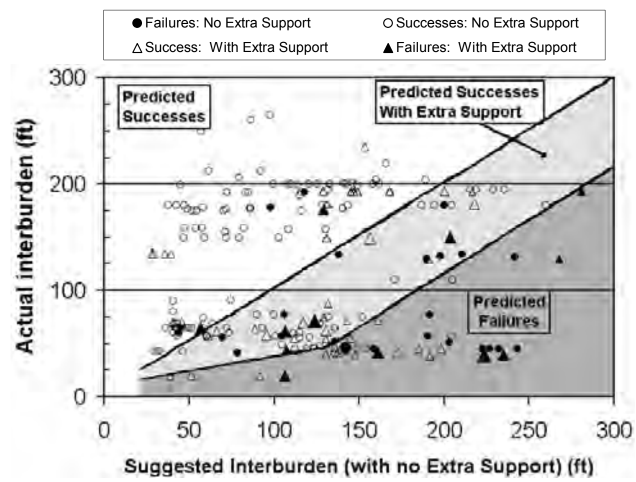

Figure 15.—Suggested critical interburden values setting EX=0.

Figures 16–19 are "design charts" that illustrate the critical interburden thickness for CMRR = 45 and CMRR = 65 situations, for undermining and overmining, with and without extra support.

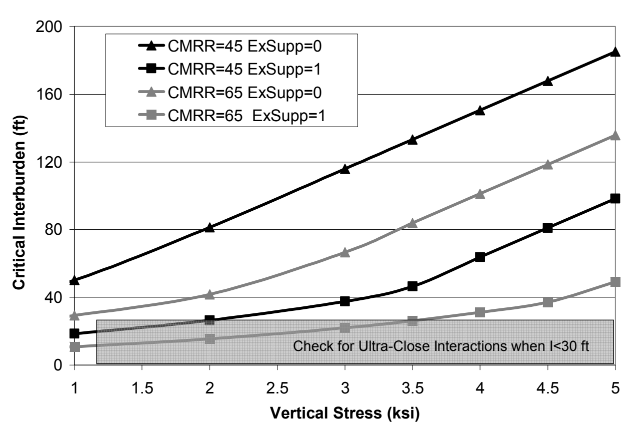

Figure 16.—Suggested values of the critical interburden for undermining a gob-solid boundary.

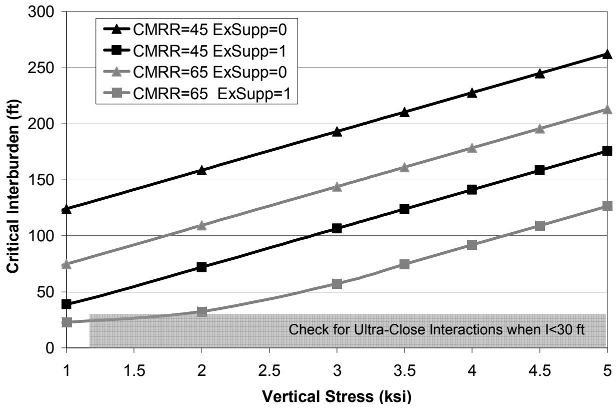

Figure 17.—Suggested values of the critical interburden for undermining an isolated remnant pillar.

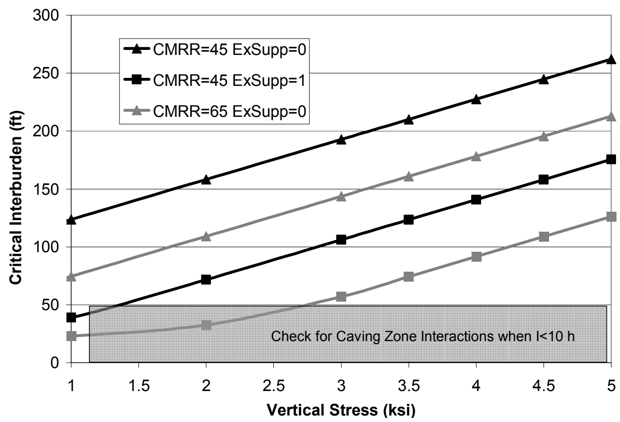

Figure 18.—Suggested values of the critical interburden for overmining a gob-solid boundary.

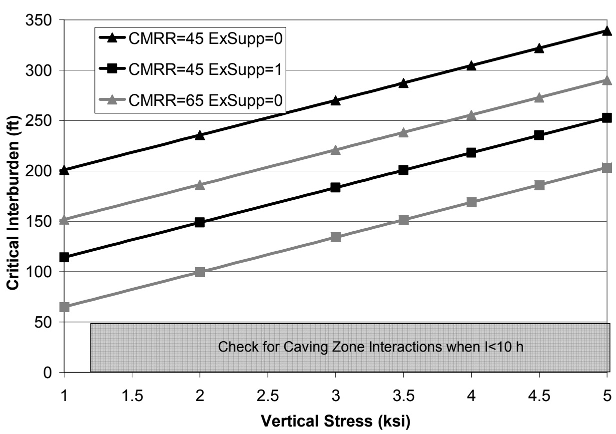

Figure 19.—Suggested values of the critical interburden for overmining an isolated remnant pillar.

LIMITATIONS OF THE STUDY

Every research study has limitations that need to be kept in mind when the findings are applied to the real world. One of the advantages of statistical modeling is that the process is relatively transparent, and the limitations are not hidden within the "black box." Although the NIOSH multiple-seam database is the largest of its kind ever collected, it is subject to at least three major limitations:

- *Data quality:* Many of the parameters included in the multiple-seam database, such as the depth of cover and the interburden thickness, can be determined very reliably for each individual case history. However, there is some uncertainty about critical parameters such as the CMRR, multiple-seam stress, interburden geology, and even (in some cases) the outcome (success or failure). The reasons for these uncertainties have been discussed earlier. Fortunately, the larger the database, the less influence that possible measurement errors will have on the overall trends.
- *Number of parameters:* The size of the database also limits the number of parameters that can be included in the model. The NIOSH database seems to be large enough to estimate the effects of the main parameters, as reflected by the stability of the model when different portions of the database are analyzed (see Table 3). However, it may not have been large enough to capture some second-order effects, such as the orientation of the panel relative to the remnant structure. The database was also not large enough to analyze interactions between the variables. For example, some analyses indicated that extra support is more beneficial to low CMRR roof than to strong roof, but this trend was not statistically significant.
- *Nonrandom sampling:* The NIOSH database includes a large percentage of the recent multiple-seam interactions that have occurred in U.S. underground mines, but even if it included every single one it would still suffer from sampling limitations. This is because the actual mines represent a tiny fraction of all the combinations of parameters that could exist. One example that has already been discussed is the lack of case histories with interburdens between 90 and 150 ft. There are also many combinations of parameters that are not represented, particularly among the smaller group of failed cases.

The most important limitation to remember, however, is the range of the data. Empirical models should always be used with caution outside the range of the data that were employed in their development. In this instance, it is possible that new failure mechanisms may occur when the CMRR is less than 45, the interburden is less than 30 ft thick, or an upper seam is developed within the caving zone of a previously mined lower seam. Checking this range limitation is therefore an important step in the suggested procedures for multiple-seam analysis that are discussed below.

PROCEDURES FOR MULTIPLE-SEAM MINE DESIGN

The results of this study can be used to evaluate the potential for multiple-seam interactions and provide guidance for pillar sizing, supplemental support, and other aspects of mine design. The suggested step-by-step process follows:

1. Identify critical remnant structures on the maps of mining in seams above and below the target seam. Every remnant structure that may be crossed by active mine workings should be evaluated.
2. For each potential remnant structure crossing, determine the—
    - Depth of cover to the target seam
    - Interburden thickness
    - Seam heights (both seams)
    - Age of the older workings
    - CMRR for the roof of the target seam
3. Check that the parameters of the case being considered fall within the limits of the NIOSH multiple-seam database. If the roof is very weak (CMRR < 45) or the stress is very high (>5,000 psi), then the equations should be used with caution. The same is true if the case involves overmining and the lower coalbed thickness-to-interburden ratio is less than 10. If the interburden thickness is less than 30 ft in either undermining or overmining, then potential for an ultraclose interaction should be given primary consideration.
4. Determine whether the remnant structure is a gob-solid boundary or an isolated remnant pillar. Equation 1 or Figure 20 may be used if the remnant structure is a pillar. If the remnant pillar is so thin that it may have failed completely, it may be helpful to determine its ARMPS SF.
5. Determine the ARMPS SF or ALPS SF (single seam) for the proposed section in the target seam. If retreat mining is planned (either pillar recovery or longwall mining), determine the maximum abutment stress applied to the critical pillar.
6. Conduct a LaM2D analysis of the remnant structure crossing to determine the multiple-seam stress applied to the critical pillar in the target seam. Also determine the TVS using Equation 3.
7. Determine the ARMPS or ALPS multiple-seam stability factor (SF_{MS}) for the target seam using Equation 2 and compare it to the recommended ARMPS or ALPS SF. If the calculated SF_{MS} is lower than the recommended value, then the pillar size should be increased.
8. Use Equation 8 to determine the critical interburden thickness, both with and without supplemental support (EX=1 and EX=0). Note that if the INT_{crit} determined from Equation 8 is less than 60 ft, then Equation 9 should be used if it provides a more conservative value.
9. Compare the actual interburden to the two INT_{crit} values determined in step 8. Three cases are possible:
    - If INT_{crit} without supplemental support is significantly less than the actual interburden, then a major multiple-seam interaction can be considered unlikely.
    - If the actual interburden is less than INT_{crit} without supplemental support but greater than INT_{crit} with supplemental support, then adding a pattern of cable bolts or other equivalent supplemental support could greatly reduce the probability of a major interaction.
    - If INT_{crit} even with supplemental support is greater than the actual interburden thickness, then a major interaction should be considered likely with this design.
10. If desired, the mine design can be adjusted by changing the pillar size or the entry width (both of which affect the TVS) and then repeating steps 5–9.

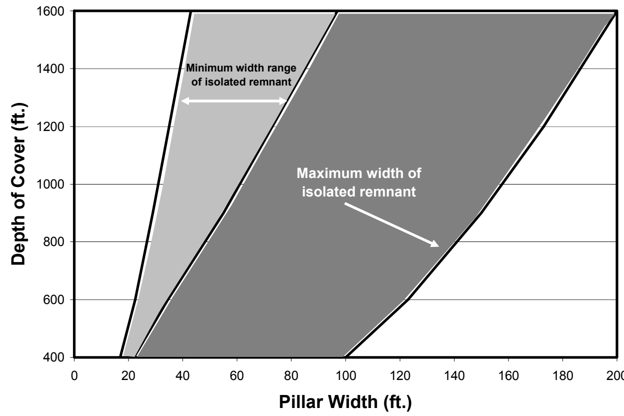

Figure 20.—Upper and approximate lower limits for determining whether a remnant structure is an isolated remnant pillar or a gob-solid boundary.

CONCLUSIONS

To conduct this study, NIOSH collected the largest database of multiple-seam case histories ever assembled. These data were analyzed with the multivariate statistical technique of logistic regression. The study also employed LaM2D to estimate the multiple-seam stress, ALPS and ARMPS to determine pillar SFs, and the CMRR to measure roof quality.

Several of the study's findings confirm the conventional wisdom about multiple-seam interactions. Overmining was found to be much more difficult than undermining, and isolated remnant pillars caused more problems than gob-solid boundaries. For the first time, however, it was possible to quantify these effects in terms of the equivalent thickness of interburden needed to compensate for them.

The study also found that pillar design is a critical component of multiple-seam mine planning. Many of the failed cases involved pillars whose SF seemed inadequate once the multiple-seam stresses were accounted for. Weaker roof was also found to significantly increase the risk of multiple-seam interactions. Some factors that were not found to be statistically significant included the interburden competence, the time lag between mining the two seams, the lower coalbed-to-interburden thickness ratio, and the angle between the active mining and the remnant structure.

The most important result of the study is an equation that predicts the critical thickness of the interburden required to minimize the likelihood of a multiple-seam interaction. This equation has been incorporated into a step-by-step methodology that allows mine planners to evaluate each potential interaction and take steps to reduce the risk of ground control failure. Such measures could include installing cable bolts or other supplemental support, increasing the pillar size, or avoiding the remnant structure entirely.

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LAMODEL: A BOUNDARY-ELEMENT PROGRAM FOR COAL MINE DESIGN

By Keith A. Heasley, Ph.D.,[1] and Zacharias G. Agioutantis, Ph.D.[2]

ABSTRACT

LaModel 2.1 is a PC-based boundary-element program for calculating the stresses and displacements in coal mines or other thin, tabular seams or veins. This type of mine modeling software can be used by mine design engineers in the industry to investigate and optimize the pillar sizes and pillar layouts in relation to pillar stress, multiseam stress, and/or bump potential (energy release). This paper introduces the LaModel program and highlights the Windows-based pre- and postprocessors.

INTRODUCTION

Mine planners have a variety of modeling methods, either empirical or numerical, available for analyzing pillar stresses and determining safe pillar sizes for various mine geometries and geologic structures. Empirical methods emphasize the collection and interpretation of case histories of pillar performance. These empirical methods are closely linked to reality, and for many "typical" mining geometries, they work extremely well.

However, it is difficult to apply these empirical methods to mining situations beyond the scope of the original empirical database. Therefore, when complicated stress conditions arise from complex single- or multiple-seam mining geometries, numerical modeling techniques such as finite-element, boundary-element, discrete-element, or finite-difference are usually applied. In general, the numerical, or analytical, design methods are derived from the fundamental laws of force, stress, and elasticity. Their main advantage is that they are very flexible and can quickly analyze the effect of numerous geometric and geologic variables on mine design. Their main disadvantage is that they require difficult-to-obtain and/or unknown information about material properties, failure criteria, and postfailure mechanics.

In order to analyze the displacements and stresses associated with the extraction of large tabular deposits such as coal, potash, and other thin, vein-type deposits, the displacement-discontinuity variation of the boundary-element technique is frequently the method of choice. In the displacement-discontinuity approach, the mining horizon is treated mathematically as a discontinuity in the displacement of the surrounding media. Using this technique, only the planar area of the seam needs to be discretized, or gridded, in order to obtain the stress and displacement solution on the seam. Often, this limited analysis is sufficient, since in many practical applications only the distributions of stress and convergence on the seam horizon are of interest. Also, by limiting the detailed analysis to only the seam, the displacement-discontinuity method provides considerable computational savings over other techniques, which discretize the entire body (such as finite-element, discrete-element, or finite-difference). It is a direct result of this computational efficiency that the displacement-discontinuity method is able to handle large areas of tabular excavations as needed in many practical coal mining problems.

A displacement-discontinuity program incorporating a laminated media was originally developed by the National Institute for Occupational Safety and Health [Heasley and Chekan 1999]. This program, called LaModel, was designed for calculating the stresses and displacements in coal mines or other thin, tabular seams in layered media. In order to facilitate the transfer of the LaModel technology to the mining industry for improving overall mine design, an intuitive, easy-to-use preprocessor, LAMPRE, and postprocessor, LAMPLT, were also developed. The LAMPRE program handles all of the numerical parameter input and allows the mine plan to be graphically entered into the program. The new postprocessor, LAMPLT, also uses an intuitive graphical interface and allows the user to quickly and easily plot and analyze the output data from the numerical calculation phase of LaModel.

LAMODEL

Traditional displacement-discontinuity programs use a homogeneous isotropic elastic formulation that simulates the overburden as one solid material. In contrast, the LaModel program simulates the geologic overburden stratifications as a stack of layers with frictionless interfaces. Specifically, each layer is homogeneous isotropic elastic and has the identical elastic modulus, Poisson's ratio, and thickness. This "homogeneous layering" formulation does not require specifying the material properties for each individual layer, yet it still provides a realistic suppleness to the mining overburden that is not possible with the classic homogeneous, isotropic elastic overburden model. From our experience, this suppleness provides

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more accurate strata response than a homogeneous overburden for modeling local deformations, interseam interactions, and/or surface subsidence [Heasley and Barton 1999; Heasley and Chekan 1999; Heasley and Salamon 1996].

To utilize the LaModel program, the user must input the seam geometry, seam orientation, stress field, and geologic material properties. Up to 26 different in-seam materials from 5 different material models (elastic, elastic-plastic, strain-softening, bilinear strain-hardening, and exponential strain-hardening) can be used in a model, and the grid size can be a maximum of 1,000 by 1,000. Once the input is developed, the LaModel program calculates the stresses and displacements at the seam level and at requested locations in the overburden or at the surface. The program also has the ability to analyze (1) the interseam stresses resulting from multiple-seam mining, (2) effects of topographic relief on pillar stress and gob loading, (3) stress changes during mining through multiple mining steps, and (4) surface subsidence.

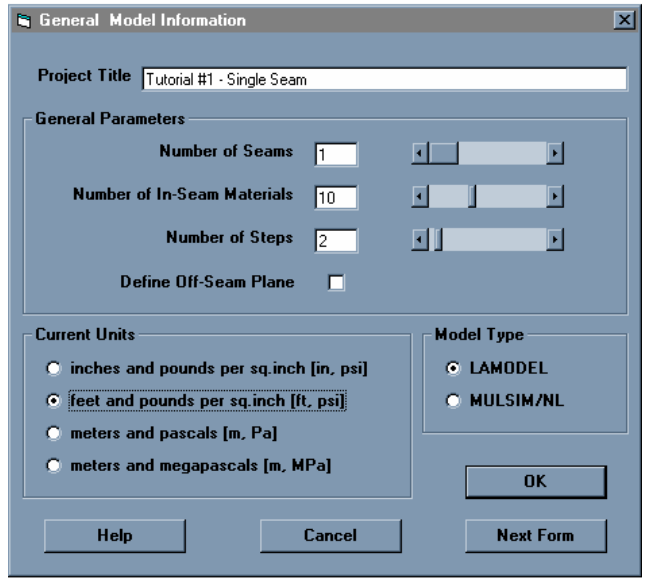

Figure 1.—Typical parameter input form for LAMPRE.

LAMPRE: THE PREPROCESSOR

In order to facilitate the transfer of the LaModel technology to the mining industry for improving overall mine design, the requirements on the occasional user for data input need to be simplified as much as possible. To this end, an intuitive, easy-to-use preprocessor, LAMPRE, that allows the user to quickly and easily enter both the required material data and the necessary model geometric data was initially developed. LAMPRE runs in the Windows environment using an intuitive graphical user interface with ample context-sensitive online help. The preprocessor handles all of the numerical parameter input and also allows graphical input of the material codes for the seam grids or automatic grid generation from an AutoCAD mine map. Also, a set of "material wizards" for automatically calculating reasonable coal and gob properties from typical values was added to LAMPRE. These wizards greatly reduce the burden on the novice user of specifying the essential material properties for the seam and gob.

A typical LAMPRE input form for parameter values is shown in Figure 1 (in this case, the form for the "General Model Information"). In this form, the input parameters are entered using either a text edit, slider, or radio button object, whichever is most convenient. If help on the parameter is needed, simply pressing the "F1" function key, while the parameter is active, will open the appropriate help topic. Also, the program checks the value of all of the input parameters before they are saved to make sure that they fall within reasonable prescribed ranges. Using a number of these input forms, all of the geometric and geologic parameters for the LaModel program are easily entered.

Once the numerical parameters are entered, the user then needs to define the geometry and material of the pillars and openings in the seam grid. In LaModel, the different materials are represented by alphabetical "material codes" (A to Z), and openings are represented by the character "1". LAMPRE provides a graphical editor for creating and modifying the various seam grids, as shown in Figure 2. The grid editor essentially works like a spreadsheet. Material codes for individual cells may be set by clicking on a cell and then typing and entering an appropriate letter from A to Z. Blocks of cells may be changed by clicking and dragging the mouse over a range and then typing and entering the material code, or entire rows/columns may be selected and changed using the row/column number. Also, a block of cells may be copied and pasted (greatly simplifying the creation of numerous pillars). Finally, the grid editor allows for automatic yield zone generation based on materials that were automatically defined using the coal property wizard.

The grid editor in LAMPRE greatly speeds the creation of "regular" rectangular pillar plans aligned with the grid. However, even with the graphical grid generation, if the mining plan is complex or the grid does not align with the pillars, then it can take hours or even days to meticulously determine and specify the material code for every grid element, especially since the maximum grid size has increased to 1,000 by 1,000, or 1 million elements.

In response to the difficulty of creating complex mine grids, one of the most recent developments in the evolutionary history of LaModel is the "automatic" grid generator, which can take an AutoCAD map of the mine pillars and automatically create the material grid for the LaModel input file. Also, a program for automatically generating the topographic input grid from an AutoCAD file was recently developed. These new automatic grid generators greatly reduce the effort and shorten the time

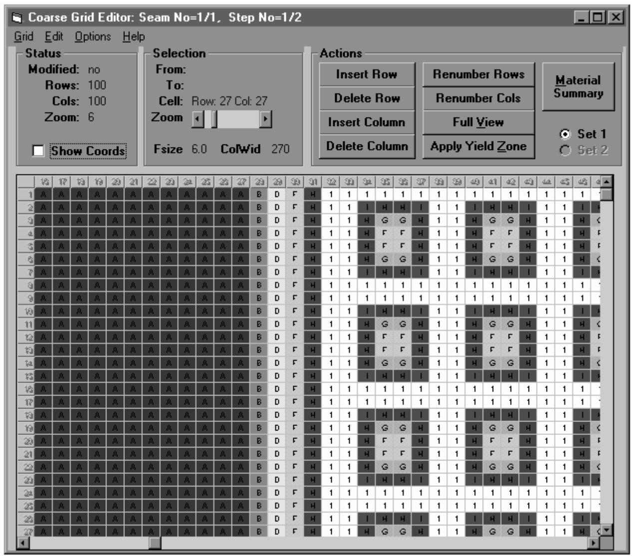

Figure 2.—Grid editor in LAMPRE.

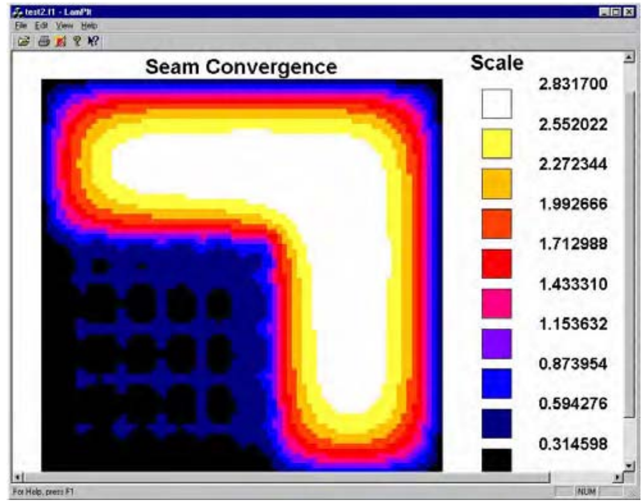

Figure 3.—Colored square output in LAMPLT.

required to produce a practical model. In most cases, the time required to create the mine model can be reduced from days and hours to minutes using the automatic grid generators.

Once the input file is created, the LaModel numerical analysis is run in batch mode for calculating the stress and displacements at the seam level. Model runs can take several minutes to several days depending on the computer speed and model complexity (which includes such factors as number of steps, number of seams, and grid size). The output from the calculation phase is stored in a data file for subsequent analysis by the postprocessing program, LAMPLT.

LAMPLT: THE POSTPROCESSOR

The postprocessing program for LaModel, called LAMPLT, allows the user to quickly and easily plot and analyze the tremendous amounts of output data from the calculation phase of LaModel. With LAMPLT, the user can interactively examine the seam convergence and the vertical seam stress, and the individual components of the seam stress from topography, multiple seams, and/or surface effects. These output values can be displayed using either a pseudo-three-dimensional (3–D) "colored-square" plot (Figure 3) or a two-dimensional (2–D) cross-section. The program also allows interactive selection of plot types, step numbers, scaling, and color. For additional output, LAMPLT allows cut-and-paste of the graphics for input to other reporting programs.

EXAMPLE CASE STUDY

The example case study site is a longwall mine in Greene County, PA, operating in the Sewickley Coal Seam. This mine is underlain by an abandoned room-and-pillar operation in the Pittsburgh Coal Seam. The primary problem at this site was the transfer of multiple-seam stress from the lower mine. Yielding of smaller pillars and the subsequent transfer of their load to larger pillars in the lower seam apparently caused increases in vertical stress in the upper seam, which were noticed during development of the headgate entries (Figure 4). Severe pillar spalling and poor roof conditions were experienced when mining the headgate over these large pillars in the lower seam. Mine management was concerned these underlying abutment pillar stresses would continue to be a problem further inby in the headgate and also in the longwall panel because there were several areas in the lower seam where similar pillar conditions seemed to exist.

In order to optimally use LaModel for accurate stress prediction at a given mine, the program should first be calibrated to the site-specific geomechanics based on previously observed stress conditions at that mine. At this site, the model properties were calibrated using underground stress mapping [Heasley and Chekan 1999]. Then, with the calibrated material properties, LaModel analyses were created and run in order to predict areas of potential problems within the remaining headgate and the future longwall panel.

Figure 4 shows two areas of the headgate and longwall panel that were modeled using optimized properties from the calibration process. These colored plots show the interseam stress, which is the additional stress on the upper mine due to the lower-seam mining. In this figure, Zone 1 covers the upper (inby) part of the headgate panel and the first 365 m (1,200 ft) of the longwall panel. Zone 2 covers the lower part of the headgate (where the stress problems were first noticed) and the last (outby) 330 m (1,100 ft) of the longwall panel. In these two zones, the lower mine pillar conditions and the overburden depths appear similar; therefore, the poor pillar conditions encountered in Zone 2 were expected in Zone 1.

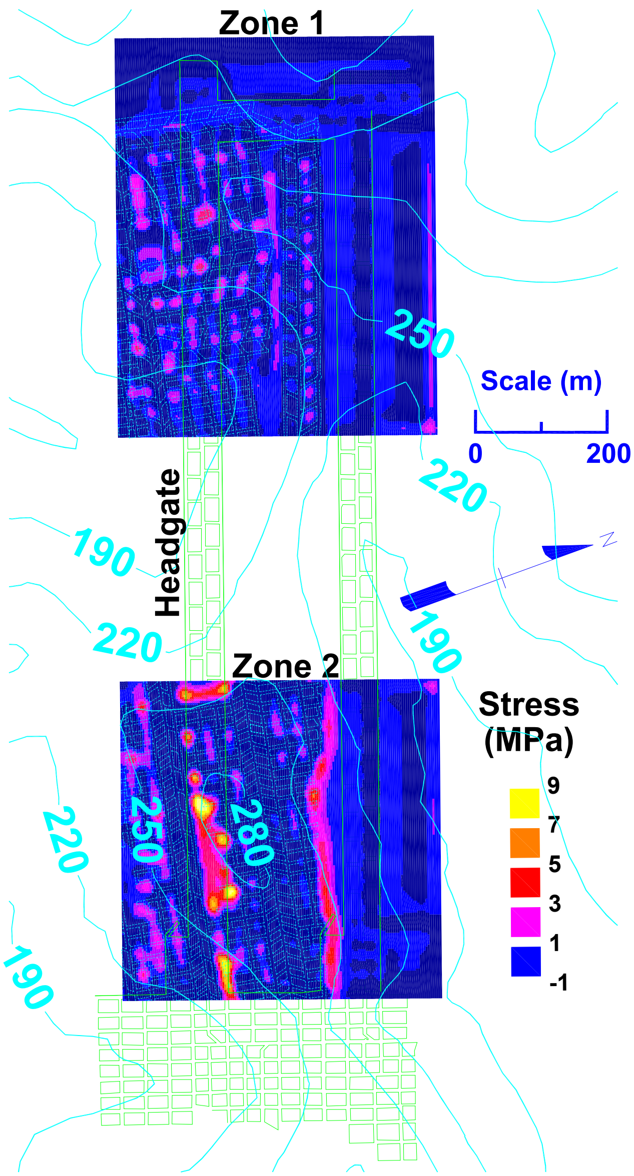

Figure 4.—Interseam stress for Zone 1 and Zone 2.

However, when comparing the interseam stress between these two zones, as shown in Figure 4, it is obvious that the stress is considerably greater in Zone 2 than in Zone 1. Closer investigation reveals two main reasons for this difference. First, the maximum depth over the gate roads and panel in Zone 2 is over 280 m (920 ft), whereas in Zone 2, the maximum depth is just over 250 m (820 ft). Second, when examining the model output for the lower mine, there seems to be less pillar yielding in Zone 1 than in Zone 2. During headgate development in Zone 1, no pillar problems were encountered. Thus, the calibrated model successfully predicted the reduced stress conditions in the headgate of Zone 1.

The mine management was also concerned about the multiple-seam stresses adversely affecting the retreating longwall panel. In particular, a large, irregularly shaped barrier pillar in the lower mine is superimposed under the center line of the initial half of the longwall panel in Zone 1 (Figure 4). However, the interseam stress calculated by the model from this barrier pillar only reaches about 3 MPa (450 psi). When the panel was mined, this slightly increased face stress posed very little problem.

However, in the lower part of the panel near the headgate location where poor ground conditions were first encountered (see Zone 2, Figure 4), an area of interseam stress up to 9 MPa (1,300 psi) is evident in the panel. Because of the underlying barrier pillar, the mine anticipated difficult face conditions in this area. Indeed, when the longwall face reached this area, ground control problems, which included severe face spalling and poor roof conditions in the headgate entries, were encountered. In fact, the stress interaction with the lower seam was severe enough to stop the longwall face about 15 m (50 ft) short of the longwall recovery chute and make recovery of the supports difficult.

SUMMARY

In this paper, the unique laminated formulation of LaModel is detailed and the realistic suppleness this provides to the mining overburden is advocated. Also, the program's ability to analyze interseam stresses, topographic stresses, and surface subsidence is promoted. Next, the preprocessor, LAMPRE, is described to handle all of the numerical parameter input and to allow graphical input of the material codes for the seam grids in LaModel. Then, the postprocessor, LAMPLT, is presented, and its 2–D and 3–D plots are illustrated.

Finally, in the case study, the numerous features of LaModel (including laminated overburden, multiseam simulations, strain-softening seam materials, and topographic effects) were used advantageously in simulating an actual mining scenario. Once realistic pillar strengths and load distributions were established by calibration, the mechanics-based overburden behavior in LaModel effectively analyzed the complicated stresses and displacements associated with the complex multiple-seam mining scenarios and successfully predicted upcoming high-stress conditions in advance of mining for preventive action by mine management.

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THE NEW TWO-DIMENSIONAL LaModel PROGRAM (LaM2D)

By Olayemi O. Akinkugbe[1] and Keith A. Heasley, Ph.D.[2]

ABSTRACT

The safe, productive exploitation of coal in multiple-seam situations requires specific design technology. At present, there are two general design approaches that the mining engineer can use to analyze the multiple-seam problem in question: simple empirical relationships or complex numerical models. Often, the empirical approaches are too general for the specific problem, and the numerical models require too much time and expertise for the practicing engineer. In this paper, a new program designed for quickly and easily calculating the stresses, strains, and safety factors associated with basic multiple-seam mining situations is presented. The program implements a simplified two-dimensional (2–D) boundary-element method in order to model the complex multiple-seam stress and displacement interactions. The program incorporates automatic coal and gob property generation to simplify the input and inherently calculates pillar safety factors to enhance the output.

INTRODUCTION

Numerical modeling as a tool for engineering design has been used for decades. During this time, the awareness of its relevance has greatly increased and, at the same time, considerable developments have been made at improving its accuracy. Presently, there are several general numerical techniques for solving engineering problems; one may choose to use finite-element, boundary-element, discrete-element, finite difference, and/or a hybrid combination of the above to solve the problem at hand. Based on the mathematical approximations involved, numerical methods can be classified into two categories: domain methods and boundary methods. The domain methods are characterized by area and volume discretization of the problem domain. They use relatively large numbers of elements, resulting in large systems of equations that usually consume large amounts of computer resources and require lengthy times for solution. The boundary-element method, on the other hand, requires only the discretization of the boundaries of the domain of interest. Relative to subsurface mineral extraction, only the planar area of the seam is discretized in order to obtain a solution for the desired problem. The boundary-element method usually leads to smaller systems of equations, faster computing times, and a reduced need for computing resources.

The displacement-discontinuity method, a version of the boundary-element method promoted early by Salamon [1963], is usually the method of choice for analyzing stresses and displacement distribution in slitlike or thin-seam openings. In this approach, the relative movement between the roof and floor of a mine is treated mathematically as a discontinuity in the displacement field of the surrounding media, in other words, a crack/slit in a continuum. The displacement-discontinuity method has been used to create several well-known computer packages for solving geomechanical problems in underground mines.

The first implementation of the displacement-discontinuity method into a personal computer code for calculating stress and displacement from multiple seams was done by the U.S. Bureau of Mines. The program was called MULSIM/BM. In 1992, MULSIM/BM was upgraded to MULSIM/NL [Zipf 1992a,b] by the addition of nonlinear seam material models, calculations for determining the mechanical strain energy changes associated with the seam materials, and a capability for "stepping" though a series of mining sequences. A new displacement-discontinuity program called LaModel was later introduced by the National Institute for Occupational Safety and Health [Heasley and Chekan 1999]. LaModel implemented the same nonlinear seam material models in MULSIM/NL, but introduced a laminated overburden model. This model assumes the overburden to be a stack of horizontally lying strata, which naturally increases the flexibility of the overburden. As a result, LaModel estimation of the stresses, displacements, and surface subsidence is considered more accurate compared to the homogeneous overburden model implemented in MULSIM/NL.

In this paper, a new 2–D boundary-element program, LaM2D, is introduced. This program implements the laminated overburden model [Heasley 1998; Salamon 1991, 1962] used in the three-dimensional (3–D) LaModel program into a greatly simplified 2–D program. This 2–D implementation of the laminated boundary-element program was specifically developed in order to provide a fast, simple, multiple-seam analysis program for the practicing engineer. LaM2D only requires that the user input the minimum geometric parameters from the multiple-seam mining situation. The program automatically incorporates default overburden, coal, and gob properties to simplify the input and inherently calculates pillar safety factors for the program output.

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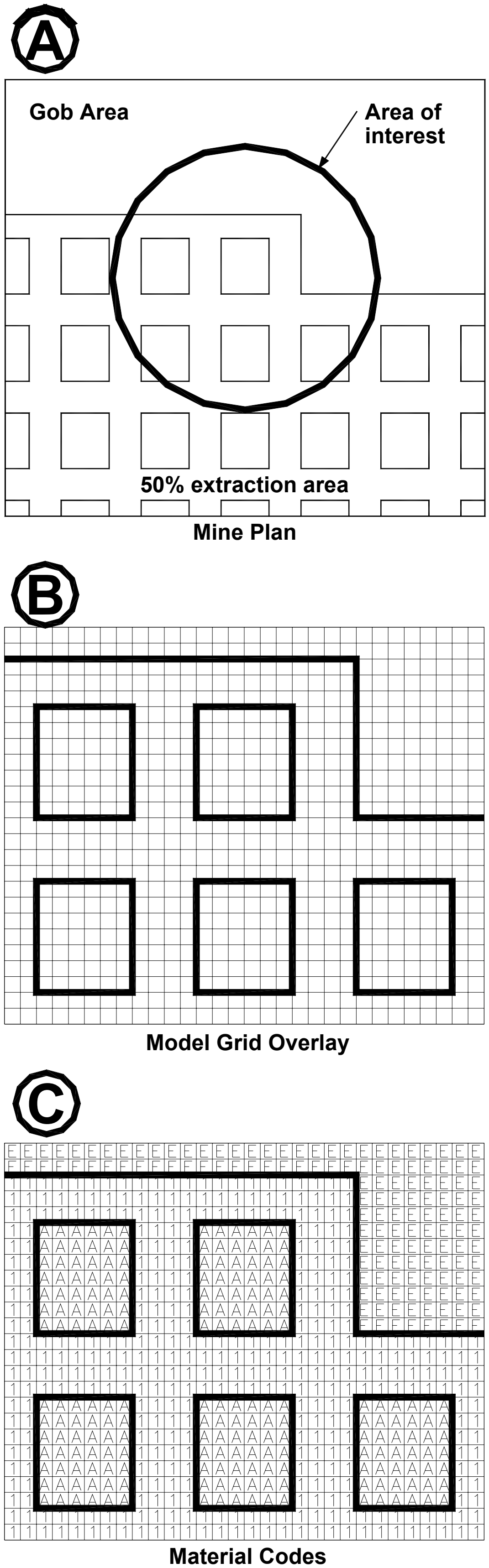

Figure 1.—Schematic of LaModel mine grid.

2–D LAMINATED OVERBURDEN MODEL

In the 3–D MULSIM and LaModel programs, the horizontal plan of the seam was used to determine a grid of elements from which the vertical (out-of-plane) stresses and displacements were determined. For example, given the mine plan in Figure 1A, a square grid (with an element size optimized to best fit the entry and pillar dimensions and large enough to cover the intended modeling area) was superimposed on the mining plan, as shown in Figure 1B. Each element of the grid was then designated as a particular material using a letter code (Figure 1C). (In this case, the pillar material is “A”, the open entries are “1”, and the gob material is “E”.) This grid of materials was then used as the representation of the mine for which the vertical stresses and displacements were determined.

In the 2–D laminated model, a cross-section of the pillars in the seam is used to determine a linear array of elements from which the vertical stresses and displacements are determined. For example, given the cross-section of pillars in Figure 2A, a linear array of elements (with an element size optimized to best fit the entry and pillar dimensions and large enough to cover the intended modeling area) is superimposed on the mining plan, as shown in Figure 2B. Each element of the material array is then designated as a particular material using a letter code (Figure 2C). (In this case, the pillar material is “A”, and the open entries are “1”.) This array of material properties is then used as the representation of the mine for which the vertical stresses and displacements are determined.

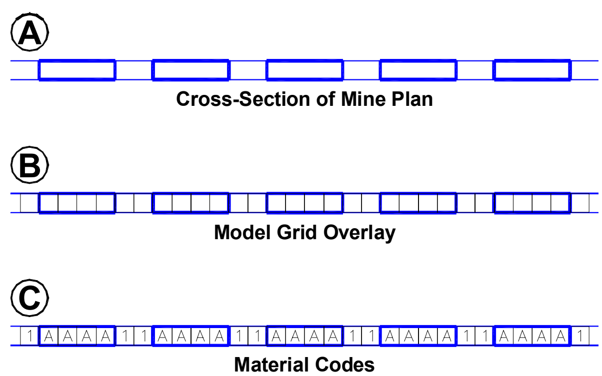

Figure 2.—Schematic of LaM2D mine grid.

Advantages

The big advantages of the LaM2D program over the previous 3–D programs are that the mine grid is much simpler and faster to input (minutes instead of hours) and the solution times are much quicker, in fact, almost instantaneous (seconds instead of minutes or hours). To further speed the input process, LaM2D (in default mode) only requires that the user input the minimum geometric parameters to define the seam geometries. Default properties for overburden, coal, and gob are automatically generated. (In the advanced mode, the user has complete control over all of the input parameters.) This ease of input and instantaneous solution enables the user to quickly analyze and compare many different design variations or perform parametric studies.

Disadvantages

The main disadvantage of LaM2D is that it is only a 2–D plane strain analysis. Therefore, the variation in the mine plan in the out-of-plane direction is ignored, and only mining plans that can be reasonably represented in 2–D can be accurately simulated. The plane strain approximation means that the pillars and entries in the cross-section are essentially assumed to be infinitely long in the out-of-plane direction. Therefore, mining plans that change dramatically in the out-of-plane direction will not be modeled properly. However, LaM2D does have a capability for inputting an out-of-plane extraction ratio, which can be used to accurately simulate the crosscuts in the "infinitely" long pillars (see below). With the out-of-plane extraction ratio, not only infinitely long pillars, but also mining plans that are reasonably continuous and symmetric across the plane of the cross-section can be accurately simulated.

Stability Analysis in LaM2D

In addition to its capability to quickly analyze basic multiple-seam interactions, LaM2D also provides several practical stability indices for the affected mine and pillars. The presently available computer programs for analyzing seam interactions in single- or multiple-seam mining situations typically produce only seam displacement and stress values as output. The new LaM2D program goes several steps further by using the seam displacement and convergence values to determine pillar safety factors, multiple-seam subsidence, and multiple-seam horizontal strain values for output.

Safety Factors

To ensure overall mine stability, the general approach is to size the pillars large enough, and therefore strong enough, to support the applied loads. In classical engineering, this generally requires a pillar safety factor greater than 1.0, with some reasonable margin for error. In situations where seam interactions exist as a result of a superjacent or a subjacent seam, simple empirical methods for calculating pillar safety factors are not generally applicable. Also, computer programs based on the single-seam empirical methods are not recommended for multiple-seam interaction analysis; rather, more complex numerical methods are often required. However, most practicing mining engineers are accustomed to working with pillar safety factors, and the stresses and displacements generated by the complex numerical modeling programs are not generally as useful or as comparable. In order to provide the customary safety factors and enhance the practical functionality of the LaM2D program, an automatic calculation of pillar safety factors has been incorporated into the program.

The primary safety factor implemented in the LaM2D program is stress-based and uses the typical safety factor calculation:

$$SF = \frac{S_p}{B} \tag{1}$$

where SF = the pillar safety factor;
S_p = the pillar strength;
and B = the pillar load.

In order to incorporate realistic pillar strengths into the program, the Mark-Bieniawski pillar strength formula [Mark and Chase 1997] was used to determine pillar strengths because of its strong empirical basis and long successful history of application in the U.S. coalfields:

$$S_p = S_i\left[0.64 + 0.54\left(\frac{w}{h}\right) - 0.18\left(\frac{w^2}{lh}\right)\right] \tag{2}$$

where S_i = the in situ coal strength;
w = the pillar width;
h = the pillar height;
and l = the pillar length.

In the program, the height of the pillar is determined from the input seam height, and the width of the pillar is automatically determined from the number of elements across the pillar. For calculating the pillar load, LaM2D averages the values of all of the calculated element stresses across the pillar. The safety factor is then determined by dividing the Mark-Bieniawski pillar strength by the average pillar stress. Ultimately, the pillar safety factors can be displayed in a colored-square or line plot (see the subsequent case study).

Multiple-seam Subsidence and Strain

When a seam is undermined, it experiences multiple-seam stress transfer similar to an overmining situation. However, a seam that is undermined by total extraction mining can also be subjected to subsidence and the associated horizontal tensile and compressive strains. The multiple-seam subsidence effects are an important ground control consideration and can result in serious roof and floor instability and damages in the overlying seam. For instance, field studies of room-and-pillar operations [Chekan and Listak 1994] showed that severe roof conditions are typically experienced within the tension and compression zones of a subsidence trough.

In previous multiple-seam analysis programs, the upper-seam subsidence and strain were never explicitly determined, although these calculations can be critical to analyzing the overlying mine stability. In order to provide the expected multiple-seam subsidence and strain values to the practicing engineer and increase the information available for design, the LaM2D program specifically calculates these values and provides them to the user. In the program, the upper-seam subsidence is calculated using the lower-seam convergence distribution and a laminated influence function. Once the seam subsidence is known, the resulting horizontal strains are determined using the method promoted by the National Coal Board in the *Subsidence Engineers Handbook* [National Coal Board 1975]. A demonstration of these strain calculations is presented later in the case study.

Out-of-plane Extraction Ratio

Because of the 2–D plane-strain formulation of LaM2D, the pillars and entries in the cross-sectional mine plan are essentially assumed to be infinitely long in the out-of-plane direction. This assumption is typically unrealistic for many pillar geometries in practical applications, where the pillars have a finite length in the out-of-plane direction. In many 2–D cross-sections, such as across a longwall gate road or through a room-and-pillar section, the pillar plan in the out-of-seam direction is fairly continuous (although not infinite). In these situations, an "out-of-plane extraction ratio" can be used to get a more accurate calculation of the true 3–D stress and displacements in the modeled mine plan.

In LaM2D, the in-plane extraction ratio is inherently provided through the specification of pillar material and openings in the input material properties (see Figure 2C). To specify the out-of-plane extraction ratio, the functional extraction ratio for the noninfinitely long pillars needs to be input. For example, consider a room-and-pillar section with 40- by 80-ft pillars and 20-ft-wide entries. The 2–D cross-section in LaM2D goes through the 80-ft length of the pillar; therefore, the input mine plan shows 80 ft of pillar material coupled with 20 ft of opening (an in-plane extraction ratio of 20%). In the out-of-plane direction for this situation, there is 40 ft of pillar coupled with 20 ft of opening. This results in an out-of-plane extraction ratio of 33%.

If the user inputs an out-of-seam extraction ratio, the stress from the infinitely long simulation will be adjusted to account for the limited pillar length. Essentially, the material stress and convergence values calculated for the infinitely long pillar are increased by a factor of:

$$\frac{1}{1-e} \tag{3}$$

where e = the out-of-plane extraction ratio. Thus, the practical result of using the out-of-plane extraction ratio is that the calculated stress values will realistically represent the average stress on the finite pillar, while the convergence values will represent an out-of-plane average across the finite pillar and the adjacent opening. Therefore, the 2–D simulation can give realistic 3–D pillar stress when the out-of-plane extraction ratio is used.

However, using the out-of-plane extraction ratio does not provide realistic 3–D safety factors. Without using the out-of-plane extraction ratio, the program calculates accurate pillar stresses, pillar strengths, and safety factors for the plane strain (infinitely long pillar) situation. When the out-of-plane extraction ratio is used, the program accurately adjusts the pillar stress values up to account for the limited length of the pillar; however, the pillar strength is still calculated based on an infinite-length pillar (for lack of sufficient information on the true pillar size). Therefore, the safety factor is realistically decreased from the 2–D situation, but is still not an accurate safety factor for the 3–D situation implied by the out-of-plane extraction ratio.

LaM2D INPUT

Compared to most numerical modeling programs, the input and output for the LaM2D program were simplified as much as possible to make it very user-friendly. Typical numerical modeling programs involve parameter input, solution of the model based on the input parameters, and an output or plot of the solution values. In many cases, three separate programs are used to perform the parameter input, solution, and the output (e.g., LaModel); however, the full-featured LaM2D program incorporates all of the numerical modeling steps into a single program.

Furthermore, the many material property input parameters necessary for modeling often seem daunting for practicing engineers who do not have the time to gather and verify specific material properties for both the seam and its surrounding rocks. In the LaM2D program, realistic average coal seam and overburden parameters are automatically defined. In fact, if the program is run in the standard mode, the only parameters required from the user are: the general model information, which includes model title, number of seams, and the system of units to be used (Figure 3); the seam geometry information, which includes element size, grid size, seam depths, and thicknesses (Figure 4); and the seam material grids (Figure 5). In standard mode, all of the seam and overburden properties are automatically entered with average values. However, if the user desires and the program is run in advanced mode, the program allows the user the total flexibility of adjusting any or all parameters in the program, including the rock mass parameters (Figure 6), in-seam element parameters (Figure 7), boundary conditions (Figure 8), and program control values (Figure 9).

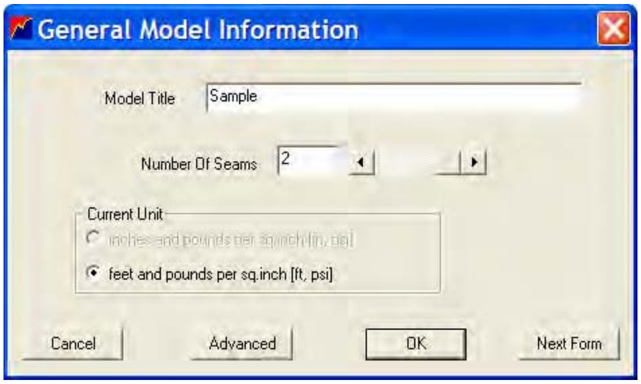

Figure 3.—General model information form.

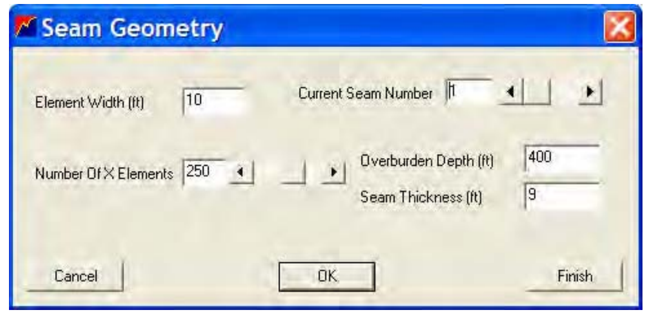

Figure 4.—Seam geometry form.

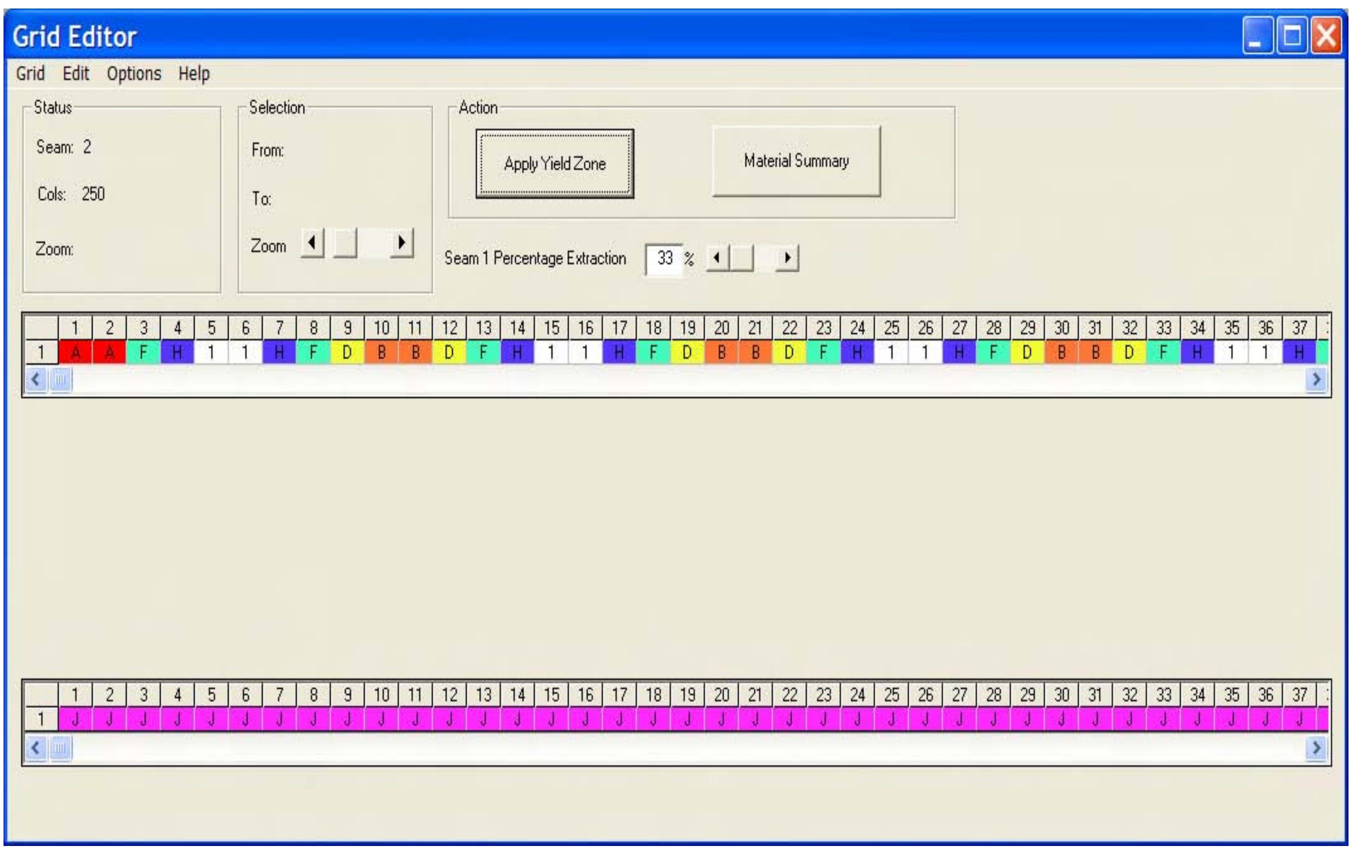

Figure 5.—Grid editor form.

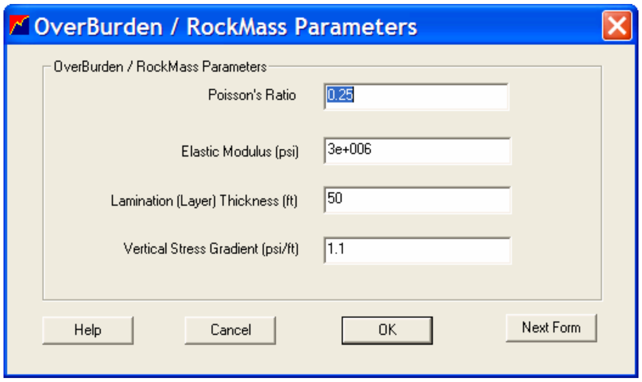

Figure 6.—Overburden and rock mass parameters form.

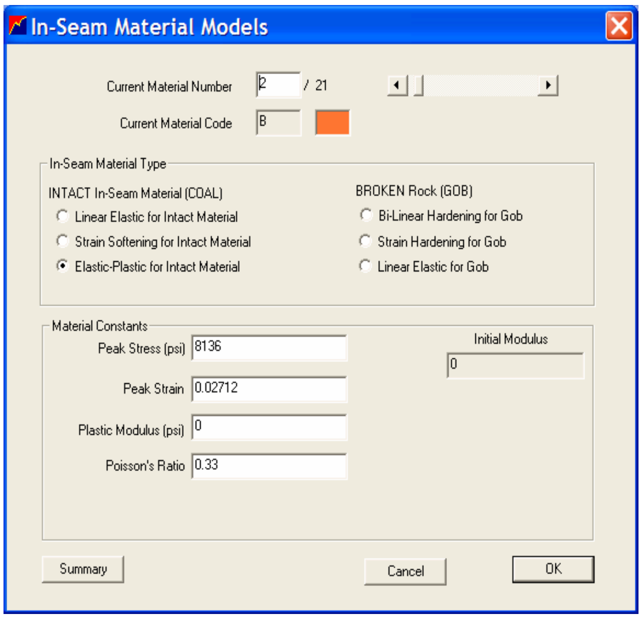

Figure 7.—In-seam material form.

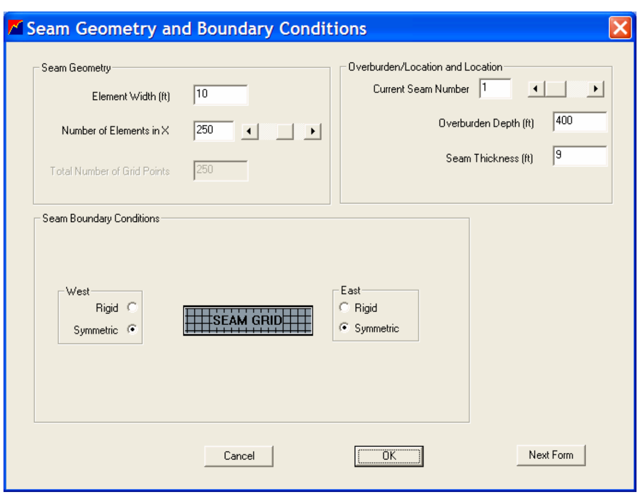

Figure 8.—Seam geometry and boundary condition form.

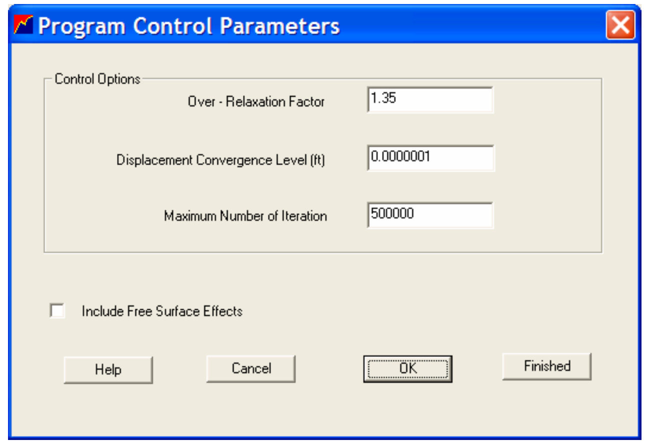

Figure 9.—Program control form.

Grid Editor

The grid editor is used for inputting the seam material codes. It contains a simulated cross-section for each of the modeled mining seams (Figure 5) where the user can enter the appropriate letter codes into the proper grid location in order to represent the 2–D mine layout. The letter codes are entered using a mouse-driven interface similar to an Excel spreadsheet. The user only needs to input the primary coal letter code for each seam, and the program automatically generates appropriate yield zones based on a Bieniawski pillar strength. Also, the grid editor is where the user inputs the out-of-plane extraction ratio.

Running the Model

Once all of the input has been completed, the LaM2D program typically runs in just a few seconds. Then, the output can be viewed using a number of plotting routines. The values output from the program include: seam convergence, seam stress, multiple-seam stress, multiple-seam displacement, and horizontal strain. Any of these values can be plotted separately using the traditional "colored-square" plot or line graph. Also, a new "comparison plot" can be used to visualize, compare, and analyze the interacting effect of different values from one seam to the other.

CASE STUDY

In order to test the accuracy and utility of using the new, simplified multiple-seam program, LaM2D, a comparative case study was performed using both LaModel and LaM2D. The case study was taken from the literature [Ellenberger et al. 2003] and documents a situation where a longwall panel undermined an active room-and-pillar mainline development. The upper mine operates in the 9-ft-thick Coalburg Seam and has driven a seven-entry mainline with 40- by 80-ft pillars. The lower mine operates in the 5.6-ft-thick No. 2 Gas Seam and was retreating a 1,000-ft-wide longwall panel directly under the overlying mains. The interburden at this site averaged 560 ft, and the maximum overburden over the upper mine was about 400 ft. The idealized mine map for this site, as used in the comparative study, is shown in Figure 10.

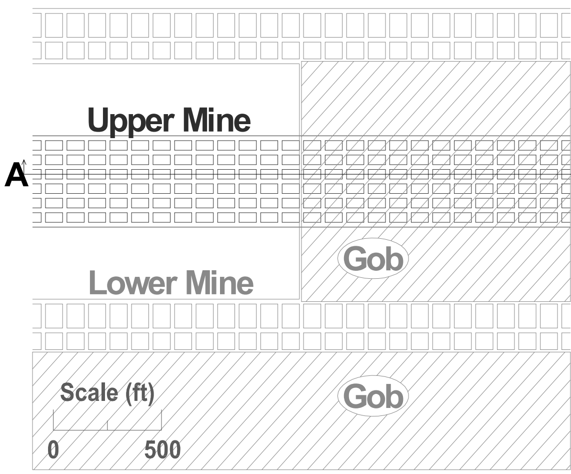

Figure 10.—Idealized mine plan for the case study analysis.

For the idealized comparative study in this paper, the mains are modeled as perfectly aligned with the middle of the longwall panel, and all of the pillars in the mains and the gate roads are modeled with consistent sizes. In reality, the mains were somewhat offset from the center of the longwall panel and slightly skewed to the longwall advance. Also, the pillars in both the mains and the longwall gate roads have some variations in dimension due to practical and operational considerations [Ellenberger et al. 2003].

In the field, when the upper seam was undermined by the longwall, tension cracks began to develop in the roof when the underlying face approached to within 70 ft. Roof and rib control problems intensified as the longwall moved under and continued beyond the upper seam. The sandstone roof in the upper mine was extensively fractured, with some apertures measured at 4 in. Several roof falls occurred and severe rib spalling was experienced. As the dynamic subsidence settled and reached equilibrium, the roof fractures mostly closed and conditions significantly improved.

For the mine plan in Figure 10, a 3–D LaModel model was developed. This model used 10-ft elements on a 250-by-250 grid to represent the mine plan shown. Entering the material parameters and the mine grid in order to build this simplified model took about 1 hr (for the real mine plan with variable size pillars and off-angle pillar, more than a day was used to build the model). The program then took another hour to solve the model for the seam stresses and displacements. Overall, LaModel took about 2 hr to build and solve the model.

Using LaM2D, a 2–D cross-section from the critical area (section A–A′) in Figure 10 was modeled. This cross-section essentially consists of the upper-seam pillars and the lower-seam longwall, as shown in Figure 11. With the simplified 2–D LaM2D, a linear array of 250 10-ft elements was used to represent each seam. The minimum parameter input for the model was used, as shown in Figures 3 and 4, and only took a minute or two to enter. Also, the material grids were entered into the program using the grid editor (Figure 5) and took another few minutes. After all of the parameters and grids were entered, the program solved for the seam stresses, displacements, safety factors, and strains in a few seconds. Overall, the total parameter input and solution required less than 10 min using LaM2D.

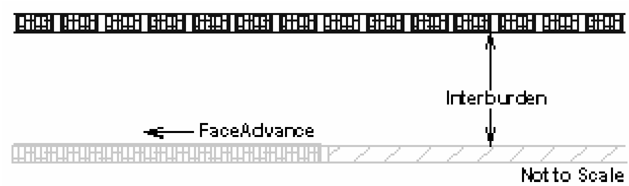

Figure 11.—Cross-section used in the LaM2D program.

Figure 12 compares the stresses calculated with the 3–D LaModel program with those calculated with the simplified LaM2D program. For all practical purposes, the vertical stresses calculated by the two models are the same. Both models show the stress abutment in front of the advancing longwall face and the reduced stress in the gob behind the longwall. Further, the LaM2D program can be used to determine the pillar safety factors and the subsidence-induced strain. For instance, the pillar safety factors for the case study are shown in Figure 13. It can be seen in this figure that the safety factors are generally high and pillar failure would not be expected. This is consistent with observations in the field, which reported pillar spalling but no pillar failure. The horizontal strain was also calculated for the case study, as shown in Figure 14. The tensile stress in front of the moving longwall and the compressive stress behind the longwall on the order of 250 microstrains are clearly evident. Based on the National Coal Board experience with surface strains [National Coal Board 1975], the 250 microstrains should only cause "slight damage." However, the correlation between strain and underground roof damage is not very well defined, and 250 microstrains could be consistent with the observed roof cracking and roof falls.

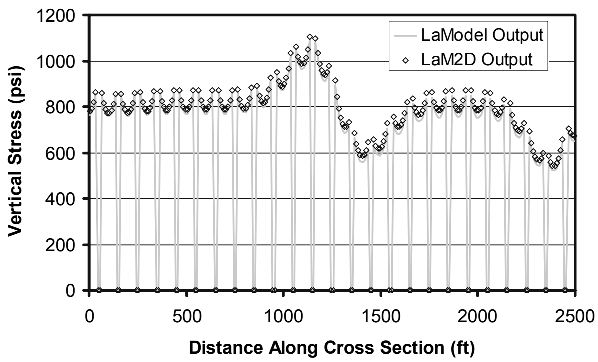

Figure 12.—Comparison of LaModel and LaM2D stresses.

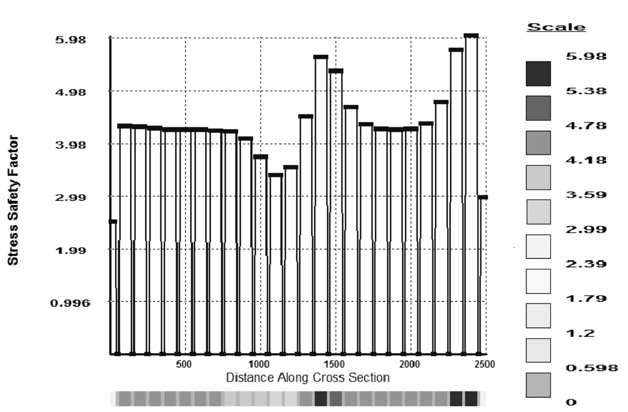

Figure 13.—LaM2D safety factor output.

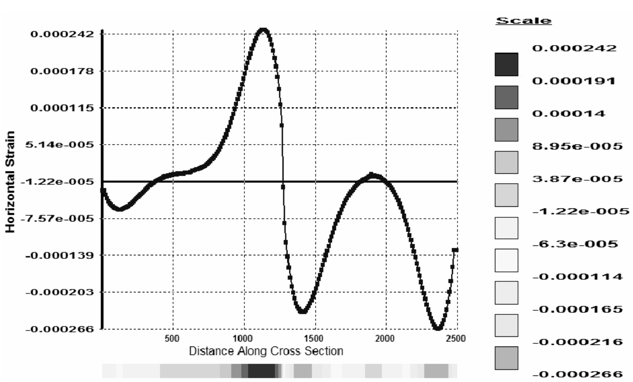

Figure 14.—LaM2D horizontal strain output.

SUMMARY AND CONCLUSIONS

A simplified 2–D boundary-element method designed to model the complex multiple-seam stress and displacement interactions has been implemented into the LaM2D program. This new program allows the user to quickly and easily calculate the stresses, displacements, safety factors, and strains associated with basic multiple-seam mining situations that can be accurately represented in two dimensions. The input to LaM2D has been greatly simplified by incorporating automatic overburden, interburden, coal, and gob property generation. Also, the program is the first multiple-seam analysis package to inherently calculate pillar safety factors and multiple-seam-induced subsidence and strain. In a practical comparison with the full-featured multiple-seam program LaModel, the simplified LaM2D provided comparable stress and displacement calculations in minutes instead of hours. Further, the unique safety factor and strain calculations of the LaM2D program provided practical accurate assessments of the observed pillar and roof behavior in the modeled mine.

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MULTIPLE-SEAM LONGWALL MINING IN THE UNITED STATES: LESSONS FOR GROUND CONTROL

By Christopher Mark, Ph.D., P.E.[1]

ABSTRACT

Relatively few longwall mines in the United States operate under multiple-seam conditions where the two seams are less than 200 ft apart. This paper describes the experience of six that do. These operations are located in Pennsylvania, West Virginia, and Utah and include examples of both undermining and overmining. Some operate above or beneath their own workings; others are in historic mining districts and must contend with abandoned mines that are decades old. The lessons learned by these mines cover a broad range of topics, including:

- Whether to stack gate roads or place them under old gob areas;
- How to size pillars and select artificial support to cross longwall stop lines;
- How to use yield pillars to minimize multiple-seam stresses and coal bump potential; and
- When to anticipate the creation of pathways for gas, water, or oxygen between current and abandoned gobs.

INTRODUCTION

Multiple-seam interactions can cause roof falls, rib spalling, and floor heave, disrupting mining operations and threatening the safety of miners. In early 2006, a West Virginia coal miner was killed by rib roll that occurred in a high-stress zone beneath a remnant pillar structure in an overlying mine [MSHA 2006]. Longwalls may be uniquely vulnerable to multiple-seam interactions because they tend to operate under deep cover, generate large abutment stresses, and have little flexibility to avoid localized zones of difficult conditions.

For the past several years, the National Institute for Occupational Safety and Health has been conducting research to develop better techniques for predicting the location and severity of multiple-seam interactions. During this research, more than 40 mines were visited across the U.S. coalfields, including a number of longwalls. The study also drew upon past studies conducted by the author and an extensive literature review. The purpose of this paper is to discuss the potential impacts of multiple-seam mining on longwalls based on an evaluation of the different geologic environments in which longwall mining is conducted, combined with analyses of past case histories.

OVERVIEW

Figure 1 shows the five major underground coal mining regions in the United States. Also shown are the numbers of operating longwall faces in each region [Fiscor 2006].

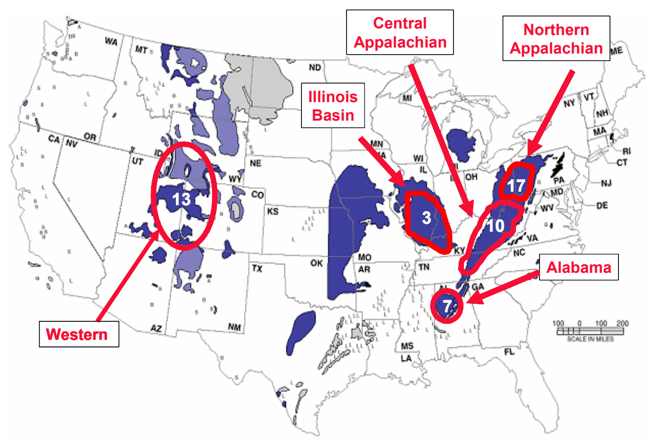

Figure 1.—The five major underground coal mining regions in the United States and the number of longwall faces in each [Fiscor 2006].

The central Appalachian region of southern West Virginia, eastern Kentucky, and southwestern Virginia is the most significant coalfield from the standpoint of multiple-seam mining. Mining has been ongoing in central Appalachia for nearly 150 years. Recent studies have indicated that perhaps 70% of the ultimate reserve base in the region has already been mined [Bate and Kvitkovich 2004]. One consequence of the maturity of the central Appalachian coalfields is that most underground reserves have been impacted by past mining activity. The mountains of the central Appalachian coalfields are honeycombed with worked-out mines located above, below, and adjacent to today's and tomorrow's operations.

Although longwall mining has a long history in central Appalachia, including the first mechanized faces in the

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United States [Barczak 1992], the 10 longwalls active there today account for less than 20% of the region's underground production [EIA 2006; Fiscor 2006]. Of these, three are extracting the very deepest minable seam in the area—the Pocahontas No. 3—without any significant mining above or below. The others are operating in multiple-seam environments, and two case histories are discussed in some detail later in this paper.

The Western United States is the next most important area for multiple-seam mining. In Utah, Colorado, Wyoming, and New Mexico, nearly 95% of underground production comes from the 13 longwall operations [EIA 2006; Fiscor 2006]. Approximately half of these are operating in multiple-seam configurations, including several mines in the Price, UT, area and three others in the North Fork Valley near Paonia, CO.

In contrast to central Appalachia, in the West the same mining company is usually responsible for all the mining on a property. As a result, a greater degree of multiple-seam planning is normally possible. Recently, however, one North Fork Valley mine was forced to abandon a panel prematurely when an interaction associated with an abandoned mine resulted in roof falls in the headgate [Buchsbaum 2006].

Multiple-seam interactions in western longwalls can also contribute to the deadly bump hazard because of the deep cover and strong roof and floor rock [Peperakis 1968]. To minimize the hazard, many western longwalls employ yield pillar gate entry designs. Some of the lessons that have been learned from their experience are discussed later in this paper.

The northern Appalachian region is home to nearly one-third of the nation's longwalls—17 faces producing 87 million annual tons [EIA 2006; Fiscor 2006]. Currently, all but one of these longwalls is extracting the Pittsburgh Seam. The Freeport Seam, the nearest minable coalbed beneath the Pittsburgh, is over 600 ft below, and it has never been extracted beneath any Pittsburgh longwall. There has been some mining in the Sewickley Seam that overlies the Pittsburgh. In the distant past it caused some disruption in the Pittsburgh [Zachar 1952], but it has not been known to impact the modern longwall mines.

Although none are operating today, in the recent past longwalls have operated in the Sewickley Seam and other seams in central Pennsylvania. These operations provide two examples of longwall mining above abandoned works that are discussed below.

More than 90% of the underground coal produced in the Illinois Basin comes from two seams: the Springfield 5/ Kentucky 9 and the Herrin 6/Kentucky 11 [EIA 2006]. These seams are often less than 80 ft apart, so there is significant potential for multiple-seam interaction. However, today there are just two longwall mines operating in the Illinois Basin. One of these does work both seams, but the mining has been planned so that the workings in one seam have never crossed previously mined gob areas in the other seam.

Seven longwalls are currently active in the Alabama coalfields. Six of these are extracting the Blue Creek Seam, which is again the deepest minable seam in the section, lying hundreds of feet below the nearest minable overlying seam. The only non-Blue Creek longwall is also free of multiple-seam interactions.

HAZARDS ASSOCIATED WITH MULTIPLE-SEAM MINING

Ground instability is usually the greatest hazard due to multiple-seam interaction. Interactions may be classified into four major categories depending on the mining method, mining sequence, and thickness of the interburden. Other potential hazards are associated with water, gas, and oxygen-deficient air.

Undermining, the first category of interaction, occurs when the upper seam has been mined first and the lower seam is the active seam (Figure 2). In an undermining situation, damage is caused by load transfer from highly stressed structures associated with full-extraction mining in the overlying seam.

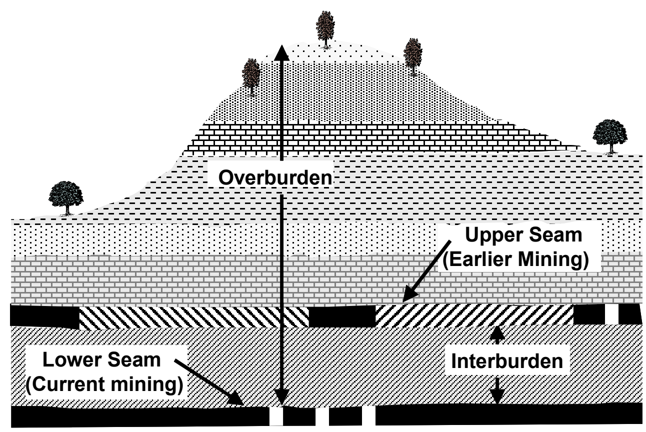

Figure 2.—Undermining interaction.

Overmining, the second type of interaction, occurs when the upper seam is extracted after mining is complete in the lower seam (Figure 3). Load transfer occurs in this situation just as it does in undermining (in other words, gob-solid boundaries and remnant pillars cause stress concentrations both above and below). In addition, however, full extraction of the lower seam normally results in subsidence of the overlying beds, potentially damaging the roof.

Dynamic interactions occur whenever active mining occurs above or beneath open entries that are in use. The most severe dynamic interactions occur when a lower seam is longwalled or pillared, resulting in subsidence of the overlying workings. Although there have been several relatively recent cases in which longwalls were extracted as far as 550 ft beneath open main entries, causing

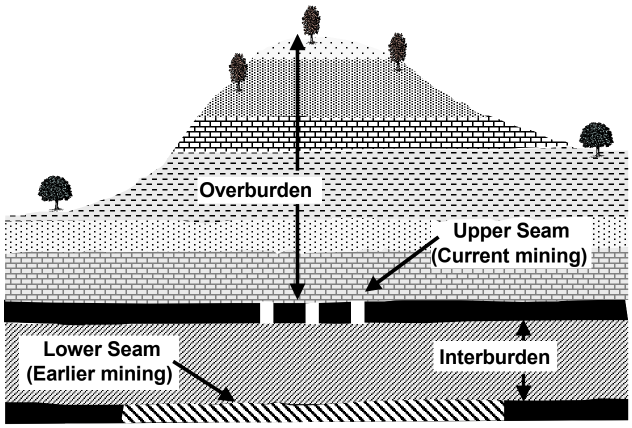

Figure 3.—Overmining interaction.

extensive damage to the upper mine [Ellenberger et al. 2003; Mark 2006], there do not seem to be any instances in the United States where a working longwall was the victim of a dynamic interaction.

Ultraclose mining is the fourth type of interaction and the only one that applies to development mining. The main concern is failure of the interburden between the two seams. Ultraclose interactions are unlikely when the two seams are more than 20–30 ft apart.

Other hazards include the potential for inundation from an overlying flooded mine, particularly where full extraction in the lower seam can create a direct pathway between the upper- and lower-seam gobs. In one example, the first longwall panel at a Kentucky mine encountered a major inflow from workings 150 ft above. In this instance, the water posed no hazard to the miners, but the lack of pumping capacity in the lower seam resulted in major mining delays [Mark et al. 1998]. Fractures in rock above subsided gob areas can also fill with methane or oxygen-deficient air, resulting in inflows of gas or blackdamp when they are intersected by overmining.

OVERMINING INTERACTIONS: TWO CASE HISTORIES FROM PENNSYLVANIA

Two Pennsylvania longwalls, both of which are now closed, provide examples of the potential for overmining previously extracted areas. The first example was a successful one, the second less so.

In Cambria County, PA, Bethlehem Mines Corp.'s No. 33 Mine employed longwall methods to extract the B Seam (Middle Kittanning) and the overlying C-prime Seam (Upper Kittanning). The mining was sequenced so that extraction was completed in the B Seam first. More than 25 longwall panels were later recovered in the upper seam over almost 2 decades [Bauer et al. 1992].

The B Seam averaged about 5 ft in thickness, and its depth of cover was 500–800 ft. High horizontal stresses were typical of the lower seam, where they caused extensive damage to the gate entries during both development and longwall retreat [Mark and Mucho 1994].

The C-prime Seam was typically 3.5 ft thick, with an additional 1 ft of drawrock normally extracted. The immediate roof consisted of interbedded sandstone and shale, with a Coal Mine Roof Rating (CMRR) of about 50. The interburden between the seams averaged 105 ft and consisted mainly of shales and sandy shales. Typically, at least 10 years was allowed to elapse between the completion of mining in the lower seam and development in the upper. Contrary to usual multiseam practice, the gate entries in the C-prime were superpositioned above the gates in the lower seam (Figure 4). In general, conditions were quite good both on development and longwall retreat. Six-ft-long fully grouted resin bolts, supplemented in the tailgate by two rows of wooden posts, provided adequate roof support. In only one instance, when an attempt was made to develop a gate road slightly over the gob, were poor ground conditions attributed to multiple-seam interactions. Conditions along the longwall face were also benign and were not noticeably different near the panel edges than they were in the center of the subsidence trough.

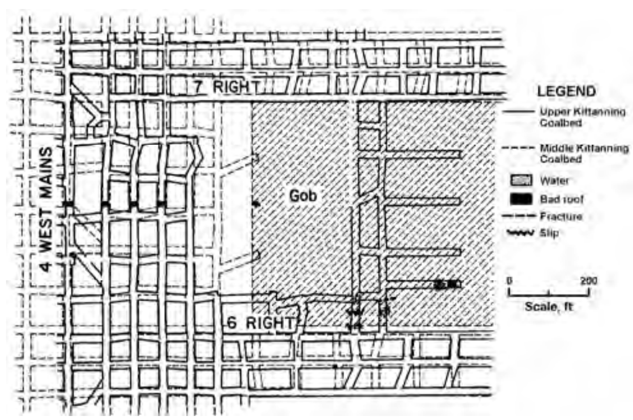

Figure 4.—Stacked gate road layout at Bethlehem Mines Corp.'s No. 33 Mine [Bauer et al. 1992].

Interestingly, ground conditions in the upper seam actually seemed to be worse above virgin, undisturbed B Seam areas than above areas where the B Seam was mined out. Above the virgin areas, C-prime workings encountered severe ground conditions and methane emissions. It seemed that perhaps the subsidence associated with the extraction of the B Seam relieved the horizontal stresses and removed the methane that would otherwise have been present.

The second example of overmining is provided by New Warwick Mining Co.'s Warwick Mine in Greene County, PA. The Warwick Mine worked the Sewickley Seam beneath 500–900 ft of cover. The Sewickley roof was a dark sandy shale with a CMRR of about 40.

The Pittsburgh Seam was approximately 100 ft below the Sewickley, and underneath one panel it had been worked by high-extraction room-and-pillar methods (Figure 5). Analysis indicated that many of the small fenders that had been left in the Pittsburgh Seam had probably yielded, transferring much of their load to a few large, isolated remnant pillars [Heasley and Chekan 1999]. Severe pillar spalling and poor roof conditions were encountered when developing gate entries above these remnants.

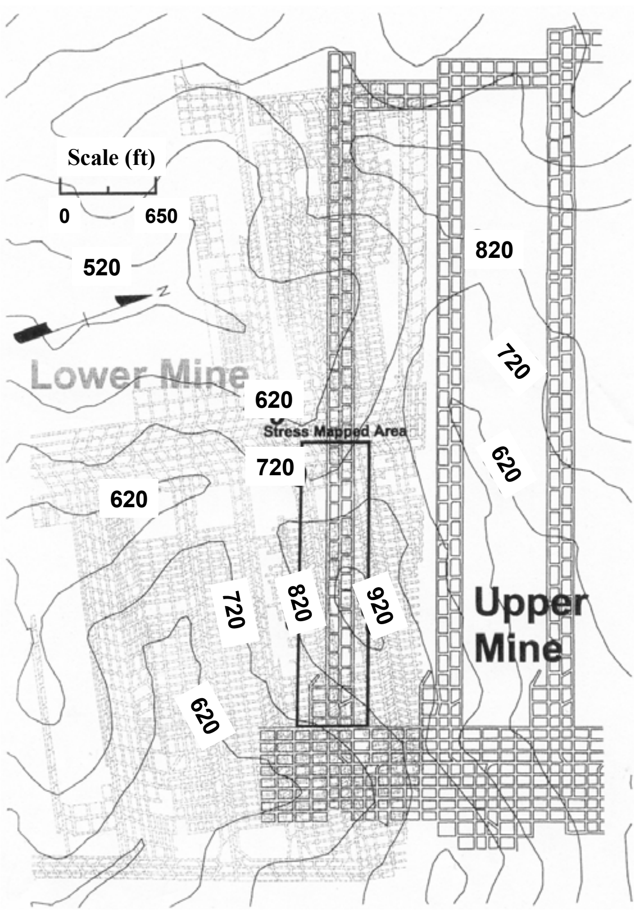

Figure 5.—Map of the Warwick Mine in the Sewickley Seam and the underlying Pittsburgh Seam workings [Heasley and Chekan 1999].

The inby portion of the Sewickley longwall panel, where the cover was shallowest, was developed and longwalled with little difficulty. However, stress mapping and LaModel analysis indicated that the most severe interactions would occur beneath the deepest cover, near the mouth of the panel [Heasley and Chekan 1999]. When the longwall face reached this area, ground control problems included face spalling and headgate roof instability. The conditions were so severe that the longwall face had to be stopped 50 ft short of the recovery chute, which greatly complicated recovery of the longwall.

UNDERMINING INTERACTIONS: TWO CASE HISTORIES FROM CENTRAL APPALACHIA

Two mines in southern West Virginia provide examples of longwalls undermining full-extraction workings in an upper seam. The first, the Harris No. 1 Mine, is operated by Peabody Energy. During the past 30 years, Harris has mined more than 60 longwall panels in the Eagle Coal Seam. The depth of cover exceeds 1,400 ft beneath the highest ridges. The roof is fairly typical of central Appalachia and consists of strong shale and sandstone, with CMRR values normally in the 45–60 range.

The Eagle is located 180–200 ft beneath the No. 2 Gas Seam. Figure 6 is a generalized stratigraphic column of the interburden that shows it contains a high percentage of massive sandstone. The No. 2 Gas has also been extensively mined. The longwall panels in the upper seam were much smaller than the recent Harris panels, and they lie in several different orientations. As a result, in many cases it has not been possible to plan the lower-seam workings to minimize the potential for interaction.

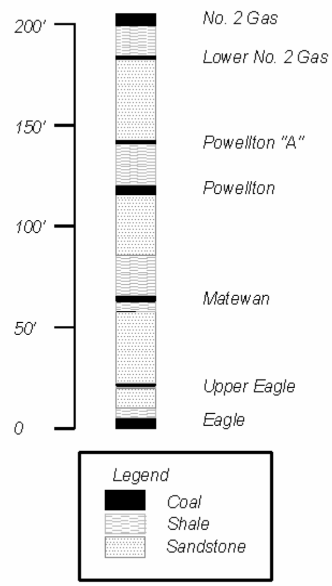

Figure 6.—Stratigraphic column from the Harris Mine, Boone County, WV.

Chase et al. [2007] evaluated 17 locations where gate entries at Harris crossed beneath remnant pillar structures in the upper seam. In about 60% of these cases, development and retreat mining were successful, although it was often necessary to install cable bolts or other secondary support to control the ground conditions. In seven cases, however, the interactions were serious enough that the headgate or tailgate squeezed shut during panel recovery.

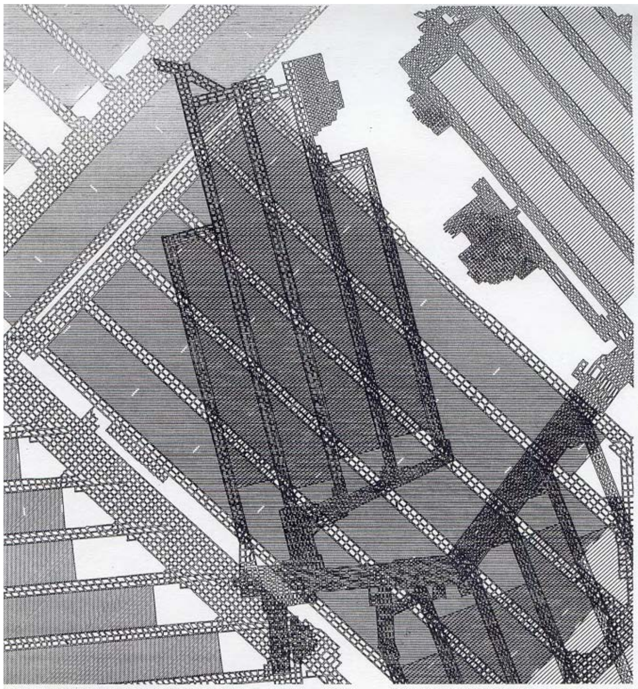

Figure 7.—Harris Mine longwalls in the underlying Eagle Seam (light gray) crossing beneath upper-seam chain pillars (dark gray).

Most of these cases occurred beneath chain pillars where the depth of cover exceeded 1,000 ft (Figure 7).

There have also been several instances when poor ground conditions on the face were attributed to overlying structures. Most often the problem was severe floor heave, although in two instances roof control was lost at the face. All but one of these incidents occurred more than a decade ago, when the longwall hydraulic face supports were much less capable than they are today.

Based on past experiences, mine planners at Harris try to adhere to the following rules of thumb: (1) the long axis of the panel to be mined should parallel that of the upper-seam panel; (2) the future headgate should be positioned under and as close to the center of the gob as possible; and (3) avoid advancing the longwall face under a gob/solid boundary [Hsiung and Peng 1987a,b].

The engineers at Harris also use the LaModel program to identify high vertical stress areas that are caused by deep cover, abutment loads, and/or multiple-seam stress transfer [Heasley and Agioutantis 2007]. Once multiple-seam stress transfer magnitudes are obtained, they can be incorporated into the Analysis of Longwall Pillar Stability (ALPS) or the Analysis of Retreat Mining Pillar Stability (ARMPS) programs to obtain more realistic pillar stability factors.

At West Virginia Mine B, longwall mining was initially conducted in the Lower Cedar Grove Seam before moving to the underlying Alma Seam. The interburden between the two seams was only 60–90 ft and consisted largely of sandstone. In the highly mountainous terrain the cover varied from 300 to 1,100 ft [Vandergrift et al. 2000]. The lower-seam roof is typically a strong siltstone or fine-grained sandstone, with a CMRR in excess of 55.

Following an extensive LaModel study, the lower-seam layout was planned to minimize the potential for interactions. Particular care was taken to ensure that no development crossed beneath the heavily loaded upper-seam chain pillars. The lower-seam mains were developed beneath the overlying ones, but the longwalls were laid out so that the gates were offset by approximately one-quarter of a panel width (Figure 8). Because the lower-seam panels were longer than the overlying ones, the gates crossed both the upper-seam start and stop line barrier pillars. At both crossings, the entry widths were reduced to 18 ft and the crosscut spacing was increased. Extra support, including truss bolts and steel props, were installed in the belt entry.

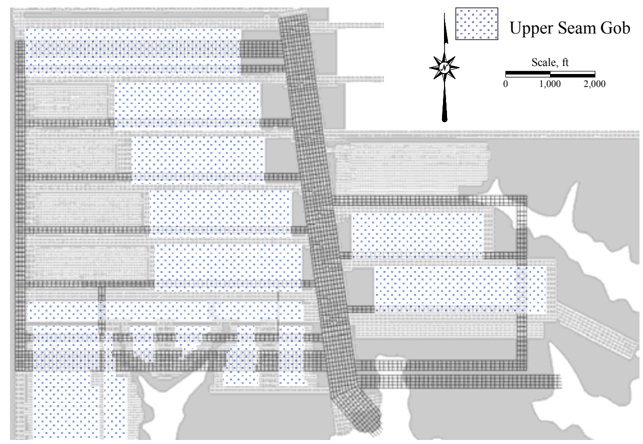

Figure 8.—Multiseam longwall layout employed in the Lower Cedar Grove Seam [Vandergrift et al. 2000].

The first panels were retreated in the lower seam (see Figure 8). No serious gate entry stability problems were encountered, although the high stress zones beneath the stop and start lines were clearly visible, particularly when the depth of cover exceeded 800 ft. Although the upper-seam chain pillars were located above the longwall face, they did not seriously impact ground conditions either. As one miner put it: “Beneath the chain pillars, the coal was so broken that the shearer didn’t have to cut anything; all it had to do was load.” Several of these faces were also successfully retreated across the upper-seam start pillars.

The next two panels were not as successful, however. They were oriented perpendicular to the initial panels and crossed a 110-ft-wide remnant barrier pillar located under about 800 ft of cover between two pillared areas in the upper seam. It was difficult to develop the gates across this structure, but when the longwall face approached it, the conditions on the face became so severe that the panel was abandoned early. To prevent a similar event, the second panel was also recovered before it reached the remnant barrier.

Subsequently, eight additional longwall panels have been extracted in the lower seam. The most serious difficulties have been associated with an unsuccessful attempt to stack the gate roads. The roof in this area consisted of an unusually thick shale, and the conditions became so severe once the depth of cover exceeded 800 ft that the development was abandoned.

MULTIPLE-SEAM LONGWALL MINING WITH YIELD PILLARS IN UTAH

Longwall mines in Utah work in a region characterized by rugged canyon and mesa topography, where cover depths can reach 3,000 ft. The roof and floor strata tend to be relatively strong (15,000–25,000 psi), and the overburden consists largely of massive sandstone units that can be as much as 500 ft thick. Many of the mining properties also contain two or more thick coal seams in close proximity [Barron et al. 1994].

Unique among U.S. coal operations, Utah longwalls rely almost exclusively on yielding pillar gate entry designs. According to DeMarco [2000], yielding pillar gate systems were developed to—

1. Mitigate the severe coal bumps (dynamic coal seam failures), most commonly experienced in the tailgate entries; and
2. Abate the high-stress concentrations associated with remnant gate pillars during close-proximity multiseam mining.

Based on his comprehensive study of yielding pillar case histories, DeMarco [2000] concluded that successful gate entry systems—

- Are largely limited to settings where the immediate roof is strong enough to withstand large deformations (the CMRR in every successful case history exceeded 50);
- Employ chain pillar width-to-height ratios of less than 5 to ensure that timely, nonviolent yielding occurs during first panel mining; and
- Normally require that artificial roof support plays a major role.

At Utah Mine A, approximately 20 lower-seam longwalls have been extracted beneath upper-seam panels. The interburden has ranged from 60 to 90 ft, with maximum depths of cover from 1,400 to 2,100 ft. Upper-seam mining was typically completed 3–5 years before development began beneath it. Both seams employ two-entry gate systems with 30-ft-wide yield pillars. The roof in the lower seam is variable, but typically a strong sandstone either lies directly on the coal or can be reached with roof bolts, so the CMRR is usually near 70.

In the very first multiple-seam application at this mine, the gate entries were stacked. A 160-ft massive roof fall ensued, and the gate had to be redriven. Since then, all gate entries have been driven beneath the upper-seam gob, normally offset at least 100 ft from the upper gate. Lower-seam panels have usually been designed so that they begin and end under the upper-seam gob. However, Figure 9 shows a multipanel layout where several of the longwall faces did cross the stop lines of the overlying panels. The depth of cover at the crossings was less than 1,400 ft in every case.

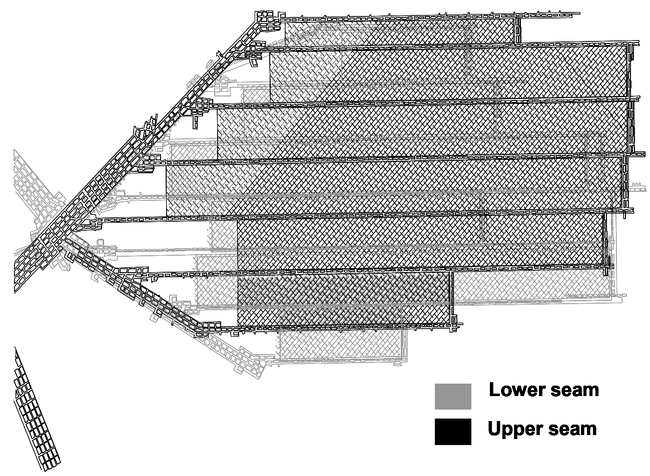

Figure 9.—Layout of yield pillar longwall panels at Utah Mine A.

No special support is normally required to develop the gates underneath the upper-seam stop lines. However, when the cover exceeds about 1,600 ft, bumps are more likely to occur if the gate crosses the stop line near the middle of the overlying panel rather than near the edge where the upper-seam stop line barrier pillar has been slightly "softened" by the presence of the upper-seam gates.

One of the big advantages of a two-seam longwall mine is that, other than the chain pillars, there should be no isolated remnant pillars in the overlying gob. One incident at Mine A illustrates just how important this advantage is. A "barrier pillar" was created in the upper seam between the longwall start line and some bleeder entries. When the lower-seam longwall had mined beneath the bleeders and partially beneath the barrier, a major bump occurred along approximately 80% of the face (Figure 10). The depth of cover at this location was in excess of 2,000 ft. Subsequently, the setup rooms in the lower seam were always placed under the gob if the cover exceeded 1,400 ft.

In general, face conditions have been excellent in the lower seam. Although the imprint of the overlying yield pillars could clearly be seen in the roof and coal face,

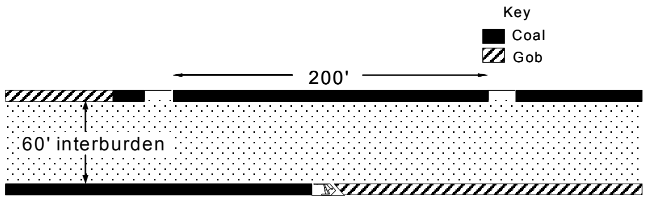

Figure 10.—Cross-section showing panel geometry at the time of a large face bump at Utah Mine A.

it caused no problems. Under deep cover, the panels start outby the upper setup rooms and stop inby the upper-seam stop line, so nearly all the longwall mining has been beneath gob.

With a 10-ft extraction height in the lower seam and as little as 60 ft of interburden, it seems likely that subsidence fractures can create hydraulic connections between the gobs of the two seams. Nonetheless, there has been just one instance where water from an insufficiently dewatered area entered the lower-seam mine in sufficient quantities to obstruct production.

At Utah Mine B, the two seams are 50–75 ft apart. The cover is lighter than at Mine A, reaching a maximum of about 1,100 ft, but the roof is weaker, with a CMRR averaging about 50. Bumps have not been a problem at this operation, but roof control is a significant concern.

The upper-seam panels at Mine B have all employed three-entry gates with 30-ft-wide yield pillars. A total of nine lower-seam panels have been extracted. As was the case in Utah Mine A, it is possible to "see" the upper-seam pillars on the face and in the setup rooms of the lower seam, but they have never caused problems.

The lower-seam panels at Mine B have been planned so that they are set up, mined, and stopped all under the gob of the upper seam. The critical zone of interaction has been where the gates cross the upper-seam stop line barriers. These have been troublesome and require substantial artificial support. Currently, cable bolts are installed in these areas as primary support on development in a pattern of four 12- to 16-ft-long cables per row, with rows on 4-ft centers. Over time, Mine B has also found that conditions are better if larger pillars (currently 100-ft centers) are used to cross the barriers (Figure 11).

Another design issue is the location of the lower-seam setup room. In the first lower-seam panels, the setup was developed just 40 ft inside the gob from the edge of the upper-seam setup (Figure 12). Conditions were less than favorable. They improved considerably when the offset was increased to 100 ft.

A mine planner at Mine B observed that one undesirable characteristic of multiple-seam interactions is that "they just keep coming." In one instance, a long-term mains crossed beneath an upper-seam gob line. Over 4 years, more than 4 ft of floor heave developed, and the roof was cable-bolted three times but still eventually failed.

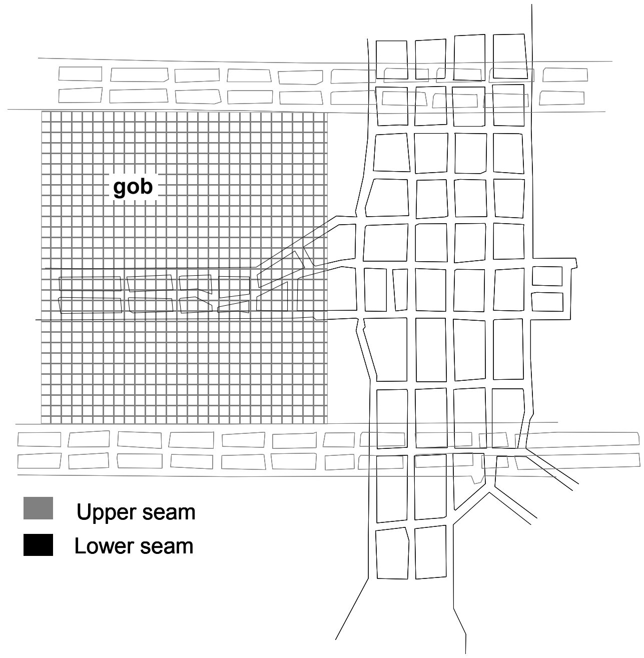

Figure 11.—Layout of stop line crossings employed at Utah Mine B.

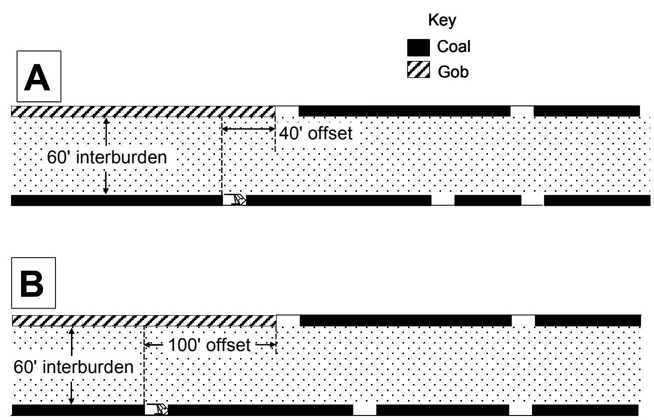

Figure 12.—Setup room offset at Mine B: (A) 40-ft offset; (B) 100-ft offset.

Spontaneous combustion is another safety concern at Mine B. In one of the panels where the setup was developed with a 40-ft offset, the caving behind the longwall created a connection that allowed oxygen to reach the upper-seam bleeder system. A heating developed, which was fortunately detected and quickly extinguished. There have also been several instances of large water inflows to the lower seam despite numerous holes drilled from the lower seam into low areas of the upper-seam gob to drain water pools from the upper-seam workings before undermining.

CONCLUSIONS

Although few U.S. longwalls face serious multiseam challenges, some valuable lessons can be learned from those that do. These include the following:

- Gate entry configuration: The first question that often faces mine planners is whether to stack the gate roads or offset them. Most of the U.S. longwall mines have preferred to offset their gate roads at least 100 ft from the gates in the previous seam. Some have had bad experiences when they tried stacking. However, the No. 33 Mine successfully employed a stacked gate configuration for many years, and the Harris Mine has used stacked pillars on occasion.
- If the offset design is employed, then the gate entries must be developed across the gob-solid boundary at the stop line of the previous seam longwall. The experience of the mines described in this paper is that this crossing may require a special pillar design or extra roof support, but it has not usually been a major concern.
- Panel layout: The preferred layout is one in which the panel start positions are set up outby the overlying or underlying setup room and stop before they reach the stop line of the previous panel. This way all longwall mining is beneath the old gob area (except for the coal beneath the chain pillars). However, there are a number of instances where these mines have successfully brought their faces across old stop lines or setup rooms, at least occasionally.
- Longwall face conditions have rarely been a problem at any of these mines, whether they are overmining, mining underneath large chain pillars, or crossing gob-solid boundaries. The most difficult interactions have been associated with large remnant pillars that were left in the previously mined seam, particularly when the remnant barrier was oriented parallel with the longwall face.
- Roof strength: The experience of these mines is that roof strength is a major factor determining the success of multiple-seam mining. For example, the weaker roof at Utah Mine B has caused it to generally have more trouble than Utah Mine A, even though Mine A's cover is significantly greater. Similarly, the Warwick Mine has weaker roof than the No. 33 Mine and also encountered greater difficulties.
- Planning: The ability to preplan the multiple-seam mining on a property is a major advantage. Mines that overmine or undermine their own longwall panels can more easily overlap the panels, offset the gates, and longwall almost entirely under gob areas. Most importantly, they can ensure that isolated remnant pillars are not left in the gob. The experience of the Utah mines also shows that yield pillars can also be a very useful planning option as long as the roof strength is adequate.
- Mines like Harris and Warwick that do not have the luxury of preplanning all the mining in advance have been forced to deal with remnant structures and gob areas at odd angles. For instance, it seems that perhaps the extra 100 ft of interburden at Harris compared to West Virginia Mine B may have compensated for Harris' more difficult remnant structures.

As the demand for coal continues to expand, mining companies are considering a number of new multiseam longwall mines in such areas as central Illinois and the Hunter Valley in Australia. Hopefully, these future operations will be safer because they have benefited from the experience of the operations described in these case studies.

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EXTREME MULTIPLE-SEAM MINING IN THE CENTRAL APPALACHIAN COALFIELDS

By Christopher Mark, Ph.D., P.E.[1]

ABSTRACT

Coal has been mined in the central Appalachian coalfields of southern West Virginia, western Virginia, and eastern Kentucky for more than a century. The dwindling reserve base consists in large part of coal that would have been considered unminable by earlier generations. Nearly every current operation is working on a property where coal has been extracted in the past from seams either above, below, or both.

The National Institute for Occupational Safety and Health (NIOSH) is conducting research aimed at helping mine planners prevent hazardous conditions due to multiple-seam interactions. To date, nearly 300 case histories have been collected from underground mines, mainly from central Appalachia. This paper focuses on several of the more challenging situations that have been encountered, including:

- Room-and-pillar development 20 ft (6 m) beneath full-extraction workings at a depth of 1,000 ft (300 m) of cover (Virginia);
- Pillar recovery 45 ft (14 m) above full-extraction workings at 900 ft (270 m) of cover (Virginia);
- Near-simultaneous room-and-pillar mining with pillar recovery, with 40 ft (12 m) of interburden and 1,500–2,000 ft (450–600 m) of cover (Kentucky); and
- Longwall mining directly beneath main entries in overlying seams (West Virginia).

Some of these operations have been highly successful in overcoming the challenges; others less so. The lessons learned from their experience will help ensure that these and similar difficult reserves can be mined safely.

INTRODUCTION

The central Appalachian region of eastern Kentucky, western Virginia, and southern West Virginia has produced more than 17 billion tons of coal since mining began there nearly 150 years ago. Production peaked in the late 1990s at approximately 275 million tons/yr (250 million tonnes/yr) and has since dropped to about 240 million tons/yr (215 million tonnes/yr). Recent studies have indicated that perhaps 70% of the ultimate reserve base in the region has already been mined [Bate and Kvitkovich 2004].

One consequence of the maturity of the central Appalachian coalfields is that nearly every remaining underground reserve has been impacted by past mining activity. The mountains of the central Appalachian coalfields are honeycombed with worked-out mines located above, below, and adjacent to today's and tomorrow's operations.

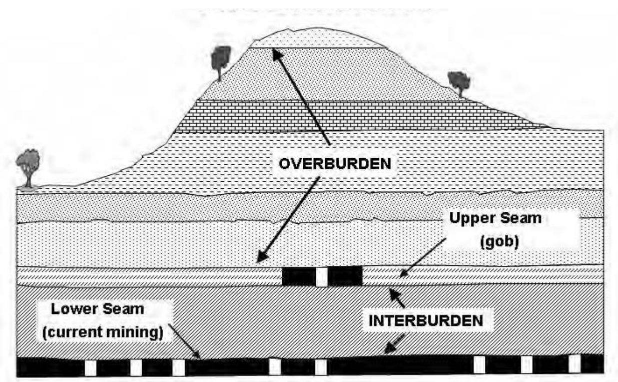

Figure 1.—Undermining.

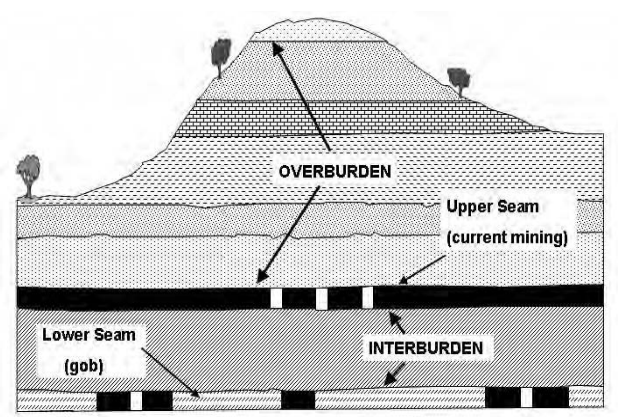

Figure 2.—Overmining.

In making future mine projections, mine planners must evaluate the potential impacts of these multiple-seam interactions. When undermining (mining beneath old workings), the new developments may be subjected to excessive load transfer (Figure 1). In the overmining situation (Figure 2), load transfer can also occur and, in addition, the ground may have been damaged by subsidence. In some cases, multiple-seam interactions can be so severe and hazardous that mining is impossible. In others, it may be possible to develop pillars, but not recover them.

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In many cases, however, the interaction may be barely noticeable.[2]

Some rules of thumb are available to aid in planning for multiple-seam interactions. Westman et al. [1997] cite traditional reserve estimation criteria that state that when the interval to mining above or below is less than 40 ft (12 m) the coal is considered to be sterilized, but otherwise accessible. Haycocks and Zhou [1990] found that load transfer interactions were unlikely when the interburden between the seams exceeded 110 ft (33 m), but that some factors (such as strong sandstone or a limited number of interbeds) could reduce this to as little as 60 ft (18 m). With thinner interburdens, interactions could be expected. Haycocks and Zhou [1990] also state that columnization of pillars "is considered the traditional approach to multiseam mining, especially when the interburden is less than 50 ft (15 m)."

For overmining situations, Luo et al. [1997] developed a technique for calculating a damage rating based on the lower-seam extraction ratio. However, Lazer [1965] reported that if the lower seam has been completely extracted, the upper seam can often be easily mined. The overburden mechanics model developed by Kendorski [1993] indicates that mining might be difficult within the "caving zone" (where the interburden-to-seam-thickness ratio (I/t) is less than 6–10) or the "fracture zone" (I/t < 24).

The time lapse between mining has also been cited as an important factor. Intervals of at least 2 years have been suggested to allow the gob to fully consolidate [Haycocks and Zhou 1990]. Some studies have indicated that the longer the time lapse, the better the conditions that are anticipated.

For the past several years, NIOSH has been studying multiple-seam interactions with the goal of providing mine planners with more precise guidelines than are currently available. Nearly 40 mines have been visited, and a total of nearly 300 individual case histories have been documented. Approximately 80% of these case histories are from central Appalachian mines, with the remainder from northern Appalachia and the western coalfields.

Each case history in the database has been classified according to the severity of the observed interaction. There are four levels:

- *No interaction* where conditions appear to be no different from those in areas where no past mining has been conducted;
- *Minor interactions* where minimal pillar spall or roof cracks indicate that there are some changes that can be attributed to past mining, but they had no significant effect on mining;
- *Difficult interactions* where conditions were severe enough to require supplemental support, design changes, or (on retreat) abandonment of a few pillars; and
- *Severe interactions* where the area was abandoned and judged unminable.

In the course of collecting the case histories, NIOSH found that mining is being conducted under many "extreme" situations, where previous mine workings are close by the target seam. Currently available rules of thumb imply that mining should be severely restricted at these operations but, in many cases, most of the target reserves are being mined with some success. Severe interactions have been encountered in some areas of nearly all these mines, however. The goal of this paper is to focus on a few of these extreme situations, identify those factors that have contributed to severe interactions, and discuss the control techniques that have proved to be successful.

CASE NO. 1: UNDERMINING WITH 20 FT (6 m) OF INTERBURDEN

In southwestern Virginia, NIOSH researchers visited two mines that have exploited seams lying just 20 ft (6 m) beneath previously worked seams. In one instance, the Marker Seam is being mined beneath the Taggart Seam; in the other, the Tiller is being mined beneath the Jawbone. The interburden geology is similar in both situations, consisting mainly of competent sandstone and siltstone. Lower-seam Coal Mine Roof Rating (CMRR) values are typically in the mid-60s. The depth of cover (H) ranges from 600 to 1,000 ft (180 to 300 m).

One of the mines is a two-seam operation, with both seams being worked by the same operator. All mining has been development, with no pillar recovery. The pillars have been stacked directly above one another. More than 800 pillars have been developed in this fashion, reportedly without serious incident.

At the other operation, mining in the upper seam was completed approximately 30 years ago and included large areas where pillars were recovered. Due to the variety of upper-seam pillar sizes and uncertainty about the surveying, there has been no attempt to columnize the pillars. Nevertheless, lower-seam mining has been largely successful beneath upper-seam first workings. In some areas, it has even been possible to partially extract pillars in the lower seam. Roof support beneath first workings consists of 4-ft, No. 5, full-column resin bolts supplemented by 6-ft "superbolts" in the intersections.

Problems have been encountered when attempting to cross upper-seam gob lines. On at least two occasions, mining had to be abandoned despite the use of longer bolts, cribs, and steel posts. Conditions were particularly

[2]Other hazards may arise when mining under abandoned works that are flooded or contain bad air [Michalek and Wu 2000], but these are not discussed in this paper.

difficult above an 80-ft (24-m) wide barrier pillar separating two gob areas. Where the gob line was successfully crossed, the pillar sizes were increased in addition to installing extensive supplemental support (Figure 3).

CASE NO. 2: OVERMINING WITH MINIMAL INTERBURDEN

Three mining operations, also in Virginia, are extracting seams that lie less than 45 ft (14 m) above previous workings. In two instances, the Jawbone is being mined above Tiller Seam workings; in the third, the target seam is the Splashdam above Upper Banner workings. The Jawbone-Tiller interburden again consists of strong, competent rock, while the Splashdam-Upper Banner interval is somewhat weaker (CMRR=45 for the immediate roof). The cover is mainly in the 800–1,000 ft (240–300 m) range for the Jawbone-Tiller mines and 500–600 ft (150–180 m) at the other operation.

At one operation, the interburden is just 20 ft (12 m). Here both seams are being mined by the same operator, and pillars have been columnized. There has been no second mining in the lower seam, but pillars have been fully extracted in four upper-seam panels with abandoned first workings directly underneath. No problems were reported.

At the other two operations, the interburden is 35–45 ft (11–14 m). Extensive second mining was conducted in the lower seams, but was completed at least 10 years ago. Recent upper-seam mining has been largely interaction-free above first workings or over gob areas. These mines typically use 5–6 ft (1.5–1.8 m) resin bolts for roof support, supplemented by "superbolts" or cables when crossing lower-seam structures (isolated remnant pillars or gob-solid boundaries).

The lower seams are 4–5 ft (1.2–1.5 m) thick, so the I/t ratio is approximately 9. Above lower-seam structures, the roof can be severely cracked or even "pulverized" into small pieces that fall out upon mining and require short cuts. Several types of lower-seam structures have been encountered:

- *Gob-solid boundaries*, where the "solid" can be either unmined coal or development pillars, and is at least 150 ft (45 m) wide;
- *Isolated remnant pillars and narrow barriers*, approximately 50–100 ft (15–30 m) wide with gob on at least two sides; and
- *Sandstone channels* that were left between gob areas. Depending on the width of the channel, these cases were classified into one of the previous two categories.

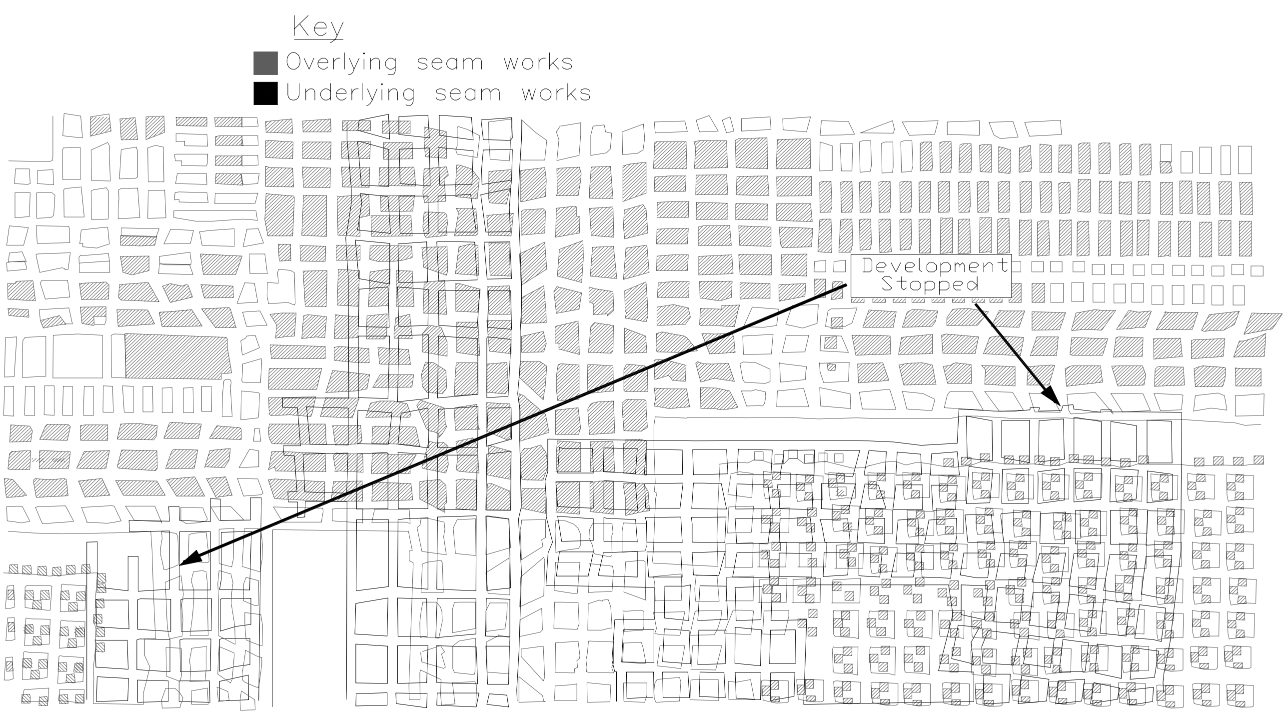

Figure 3.—Interactions resulting from undermining remnant structures with just 20 ft (6 m) of interburden.

Figure 4 illustrates these different kinds of structures.

At the two mines, a total of 23 crossings or attempted crossings were analyzed. In 11 of these cases, the panels were subsequently pillared. Such panels were analyzed twice, first as successful development cases and then as retreat mining cases.

Tables 1 and 2 show the results. During development, difficult or severe interactions were encountered above only 2 of the 16 gob-solid boundaries (13%). In contrast, of the seven isolated remnants that were overmined, four caused interactions that were so severe that they stopped mining completely, and a fifth resulted in very difficult conditions on advance (71% total). The two relatively successful crossings were both at relatively shallow cover.

Nine of the successful gob-solid crossings were subsequently pillared, about half with minimal problems. When pillars were retreated above the two successful isolated remnant crossings, one resulted in difficult conditions.

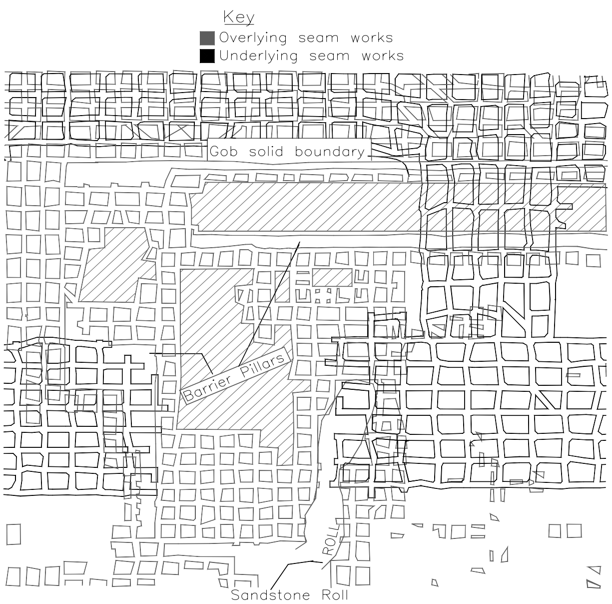

Figure 4.—Different types of remnant structures in the underlying workings.

Table 1.—Conditions encountered crossing lower remnant structures: development (case history No. 2)

Structure type	Condition		
	Minor/None	Difficult	Severe
Gob-solid boundary	9	5	2
Isolated remnant pillar	2	1	4

Table 2.—Conditions encountered crossing lower remnant structures: retreat (case history No. 2)

Structure type	Condition		
	Minor/None	Difficult	Severe
Gob-solid boundary	4	5	0
Isolated remnant pillar	1	1	0

Clearly, isolated remnants pose much more significant hazards at these mines than gob-solid boundaries. The obvious explanation is that isolated remnants can result in much greater stress concentrations in the adjacent seams. First, they normally carry two stress abutments (one from each gob), while gob solid boundaries usually only carry one. Perhaps just as important is the load distribution that develops within the remnant. As Chase et al. [2007] point out, three different kinds of pillars may be defined based on their load distributions:

- Small yielded structures that carry relatively small loads (Figure 5A);
- Wide pillars or gob-solid boundaries that have localized high-stress zones, but distribute the load (Figure 5B); and
- Isolated remnants that are highly stressed throughout (Figure 5C).

Wide pillars may carry the same (or even greater) load as a remnant, but because their load is distributed over a much larger area, their "footprint" is less noticeable in seams above or below.

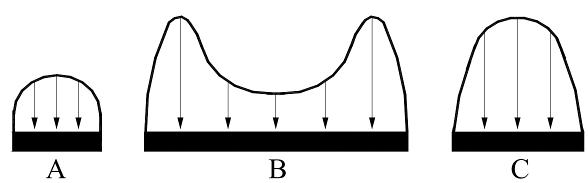

Figure 5.—Stress distributions within three types of remnant structures.

CASE NO. 3: NEARLY SIMULTANEOUS MINING

A mining complex in Kentucky is extracting the Kellioka and Darby Seams, which are separated by 40–70 ft (12–21 m) of interburden. The interburden consists largely of sandstone. The depth of cover reaches 2,000 ft (600 m), so the H/t ratio can be as high as 50.

Both mines are room-and-pillar with full-pillar extraction. Mining is sequenced from the top down. During the 15 years since mining began on the property, a number of lessons have been learned and incorporated into mine planning.

Figure 6 shows three early attempts to develop production panels beneath fully extracted Darby Seam works. In each case, severe roof conditions above thin barrier pillars isolated between two gob areas. The problems were encountered despite modifications to the pillar size and supplemental roof support.

Subsequently, Kellioka workings have been laid out to parallel the overlying workings. The width of the Kellioka retreat panels, including slab cuts, exactly matches that of the Darby gobs. With this panel stacking design, most of the lower-seam panel development and pillar recovery takes place under the Darby gob. The potential difficulty with panel stacking is that the development must cross a gob-solid boundary in order to access the reserve beneath the gob. At the time NIOSH visited the complex, seven lower-seam panels had been successfully extracted using the stacking design. Although some difficult conditions were encountered at gob-solid boundaries, they were much less severe than those associated with the thin isolated barrier pillars.

In the early planning, the mine tried to wait at least 6 months after completion of the upper-seam retreat mining before developing the lower-seam works. However, experience showed that "settling time" did not have a large effect on the conditions encountered. Recently, some lower-seam developments have begun as early as 1 month after the overlying panel was extracted.

CASE NO. 4: UNDERMINING PREEXISTING WORKINGS

In southern West Virginia, mining on several properties has been conducted in as many as 10 seams. Longwalls have mined large portions of the Powellton Seam and are currently working near the bottom of the geologic column in the Eagle and No. 2 Gas Seams.

NIOSH studies found numerous instances of successful mining above previously longwalled areas. In most of these cases, the interburden between the target seam and the longwall gob is at least 180 ft (55 m).

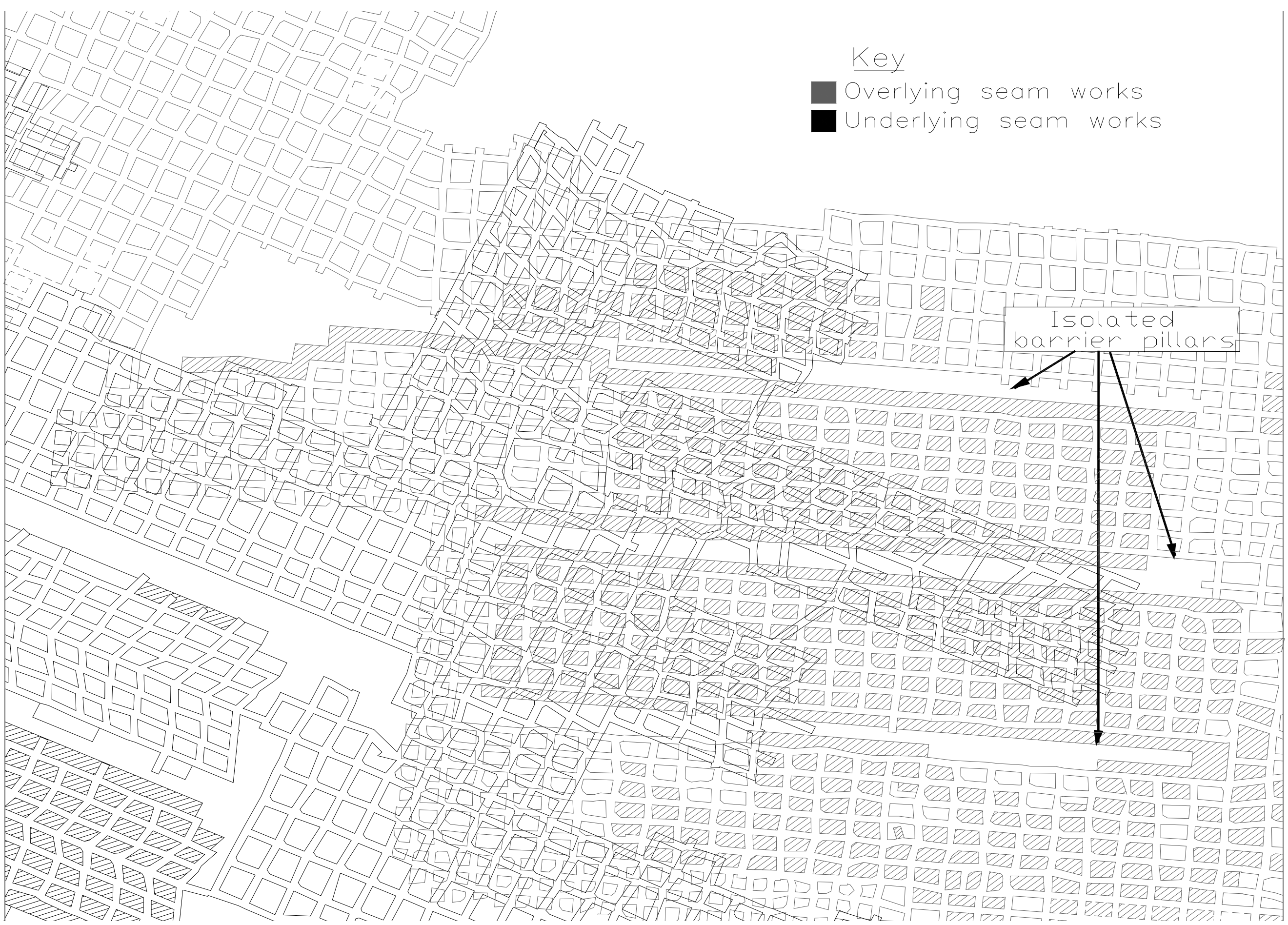

Figure 6.—Interactions caused when trying to undermine thin isolated barrier pillars in an overlying seam.

There have been several instances in which longwalls undermined open entries, usually mains, in overlying mines. The results have almost always been unsatisfactory. In one instance, a mine was maintaining main entries in the 9-ft (2.7-m) Coalburg Seam, 560 ft (170 m) above the 6-ft (1.8-m) No. 2 Gas. The I/t ratio in this case was nearly 100, and the overburden-interburden ratio was less than 1.0. In addition, over 50% of the overburden was sandstone, and the immediate roof consisted of competent sandstone (CMRR=70). Finally, 16-ft (4.9-m) vertical cable bolts and cable straps were installed together with standing supports (steel props).

The longwall directly undermined the mains, as shown in Figure 7. Within days, the Coalburg Seam subsidence measured 36–42 in (0.9–1.1 m). The immediate roof was severely fractured, with some open apertures of 4 in (100 mm). Numerous large roof falls resulted (Figure 8).

This example, and at least four others in the database, show that the normal subsidence prediction rules are completely inapplicable when open entries are involved. The reasons are not hard to understand. Referring again to Kendorski's overburden mechanics model, the Coalburg Seam would normally have been safely within the "confined zone" within which the ground subsides but no new fracturing takes place. However, the entries removed the compressive confining pressure, so the rock around the mine openings was subjected to severe tensile stress. If the mains had been developed after the longwall had been extracted, there might have been no obvious evidence of its passage.

Another curious case in the database involved a mining complex in Kentucky. A room-and-pillar panel was retreated in the Pond Creek Seam, and approximately 2 years later a set of main entries was developed in the Cedar Grove Seam 180 ft (55 m) above. The I/t ratio was about 5, and conditions were initially excellent with just 4-ft (1.2-m) fully grouted bolts. After about 2 years, however, the roof began to deteriorate dramatically. Extensive supplemental support, including full cable bolting, wood cribs, and polyurethane injection, eventually had to be installed. The most likely explanation is that ground between the two seams had not fully subsided when the upper-seam entries were developed. When it did subside later, it apparently caused the same kind of damage as in the longwall case described previously.

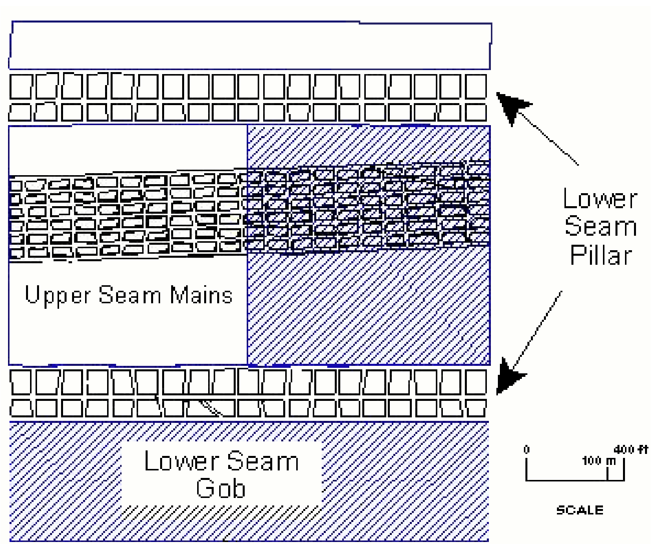

Figure 7.—Longwall mining that subsided open entries 560 ft (170 m) above.

Figure 8.—Damage caused when open entries were subsided.

CONCLUSIONS

The case histories presented in this paper, and others contained in the NIOSH database, clearly show that the existing multiple-seam guidelines should be refined. One general point is that it is seldom possible to evaluate the minability of an entire reserve with broad criteria based on factors like the extraction ratio or interburden thickness. Multiple-seam interactions are highly localized, so it is necessary to evaluate the interaction potential from each structure left in the previously mined seam.

Experience seems to show that where the previous mining has been limited to development, it may have little impact on reserves separated by interburdens of as little as 20 ft (6 m). In one instance described in this paper, columnization was not even necessary. Similarly, mining beneath gob areas, where the ground has been largely destressed, seldom presents serious problems.

When mining above gob areas, some roof fracturing can be expected up to a distance of perhaps 24 times the lower-seam height. However, the mines described here have encountered few difficulties even just 40 ft (12 m) above gob areas.

Difficult ground conditions are often encountered when crossing from the solid into the gob (or vice versa). However, by using control techniques including longer pillars, narrower entries, and additional roof support, the mines described in this paper have been able to cross most of these structures.

The most serious interactions occur above or beneath isolated remnant pillars, normally 40–100 ft wide, located between two gob areas. These types of structures are apparently too wide to have yielded, but too narrow to effectively distribute the load. The high stresses associated with these types of structures have often stopped mining completely. A reserve area that contains many such isolated remnants may indeed be unminable.

Severe interactions are also likely if an open entry is undermined by longwall or pillar extraction. A large interburden thickness, a low depth of cover, and even strong roof may be no protection from the damage caused when an open entry is subsided.

The case histories seem to indicate that the necessary time lag between mining the two seams may not be fully understood. In one instance, as little as 1 month seemed to be an adequate "settling time"; in another case, 4 years may not have been enough. The important factor may not be the elapsed time, but whether the subsidence is complete. Observations from longwall mining indicate that subsidence at the surface is often complete within weeks, while some abandoned mines have collapsed decades after mining [Iannacchione and Mark 1990].

NIOSH is continuing its evaluation of the entire multiple-seam case history database. The results will be used to develop suggested guidelines for analyzing potential multiple-seam interactions. It is hoped that these guidelines will help mine operators to more safely extract the increasingly difficult reserves in central Appalachia and elsewhere.

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MULTIPLE-SEAM MINING INTERACTIONS: CASE HISTORIES FROM THE HARRIS NO. 1 MINE

By Frank E. Chase,[1] Phyllip Worley,[2] and Christopher Mark, Ph.D., P.E.[3]

ABSTRACT

The Harris No. 1 Mine, located in Boone County, WV, has been longwalling the Eagle Coalbed for over 30 years. Harris has experienced numerous interactions associated with the extensive room-and-pillar and longwall mining operations that have been conducted in the overlying No. 2 Gas Coalbed. The problems have included roof falls, excessive rib sloughage, and gate road and bleeder entry closure. A detailed evaluation of the multiple-seam experiences at Harris No. 1 Mine was conducted as part of the National Institute for Occupational Safety and Health (NIOSH) nationwide multiple-seam mining case history database. One observation from the Harris gate road case histories was that smaller, critically loaded, upper-seam pillars seemed to cause more severe ground conditions than wider pillars. The LaModel program was used to investigate this supposition. The results confirmed that "critical" sized pillars do transmit the highest amounts of stress to adjacent seams. In addition, the data suggest that the probability of a major multiple-seam mining interaction increases when the depth of cover is 1,000 ft or greater and when the Eagle Seam pillars have an Analysis of Longwall Pillar stability factor less than 1.50.

INTRODUCTION

NIOSH recently completed a comprehensive nationwide database of multiple-seam mining case histories. To collect the case histories, underground geotechnical evaluations were conducted at more than 45 U.S. coal mines. The data are currently being analyzed to ascertain the relative importance of the various contributory mining and geologic parameters responsible for multiple-seam mining interactions. The ultimate goal is to provide the mining community with a design methodology for multiple-seam mining that will aid in determining the likelihood of adverse interactions so that corrective measures can be taken to prevent injuries and fatalities.

During the study, 22 multiple-seam case histories were collected from the Harris No. 1 Mine, more than at any other mine site. An area was deemed to be a case history if a multiple-seam interaction occurred or should have been anticipated. The accumulation of such a significant number of cases over a relatively small geographic area presented an excellent opportunity to conduct a study that would evaluate the current state of the art in multiple-seam design. In other words, can the criteria that engineers employ to predict whether or not a multiple-seam interaction will occur be used to explain Harris' experiences?

The Harris No. 1 Mine is operated by Eastern Associated Coal Corp., a subsidiary of Peabody Energy. Harris is located in Wharton, Boone County, WV, (Figure 1) and began operations in 1966. Since then, Harris has driven and retreat mined more than 60 longwall panels in the Eagle Coalbed. The No. 2 Gas Coalbed is situated approximately 200 ft above the Harris Mine workings. Both longwall and room-and-pillar retreat mining have been conducted in the No. 2 Gas. In many cases, remnant structures such as barrier pillars, isolated gate roads (gate roads that are bordered by gob on both sides), etc., that were left in the 2 Gas have caused difficult ground conditions in Harris due to downward load transfer. In other instances, upper-seam structures have not noticeably impacted mining. From the mine planning perspective, the paramount question is: When will multiple-seam problems occur, and how severe will the interaction be? The purpose of this investigation was to shed some light on these questions by conducting detailed analyses of Harris' experiences.

Figure 1.—Location of Harris No. 1 Mine in Wharton, WV.

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GEOLOGIC SETTING

The topography above Harris No. 1 Mine is fairly rugged. The valleys are narrow and V-shaped, and ridges are steep and prominent. These physiographical features can cause rapid changes in cover over relatively short horizontal distances. The overburden at Harris ranges from 100 ft at the drift to slightly over 1,400 ft under the highest ridges. As is the case with most central Appalachian coal mines, the overburden is relatively competent.

Previous researchers [Holland 1947; Stemple 1956; Haycocks et al. 1982] have determined correlations between multiple-seam interactions and the interburden competency, thickness, and number of interbeds (number of distinct rock units within the interburden). Therefore, considerable emphasis was placed on obtaining corehole information as close to the case history sites as possible. The information on interburden characteristics is listed in the appendix to this paper. As indicated in the appendix, the interburden between the Eagle and No. 2 Gas ranges in thickness from 176 to 213 ft.

Figure 2 is a generalized stratigraphic column of the interburden between the No. 2 Gas and Eagle Coalbeds. It should be noted that the major sandstone and shale units shown in Figure 2 vary in thickness. For example, in a few of the coreholes the upper two sandstone units merge into a 100-ft-thick unit. The same can be said for the lower two sandstone units. These rock unit thickness variations suggest ancient stream channel activity. Usually, the interburden contains six distinct rock units; however, the actual number varies from four to seven. In general, the interburden is rather competent, with the percentage of sandstone, sandy shale, and limestone ranging from 59% to 80%. The coalbeds between the Eagle and No. 2 Gas shown in Figure 2 have not been mined above Harris.

Another factor identified in determining the magnitude of the interaction is the immediate roof rock competency [Luo et al. 1997]. The shale unit shown in Figure 2 directly above the Eagle Coalbed varies in thickness from 0 to 10 ft. In areas of Harris, this shale unit can be either laminated, sandy, or nonexistent (replaced by a sandstone scour). These fluctuations explain the range in Coal Mine Roof Rating (CMRR) values [Molinda and Mark 1994] from 44 to 71. These values indicate that the immediate roof rock is moderately strong to strong.

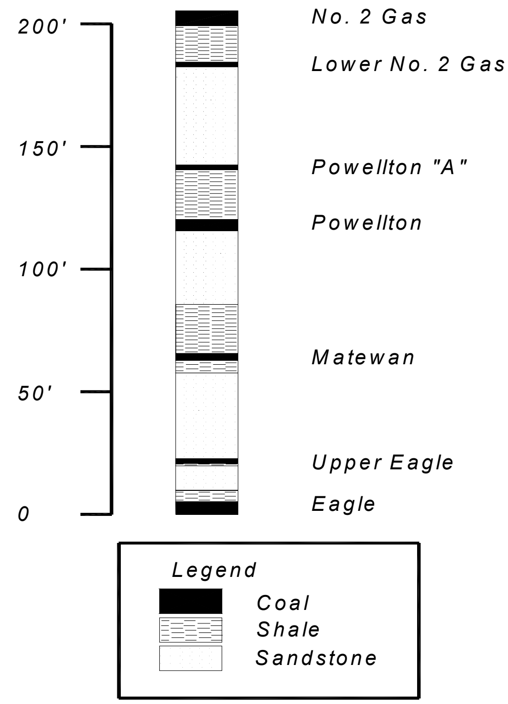

Figure 2.—Generalized interburden stratigraphy.

GATE ROAD DESIGN AND SUPPORT

Harris began longwall operations with a 300-ft-wide plow face and 40-ton walking frames in 1966. Since then, numerous technological innovations have led to improvements in the longwall systems and gate road supplemental supports used. Currently, Harris is mining 3.2 million clean tons of coal per year. Gate road pillar design and supplemental support selection have also gone through an evolutionary process at Harris based on the performance of past longwall faces and gate roads. In fact, 12 different gate road designs that incorporated various elements of a three-entry, four-entry, and yield pillar designs have been tried at Harris. The gate road system design was progressively refined and calibrated through the back analyses of previous successful and not so successful mining attempts.

The engineers at Harris use the novel approach of integrating the multiple-seam stress transfer values obtained from the LaModel program [Heasley 1998] into the Analysis of Longwall Pillar Stability (ALPS) program [Mark 1990] in order to obtain a more realistic stability factor (SF). This methodology is described later in the "Discussion" section of this paper. For the past 5 years, Harris has been using a three-entry gate road system with entries on 90-ft centers and crosscuts on 140-ft centers. This system has worked well, and no gate road blockages have occurred since its usage began. Based on past experiences, during mine design Harris' engineers adhere to the following rules of thumb as much as possible: (1) the long axis of the panel to be mined should be parallel to that of the upper-seam panel; (2) the future headgate should be positioned under and as close to the center of the gob as possible; and (3) avoid advancing the longwall face under a gob/solid boundary [Hsiung and Peng 1987a,b].

Harris uses 5-ft full-column resin bolts on 4-ft centers in the headgate entry. In the remaining gates and bleeders, 4-ft full-column resin bolts on 4-ft centers are standard. The roof control plan also stipulates that a minimum of two crib equivalents be installed every 12 ft in the tailgate.

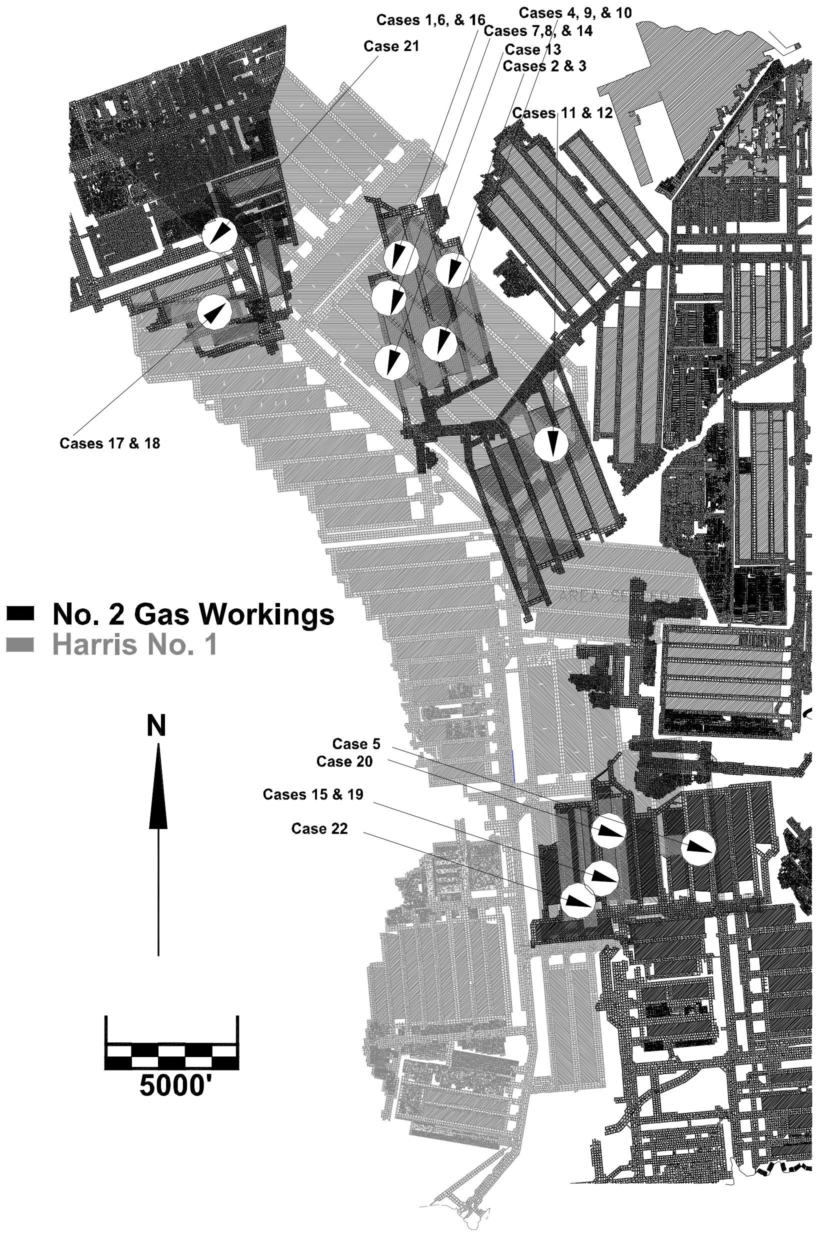

Figure 3.—No. 2 Gas workings superimposed on Harris No. 1 Mine.

Floor heave has always been a major concern at Harris. Because conventional cribs (both four- and nine-point) are inclined to roll out when subjected to heave, Harris began using 30-in engineered timber supports. These supports have performed well in that the floor tends to heave up around the supports.

The engineers at Harris also use the LaModel program to identify high vertical stress areas that are caused by deep cover, abutment loads, and/or multiple-seam stress transfer [Heasley and Agioutantis 2007]. In highly stressed areas, either two or four 12-ft-long cable bolts are installed in between each row of primary supports. Sometimes additional engineered timber supports are warranted in tailgate locations. The spacing of these supports is dependent upon the expected level of stress.

CASE HISTORY ANALYSES

A detailed examination of both the No. 2 Gas and Harris No. 1 workings (Figure 3) revealed 22 case histories where multiple-seam interactions happened or might have been anticipated. In each case history, gate roads were driven and panels were extracted under various upper-seam structures, and the outcomes are listed in the appendix. Overburden depth, interburden thickness and composition, and additional consequential mining parameters that are believed to determine whether or not interactions will occur [Holland 1947; Stemple 1956; Haycocks et al. 1982] are also listed in the appendix. Prior to the analyses, the database was separated into two categories—gate entry workings (17 cases) and longwall face stability (5 cases)—because of the major differences between the two. A rating system from 1 to 6 (see the appendix for details) was developed to numerically evaluate the conditions or degree of interaction for each case. For the purpose of analyses, conditions 1 and 2 were combined and categorized as a "minor" interaction because the interactions were "barely negligible" to "minor." Conditions 3 through 6 were combined and designated as a "major" interaction because the interactions were "troublesome" to "major" and warranted that special measures be taken.

A series of XY scatter plots were generated to examine the various mining and geologic parameters for correlations. Figure 4 shows that six out of seven of the major interaction gate road workings cases occurred when Harris' depth of cover was 1,000 ft or greater and the ALPS SF was less than 1.50. Further, Figure 5 shows that five out of seven of the major interaction cases occurred when the No. 2 Gas ALPS SF was less than 1.0 and the depth of cover was 1,000 ft or more in Harris. Finally, Figure 6 illustrates a weak correlation between problematic cases and a No. 2 Gas overburden/interburden ratio of 3.9 or greater. As for the five longwall face stability cases, the only parallels that could be drawn were that the depth of cover was primarily 1,000 ft or greater and the immediate roof rock was generally relatively weak. Upper-seam pillar design did not seem to be an issue; however, both it and the findings mentioned in this section warrant additional examination and discussion.

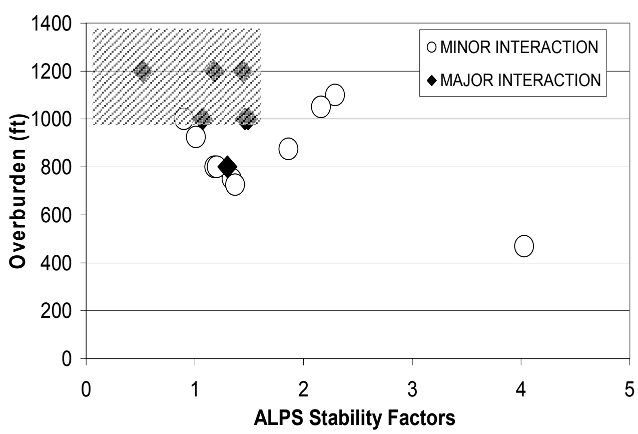

Figure 4.—Relationship between degree of interaction and the Harris No. 1 ALPS stability factors and overburden.

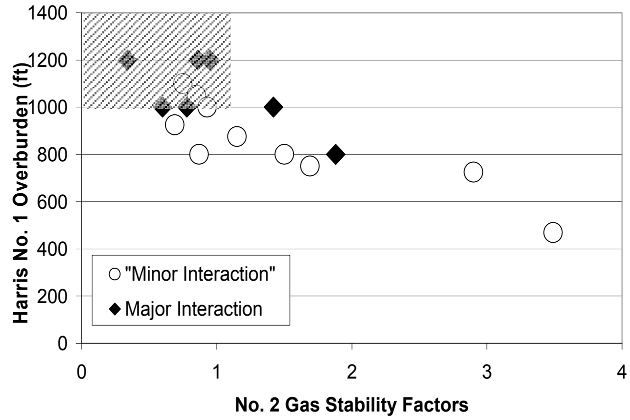

Figure 5.—Relationship between degree of interaction and the No. 2 Gas ALPS stability factors and Harris No. 1 overburden.

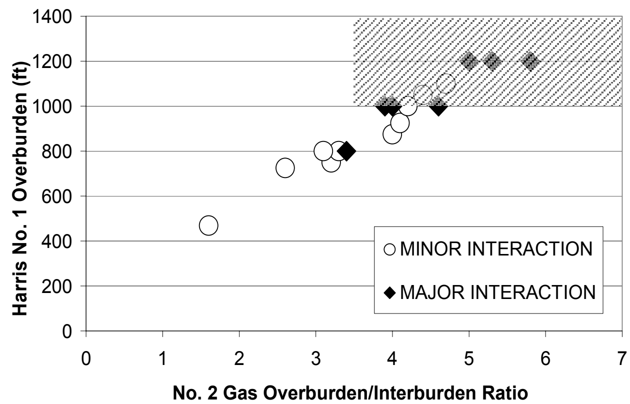

Figure 6.—Relationship between degree of interaction and the No. 2 Gas overburden/interburden ratio and Harris No. 1 overburden.

UPPER-SEAM PILLAR DESIGN

As indicated in the previous section, most of the multiple-seam interaction problems in Harris' gate entries occurred when the upper-seam ALPS SFs were less than 1.00. At first, it might seem counterintuitive that smaller upper-seam pillars would cause more severe stress conditions in an underlying seam than wider pillars. However, a consideration of the load distribution in the upper-seam pillars provides an explanation. Essentially, three load distributions are possible:

- Figure 7A illustrates a small, yielded pillar that carries a relatively small load;
- Figure 7B illustrates a wide pillar with localized high-stress zones near the ribs, but a lightly loaded core; and
- Figure 7C illustrates the load distribution of a critical pillar, with a highly loaded core.

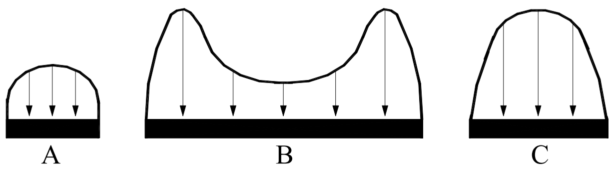

Figure 7.—Pillar load distribution diagrams: (A) yielded, (B) wide, (C) critical.

The critical pillar would result in the most severe "footprint" on the lower seam, because it produces an intensified downward "point load" type of stress transfer to the underlying workings. The wide pillar may carry a larger total load, but because that load is distributed over a much larger area, its effect on the lower seam is less noticeable. A good analogy would be the imprints that a petite woman in high heels might make in wet sand compared with those made by a sizable football player wearing tennis shoes.

LaModel, a displacement-discontinuity boundary-element program, was used to evaluate the hypothesis described above. The models were run using standard default parameters and yield zones. Figure 8 displays the basic layout of the two mine designs that were modeled. In the Harris design case, a three-entry longwall gate entry development section (oriented from top to bottom in Figure 8) was driven on 120-ft-entry and crosscut centers in a 6-ft-high reserve. The pillars had an ALPS SF of 3.07, and the depth of cover was 1,200 ft. A three-entry isolated gate road system (oriented from left to right in Figure 8) was then situated 200 ft above Harris. The crosscut center spacing in the No. 2 Gas remained constant at 140 ft. The entry centers were varied from 30 to 180 ft in 10-ft increments for each LaModel run, and the mining height was 6 ft. As shown in Figure 8, the No. 2 Gas and Harris workings are situated perpendicular to one another so that four pillars were stacked in the center of the LaModel grid. Figure 8 also displays the LaModel analysis results for a No. 2 Gas gate road system with 60-ft-wide pillars. Figure 8 clearly shows that the multiple-seam stress transfer magnitudes in Harris are the highest beneath the isolated gate roads. Conversely, the destressing effects of the overlying gob are also evident in Figure 8.

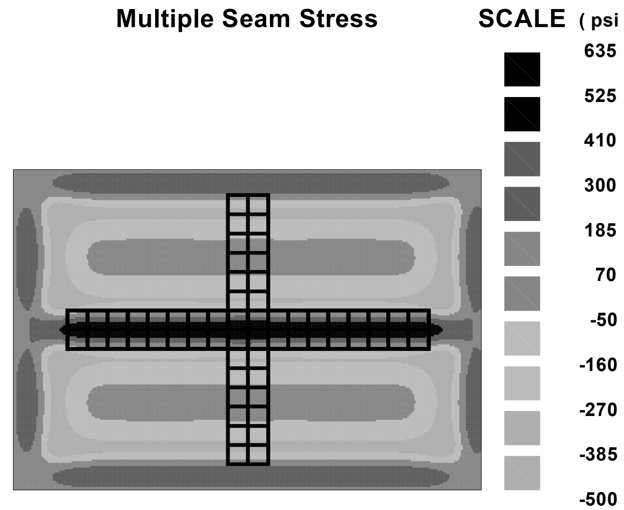

Figure 8.—LaModel output for 60-ft-wide No. 2 Gas pillars.

Figure 9 displays the peak multiple-seam stress transfer value and the ALPS SF for each pillar width modeled. Figure 9 shows the wide range in multiple-seam peak stress transfer values, which are dependent on the width of

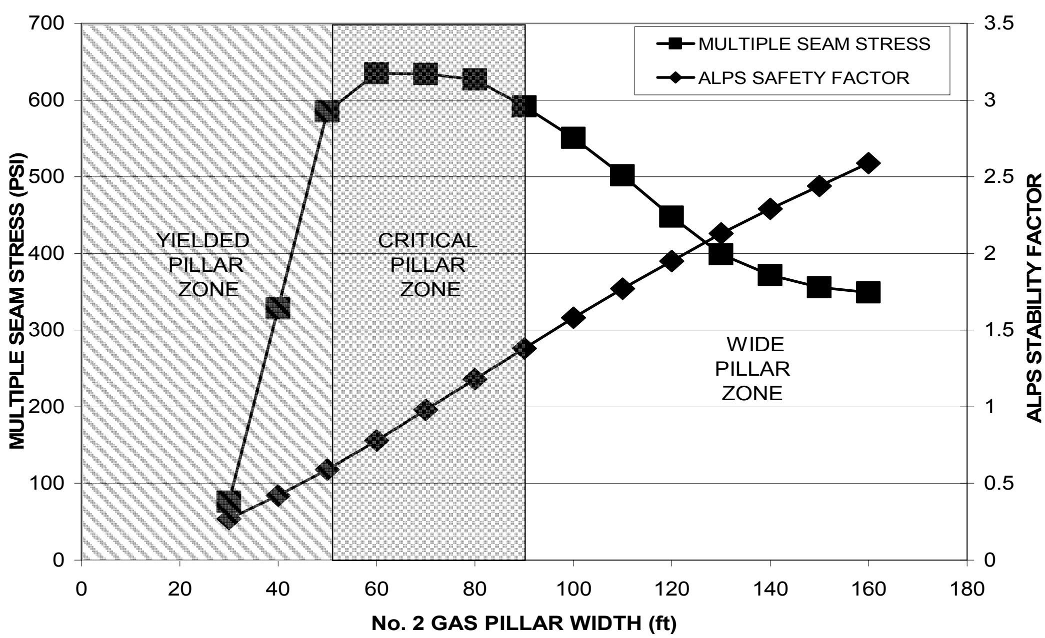

Figure 9.—Peak multiple-seam stress transfer values and the ALPS SFs for modeled pillar widths.

the pillar. The multiple-seam stress transfer curve in Figure 9 seems to have three distinct regions that correspond to the three upper-seam load distributions shown in Figure 7. The peak or "critical" multiple-seam stress transfer values occur when the chain pillars in the upper seam are in the 50- to 90-ft range. The models indicated that the cores of these pillars were all heavily loaded. On the left side of the critical pillar region, the models showed that the stresses in the cores of smaller, upper-seam pillars were much lower than for the critical pillars. The smaller the pillar, the lower the peak stress and the less the multiple-seam stress experienced in the lower seam. On the right side of the critical pillar region, as the upper-seam pillars get wider, they distribute their load more evenly. The result is a steady decreasing trend in downward stress transfer as the pillar width is increased up to around 130 ft. Once the pillar reaches a certain width, there is essentially no interaction between the two high-stress zones at the ribs, and the peak stress transfer levels out at approximately 350 psi.

DISCUSSION

For lack of a better adjective, the term "critical" was used to describe the pillars whose size transferred the highest multiple-seam stress values. Obviously, the word "critical" conjures up different meanings depending on whether you are designing deep-cover gate road yield pillars or mining in bump-prone ground conditions. However, from a multiple-seam aspect, the LaModel analyses indicate that critically sized upper-seam pillars can increase the lower-seam pillar stresses substantially. In this study, the LaModel results were used to calculate the average stress increase in a Harris tailgate pillar system caused by isolated No. 2 Gas gate roads on 80-ft-wide entry centers. The calculated average multiple-seam pillar stress was 396 psi, which is approximately equivalent to increasing the depth of cover by 360 ft. Therefore, a Harris tailgate system that was initially designed for 1,200 ft of overburden with a conservative ALPS SF of 1.23 was, in actuality, being subjected to cover loads equivalent to 1,560 ft of overburden, which effectively reduces the ALPS SF to 0.88. This example emphasizes the importance of both estimating and incorporating multiple-seam stress transfer into the pillar design process. It implies that wider pillars with higher ALPS SFs should be used; however, gate road developmental constraints also need to be considered. The engineers at Harris are currently using this methodology to design gate road pillar systems and, based on past experiences, an ALPS SF in the 1.0–1.2 range (taking into account the additional multiple-seam stress) has been determined to provide satisfactory results. It should be noted that the stress transfer values and critical pillar dimension widths previously mentioned are case-specific and will vary depending on the input parameters.

As stated in the "Case History Analyses" section, six out of the seven major interactions occurred when the Harris depth of cover was 1,000 ft or greater and the ALPS SF was less than 1.50 (Figure 4). The cover relationship is noteworthy in that most operators maintain that there is a correspondence between multiple-seam interaction difficulties and overburden. Typically, operators state that problems generally begin occurring at roughly 800 ft of cover. Essentially, it takes a certain amount of cover load to cause downward load transfer problems. One possible explanation for the higher cover value at Harris may be interburden competency. It is conceivable that the three sandstone units, which comprise 59%–80% of the interburden, are bridging and therefore dampening the downward load transfer. As for the Harris ALPS SFs, Figure 4 suggests that the probability of a major interaction occurring decrease as the stability factor increases. The same can be said for the No. 2 Gas ALPS SFs. As shown in Figure 5, five out of seven (71%) of the major interaction cases occurred when the No. 2 Gas ALPS SF was less than 1.0 and the depth of cover was 1,000 ft or more in Harris. Based on the abovementioned findings, a certain amount of concern and supplemental support are probably warranted when dealing with deep cover and lower upper- and lower-seam ALPS SFs. As the old longwall adage goes, "it is better to be safe than be shut down." (It should be noted that multiple-seam stress transfer values were *not* taken into account when determining the ALPS SFs listed in the appendix or shown in the figures.)

Data analyses also indicated that there was no relationship between the degree of interaction and the percentage of competent interburden. The same can be said for the interburden thickness/number of beds ratio. Conversely, there was a weak correlation with immediate roof rock competency. Generally, the CMRR was higher for the minor interaction cases. Another weak association previously indicated was the overburden/interburden thickness ratio value of 3.9. As a rule of thumb, problems generally do not occur until this ratio reaches 7 or 8. However, critically sized pillars may be an overriding factor in this particular situation.

CONCLUSIONS

The most significant finding of this investigation was that the size of the remnant upper-seam structure can influence the extent of the multiple-seam interaction. More specifically, this study suggests that smaller, critically loaded upper-seam pillars are more likely to cause lower-seam ground control problems than wider pillars. The LaModel program was used to examine this supposition, and the results verified this premise.

This investigation also demonstrated the effectiveness of LaModel in determining multiple-seam stress transfer magnitudes. Once this value is obtained, it can be incorporated into the ALPS or the Analysis of Retreat Mining

Pillar Stability (ARMPS) programs to obtain a more realistic stability factor.

The back analyses of 17 gate road case histories at Harris No. 1 indicate that the probability of a major multiple-seam mining interaction occurring increases when (1) the depth of cover is 1,000 ft or greater, (2) the upper-seam pillars are critically loaded, and (3) the Eagle Seam pillars have a nonadjusted ALPS SF (excludes multiple-seam load transfer) less than 1.50. In areas where these criteria are met, Harris engineers have mitigated problems through pillar design modifications and the installation of supplemental support. Based on past experiences, the engineers at Harris have determined that an adjusted ALPS SF in the 1.0–1.2 range provides satisfactory results.

Finally, the analyses also identified a weak correlation between the degree of multiple-seam interaction and the immediate roof rock competency (CMRR) and the overburden/interburden thickness ratio. However, no relationship between the degree of interaction and the percentage of competent interburden or the interburden thickness/number of beds ratio was evident. This may be attributable to the lack of variability in this site-specific database. Possibly, the conclusions drawn from the analyses of the nationwide multiple-seam mining database will concur with previous researchers' findings.

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APPENDIX.—HARRIS NO. 1 CASE HISTORY DATABASE

Case	H	h	LC	SF	INT	COMP INT %	No. 2 Gas h	LC	SF	H/ INT	# Beds	Angle	CMRR	Rating and comments
1	750	6.6	TGL	1.34	180	62	6.0	ISO	1.69	3.2	25.7	33	54	(1) No problems were encountered while crossing under isolated gate roads.
2	925	6.3	TGL	1.01	180	62	6.0	ISO	0.69	4.1	25.7	33	54	(1) No problems were encountered while crossing under isolated gate roads.
3	469	6.6	HGL	4.03	180	62	6.0	BL	3.49	1.6	25.7	33	54	(1) Headgate was driven under bleeder entries without any problems. Panel was recovered without gate road cribbing.
4	875	6.7	HGL	1.86	176	59	6.0	HGL	1.15	4	25.1	32	63	(1) No problems were encountered during gate road advance or panel retreat under gate road pillars.
5	725	6.8	TGL	1.37	199	72	6.5	BL	2.90	2.6	33.2	0	47	(1) Gate roads were successfully driven under longwall bleeder entries the entire length of the panel.
6	800	6.8	TGL	1.18	180	62	6.0	ISO	1.50	3.3	25.7	33	54	(2) Additional gate entry cribbing was required while crossing under isolated gate roads.
7	1,000	6.1	TGL	0.90	193	74	6.0	ISO	0.93	4.2	32.2	33	56	(2) Additional gate entry cribbing was required while crossing under isolated gate roads.
8	1,100	6.2	DEV	2.29	193	74	6.0	ISO	0.75	4.7	32.2	33	56	(2) Poor ground conditions required cable bolting on development while crossing under isolated gate roads.
9	800	6.8	TGL	1.20	193	74	6.0	ISO	0.87	3.1	32.2	33	56	(2) Additional gate entry cribbing was required while crossing under isolated gate roads.
10	1,050	7.2	DEV	2.16	193	74	6.0	ISO	0.85	4.4	32.2	33	56	(2) Poor ground conditions required cable bolting under isolated gate roads.
11	1,000	7.1	TGL	1.07	201	80	6.0	ISO	0.60	3.9	50.3	25	44	(3) Tailgate entries located below isolated gate roads experienced several roof falls. Numerous tensioned cable bolts were installed on 4-ft centers.
12	1,200	7.3	TGL	0.52	201	80	6.0	ISO	0.34	5	50.3	25	44	(3) During face recovery, tailgate entries situated below isolated gate roads experienced excessive floor heave and roof falls.
13	1,200	6.9	HGL	1.18	176	59	6.0	BL	0.95	5.8	25.1	32	63	(4) During panel recovery, 500 ft of tailgate closed.
14	800	6.1	TGL	1.30	180	62	6.0	BL	1.88	3.4	25.7	33	54	(4) During panel recovery, 1,200 ft of the headgate entry heaved closed.
15	1,000	6.3	HGL	1.49	199	72	6.5	ISO	0.78	4	33.2	0	47	(5) During panel recovery, the tail-gate squeezed closed under a headgate.
16	1,000	6.2	BL	1.46	178	71	6.0	BL	1.42	4.6	35.6	58	71	(5) During panel recovery, 750 ft of a four-entry bleeder system squeezed shut.

APPENDIX.—HARRIS NO. 1 CASE HISTORY DATABASE–Continued

Case	H	h	LC	SF	INT	COMP INT %	No. 2 Gas h	LC	SF	H/ INT	# Beds	Angle	CMRR	Rating and comments
17	1,200	5.8	HGL	1.44	192	66	6.0	BL	0.86	5.3	32	76	44	(5) The headgate squeezed closed beneath bleeder entries after panel extraction.
18	1,181	6.8	LW face	NA	192	66	6.0	ISO	0.73	5.2	32	14	44	(2) 2 ft of face heave occurred while mining under isolated gate roads.
19	1,000	6.7	LW face	NA	199	72	6.5	ISO	0.69	4	33.2	0	47	(2) 2 ft of face heave occurred while mining under isolated gate roads.
20	675	7.6	LW face	NA	199	72	6.5	ISO	1.77	2.4	33.2	0	47	(2) 2 ft of face heave occurred while mining under isolated gate roads.
21	1,200	5.7	LW face	NA	178	79	5.1	LC2	15.86	5.7	44.5	63	62	(5) Longwall face went on squeeze under a gob/barrier pillar boundary.
22	1,200	6.6	LW face	NA	213	71	6.5	BL	1.22	4.6	35.5	90	44	(5) Roof falls and weight on the face halted recovery under bleeder/gob boundary.

Appendix abbreviations

Angle	Intersection angle (degrees)
BL	Bleeder loading
CMRR	Coal Mine Roof Rating
COMP	Competent
DEV	Development loading
H	Mining height (ft)
h	Overburden (ft)
HGL	Headgate loading
INT	Interburden thickness (ft)
ISO	Isolated loading
LC	Loading condition
LC2	Loading condition 2 (ARMPS)
LW	Longwall
NA	Not applicable
SF	Stability factor
TGL	Tailgate loading
# Beds	Number of beds in interburden
%	Percentage

Rating scale

1 Panel was developed and retreat mined with little or no evidence of multiple-seam interactions.

2 Panel was developed and retreat mined with minor to moderate floor heave (less than 2 ft) and/or rib sloughage (less than 4 ft). Infrequent roof falls may also have occurred.

3 Panel was developed with minor difficulties. On retreat, pillars were occasionally abandoned due to roof falls and/or heavy pillar loading.

4 Panel was developed with greater difficulties, and several pillars were lost on retreat due to adverse conditions.

5 Panel was extremely difficult to advance and could not be retreat mined.

6 Ground conditions necessitated that the panel be abandoned on development, or deteriorating conditions over time closed the section.

FAILURE MECHANICS OF MULTIPLE-SEAM MINING INTERACTIONS

By R. Karl Zipf, Jr., Ph.D., P.E.[1]

ABSTRACT

Multiple-seam mining interactions caused by full-extraction mining, whether due to undermining or overmining, frequently involve tensile failure of the affected mine roof. The adverse ground control conditions may prevent mining for both safety and economic reasons. Prior research has identified the geometric, geologic, and mining factors controlling multiple-seam mining interactions. This numerical study examines the mechanics of these interactions using a modeling procedure that (1) incorporates the essential constitutive behavior of the rock, such as strain-softening of the intact rock and shear and tensile failure along bedding planes, and (2) captures the geologic variability of the rock, especially the layering of weak and strong rocks and weak bedding planes.

Specifically, the numerical study considered the effect of vertical stress, interburden thickness, and the immediate roof quality of the affected seam in both undermining and overmining situations. The models show that for overburden-to-interburden (OB/IB) thickness ratios of less than 5, interactions do not occur and that for OB/IB more than 50, extreme interaction is a certainty. In between, the possibility of an interaction was found to depend on gob width-to-interburden thickness ratio, site-specific geology, and horizontal stress to rock strength ratio, in addition to the OB/IB ratio. The models also showed that horizontal stress was profoundly altered well above or below a full-extraction area and that these changes are likely to influence the success or failure of multiple-seam mining. The role of horizontal stress in multiple-seam mining interactions has received little attention in prior investigations.

Four factors control the mechanics of multiple-seam mining interactions:

1. Vertical stress concentration;
2. Horizontal stress concentration;
3. Stress redirection; and
4. Bedding plane slip bands.

A combination of vertical and horizontal stress increase and high-stress gradients in the vicinity of full-extraction areas reorients principal stresses into a very unfavorable direction. This seemingly small stress reorientation has a profoundly adverse effect on bedded rock.

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INTRODUCTION

Most underground coal mines face multiple-seam mining situations with the potential for interactions that can pose challenging ground control conditions. Knowing the location of prior mining, planning engineers may seek to access and mine new reserves above or below old workings. Two common questions arise:

1. Will workings above or below cause excessive stresses in the proposed workings that lead to difficult ground control conditions?
2. Will subsidence from workings below cause ruinous ground control conditions in the upper seam?

In addition to ground control issues, multiple-seam mining interactions can create other safety issues. For example, an interaction can produce pathways for air, gas, or water migration that can cause spontaneous combustion and inundation hazards.

Whether an adverse multiple-seam mining interaction occurs or not depends on numerous factors that are well documented by many ground control experts [Chekan and Listak 1993, 1994; Haycocks and Zhou 1990; Hill 1995; Hladysz 1985; Hsiung and Peng 1987a,b]. These include:

1. *Mining geometry* – overburden depth, interburden thickness, and seam thicknesses;
2. *Mine design* – layout, sequence, and percent extraction; and
3. *Geology* – immediate roof rock quality and interburden rock strength.

Combination of these factors may lead to various degrees of multiple-seam mining interaction ranging from none to additional ground support required to abandonment of an area.

The ground control research program at the National Institute for Occupational Safety and Health (NIOSH) is seeking to reduce ground control failures resulting from multiple-seam mining interactions through the development of design-based control technology. This study reexamines the failure mechanics of multiple-seam mining interactions using a new numerical modeling approach under development at NIOSH. In this approach, numerical models are created with sufficient geologic detail and proper constitutive behavior. With these two conditions met, numerical models can predict the behavior of the rock mass and indicate whether an adverse multiple-seam mining interaction might occur.

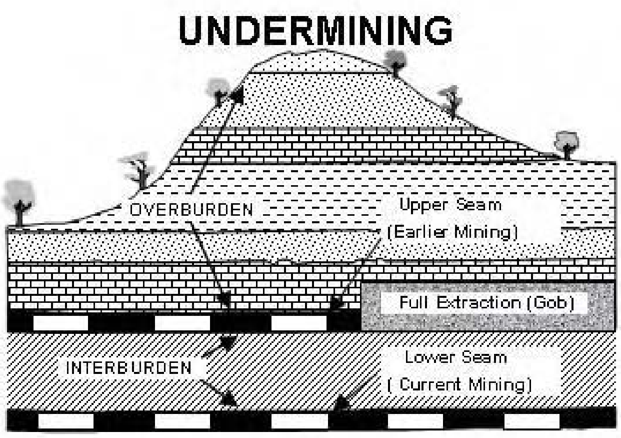

Figure 1A.—In undermining, the upper seam is mined first and abandoned, followed by lower-seam mining.

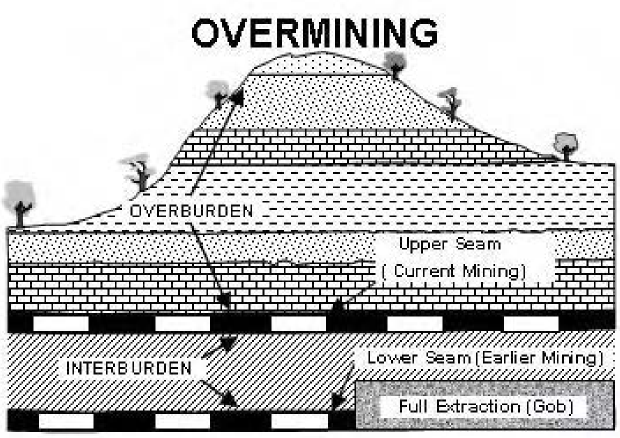

Figure 1B.—In overmining, the lower seam is mined first and abandoned, followed by upper-seam mining. The upper seam is fully subsided prior to its mining.

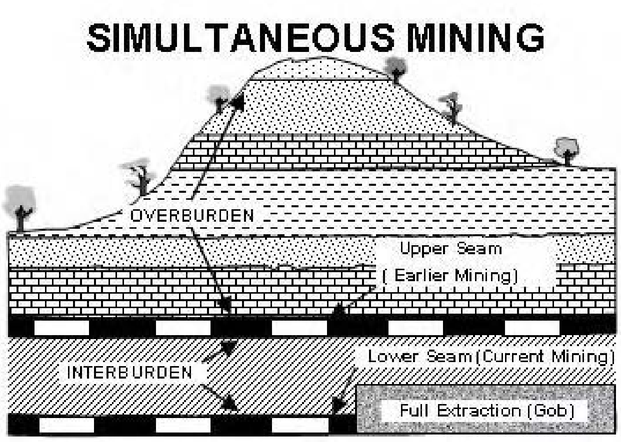

Figure 1C.—In simultaneous mining, the upper seam is developed first, followed by lower-seam mining. Full-extraction mining of the lower seam subsides existing upper-seam workings.

This study examines three fundamental types of multiple-seam interaction:

1. *Undermining* (Figure 1A): This situation represents classic top-down multiple-seam mining. The upper seam is mined first and abandoned prior to mining the lower seam. Gob-solid boundaries, barrier pillars, pillar remnants, or other structures left over from full-extraction mining in the upper seam may cause adverse stress concentrations in the lower seam.
2. *Overmining* (Figure 1B): This situation represents classic bottom-up multiple-seam mining. Full-extraction mining in the lower seam causes the upper seam to fully subside prior to its development. In addition to stress concentrations due to pillar remnants or gob-solid boundaries in the lower seam, the upper seam and surrounding rock may suffer damage from subsidence-induced displacement and fracture.
3. *Simultaneous mining* (Figure 1C): This situation implies that both seams are active simultaneously. In the worst case, workings are developed in the upper seam followed by full-extraction mining in the lower seam. Subsidence of the upper seam occurs after the lower-seam workings are extracted.

NIOSH INPUT PARAMETERS FOR NUMERICAL MODELING

Ground control researchers at NIOSH follow a philosophy developed by Gale [Gale and Tarrant 1997; Gale 2004; Gale et al. 2004] of "letting the rocks tell us their behavior." Numerical models that are constructed with sufficient geologic detail and proper constitutive behavior can predict response of the rock mass, including deformation, stress redistribution, failure modes, and support requirements. For general modeling of rock behavior in coal mine ground control, Itasca's FLAC program [Itasca Consulting Group 2000] contains many useful features, in particular, the SU constitutive model. SU stands for the strain-softening, ubiquitous joint model and is ideal for simulating laminated coal measure rocks. In essence, this constitutive model allows for strain-softening behavior of the rock matrix and/or failure along a predefined weakness plane (in this case bedding planes). Failure through the rock matrix or along a bedding plane can occur via shear or tension, and the dominant failure mode can change at any time. Conveniently, the "state" variable within FLAC tracks the failure mode in each model element as either shear or tensile failure through the rock matrix or along a bedding plane.

The SU constitutive model requires four major input parameters, namely, cohesion, friction angle, dilation angle, and tensile strength for both the rock matrix and the

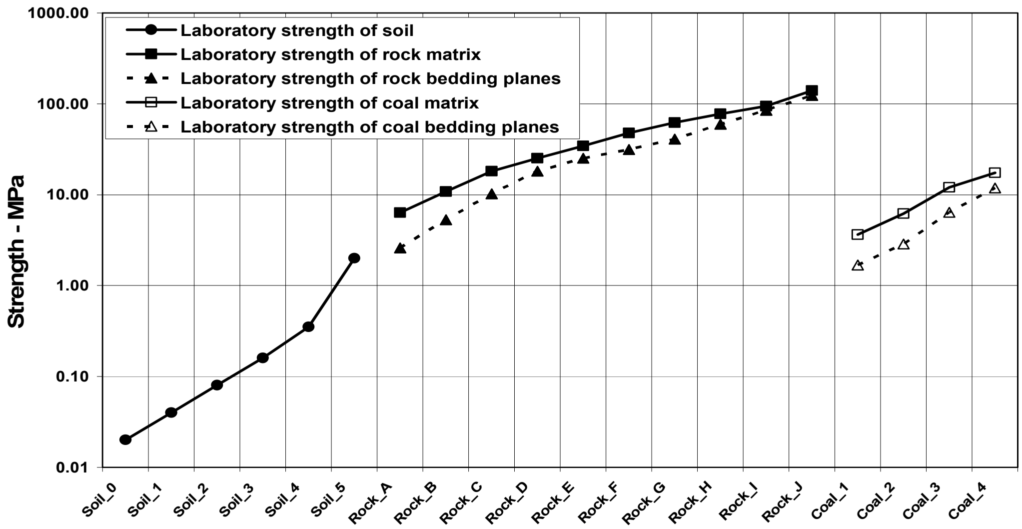

Figure 2.—Laboratory-scale strength of matrix and bedding planes for suite of "numerical rocks."

bedding planes. Each of these parameters begins at some peak value and decreases to a residual value as postfailure strain increases. It is this decrease in parameter value with postfailure strain that gives rise to strain-softening behavior of both the rock matrix and the weakness planes. FLAC permits an infinite combination of these requisite input parameters; however, in order to facilitate rational numerical modeling, NIOSH researchers created an organized suite of material input parameters. Figure 2 summarizes the names for this suite of "numerical rocks" and the corresponding values for the unconfined compressive strength (UCS) of the rock matrix and the strength of the bedding planes.

The strength values shown in Figure 2 are laboratory-scale values determined from standard UCS tests. Alternatively, the point load test provides excellent, economic estimates of the UCS. These UCS values require scaling to reduce the laboratory values to the field values needed by the numerical model. Following the lead of Gale and Tarrant [1997], laboratory values of UCS are reduced by 0.56 universally.

The material suite shown in Figure 2 includes very weak soils and claylike materials with a UCS of 0.02 MPa and weak, medium, and finally strong rocks with a UCS of about 150 MPa. Also included is coal, which ranges from the most friable with a UCS of 2 MPa to a strong coal with a UCS of 12 MPa. The soil material models are isotropic, that is, the soil matrix properties are the same as those for the horizontal weakness plane. However, the rock models exhibit anisotropy since the strength along bedding planes is less than the UCS of the rock matrix. Following results of point load tests by Molinda and Mark [1996], weak rocks are the most anisotropic with the strength along bedding planes about 50% of the rock matrix UCS, while stronger rocks have less anisotropy with the strength along bedding planes about 90% of the rock matrix. The coal models have a similar trend in strength anisotropy, with the stronger coal less anisotropic than the weaker coal.

Note that in proposing this suite of numerical rocks, the UCS of the rock matrix is independent from the strength of the bedding planes. In the absence of specific data, the user will usually specify the rock matrix and bedding plane strength as a pair, with strength ratio similar to that noted by Molinda and Mark [1996] for an extensive database of axial and diametral point load tests. However, the strength values for the rock matrix and bedding planes are independent in the material property suite, and the user can specify any value for the bedding plane strength up to that of the rock matrix UCS.

Also note that the material model suite has a relation to the unit ratings in the Coal Mine Roof Rating (CMRR) system. Mark et al. [2002] proposed that the CMRR unit rating for a coal measure rock layer is comprised of a UCS rating for the rock matrix strength and a discontinuity rating for the bedding plane strength. The UCS rating ranges from 5 to 30 points for a rock matrix strength ranging from 0 to 138 MPa as determined from axial point load tests. Similarly, the discontinuity rating ranges from 25 to 60 for a bedding plane strength ranging from about 6 to 52 MPa as determined from diametral point load tests. The proposed material property suite correlates to CMRR unit ratings from 30 to 90 and represents the range from the weakest to the strongest coal measure rocks. Figure 3 shows these relations. Given CMRR unit ratings from core logging, the relations shown in Figure 3 provide approximate material choices for input to numerical models.

The material model suite and UCS values shown in Figure 2 imply a range of cohesion and friction angle values for the rock matrix and bedding planes. Based on a Mohr-Coulomb strength model, the UCS of a rock depends on cohesion and friction angle as—

$$UCS = \frac{2\,c\cos\phi}{1-\sin\phi} \qquad (1)$$

where c is the cohesion and ϕ is the friction angle. Friction angle for the different materials in the suite is assumed to vary, as shown in Figure 4. Soil and claylike materials have friction angles of 21°, while progressively stronger rocks have friction angles up to 36°. This assumption for friction angle along with Equation 1 implies the values for peak cohesion shown in Figure 5. Thus, the UCS of the rock matrix and the bedding plane strength provide two of the four major input parameters to the SU constitutive model in FLAC.

Other major assumptions within this material model suite are as follows:

1. Moduli for the materials range from 1 to 20 GPa, as shown in Figure 6. Weaker materials have a lower modulus, while stronger materials have a higher modulus. The ratio of modulus to UCS of the rock matrix varies from about 10,000 for the weakest to about 100 for the strongest materials.
2. Cohesion decreases from its peak value given in Figure 5 to a residual value of 10% of peak over 5 millistrain of postfailure strain.
3. Friction angle remains constant at the values shown in Figure 4, even in the postfailure regime.
4. Tensile strength is equal to cohesion for the soil materials and decreases to 0 over 1 millistrain of postfailure strain.
5. Tensile strength ranges from about 10% of UCS for the weakest rocks to about 2% of UCS for the

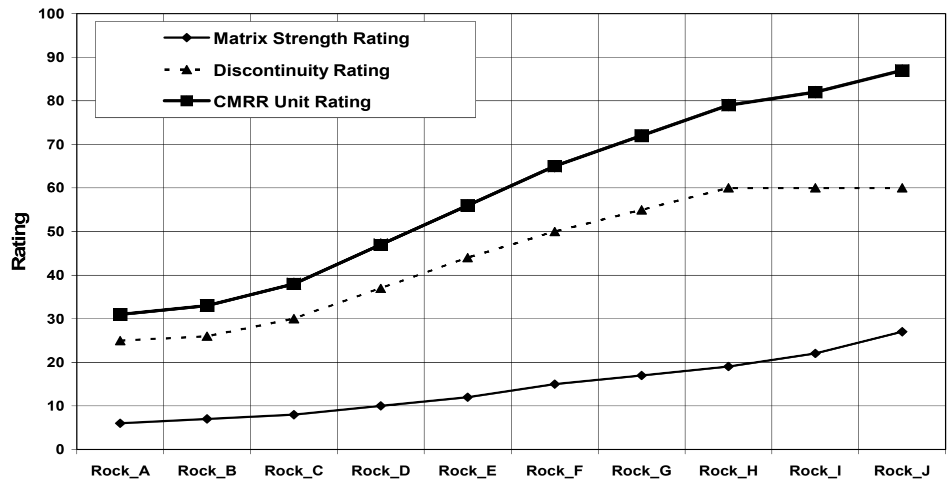

Figure 3.—Correlation of "numerical rocks" to unit ratings of the Coal Mine Roof Rating (CMRR) system. Weak rocks have a CMRR unit rating from 30 to 45; moderate rocks, from 45 to 60; and strong rocks, from 60 to 85.

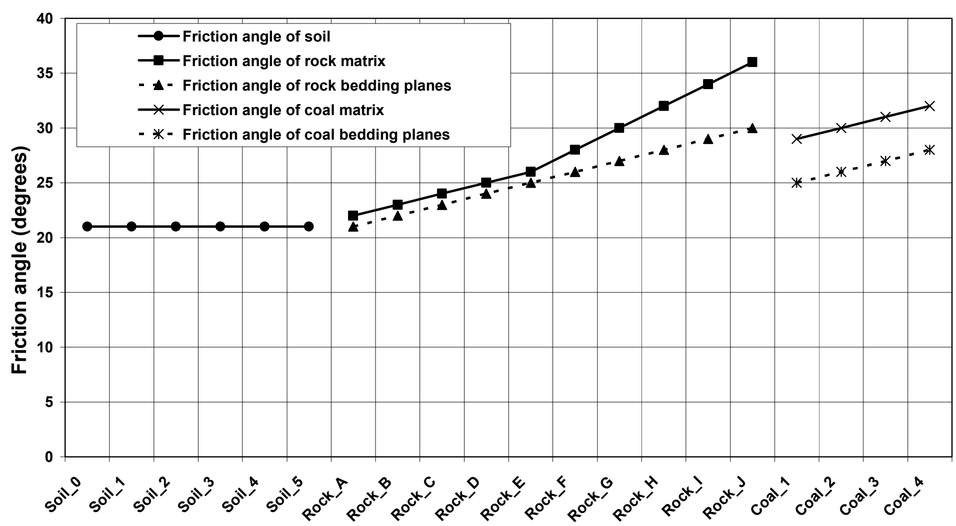

Figure 4.—Friction angle for matrix and bedding planes in suite of "numerical rocks."

strongest rocks. It also decreases to 0 over 1 millistrain of postfailure strain.

6. Dilation angle is initially 10° and decreases to 0° over 5 millistrain of postfailure strain.

This suite of material models provides a convenient method for the modeler to go from a geologic log to a numerical model in a rational, systematic, and efficient manner. Table 1 illustrates this process and shows the level of detail needed for geologic logging. On the left is a typical core log with geologic description. Geologic features at a scale as small as 50 mm are typically recorded for this log. Of particular importance to note are soft clay layers or major bedding planes with weak infilling. In the middle of

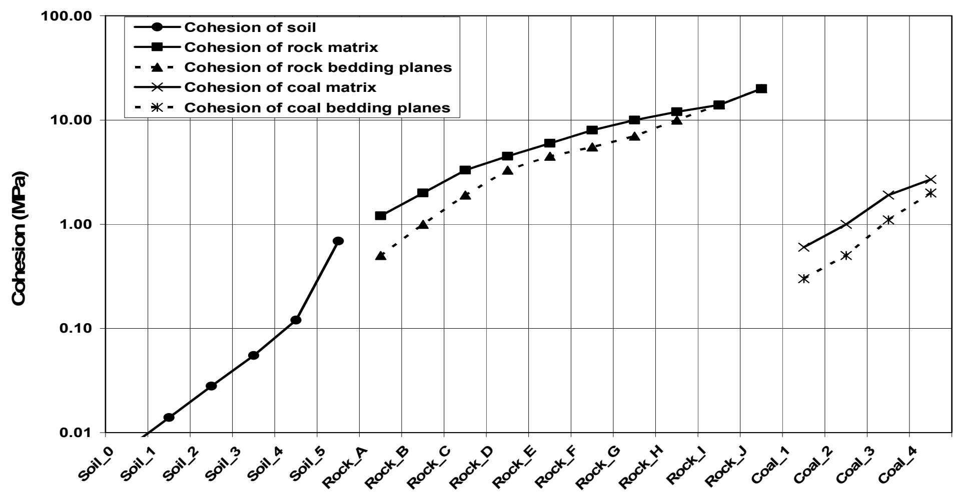

Figure 5.—Cohesion of matrix and bedding planes in suite of "numerical rocks."

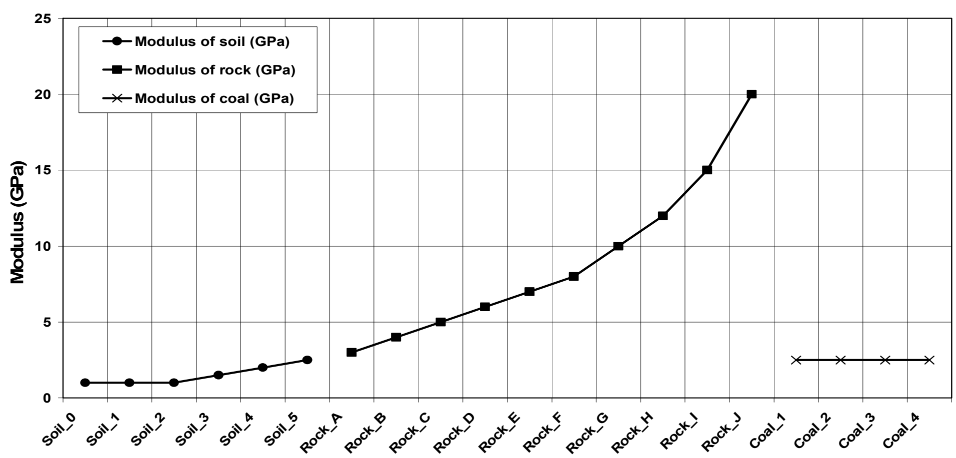

Figure 6.—Modulus of matrix in suite of "numerical rocks."

Table 1.—Going from core log to numerical model input parameters

Stratigraphic column		UCS from axial point load tests (MPa)	UCS from diametral point load tests (MPa)	Rock matrix strength code	Bedding plane strength code
Rock type	Thickness (m)				
Strong sandstone	2.4	90	80	Rock_I	Rock_I
Siltstone (stackrock)	1.2	35	5	Rock_E	Rock_B
Black shale	1.9	10	5	Rock_B	Rock_B
Soft clay	0.05	0.2	0.2	Soil_3	Soil_3
Gray shale	1.8	25	10	Rock_D	Rock_C

Table 1 are UCS estimates for each unit from axial and diametral point load tests. Finally, on the right of the table are property codes for generating input parameters to numerical models using the material model suite presented herein. The modeling approach described has been verified against detailed monitoring of a coal mine entry done by Oyler et al. [2004].

MULTIPLE-SEAM MINING INTERACTION MODEL CONSTRUCTION

Using the material input parameters described above, models were created for the three interaction types, as shown in Figure 7. All models examine mining either above or below a gob-solid boundary, which is representative of most interactions, including mining above or below pillar remnants or barrier pillars. In undermining, a longwall is mined first in the upper seam followed by room-and-pillar development in the lower seam. In overmining, a longwall is mined first in the lower seam followed by room-and-pillar development in the upper seam. In simultaneous mining, room-and-pillar development is done in the upper seam followed by longwall mining in the lower seam. These model types enable detailed examination of the failure mechanics of coal mine entries subject to multiple-seam mining interactions, with the focus on the transition zone either above or below the gob-solid boundary.

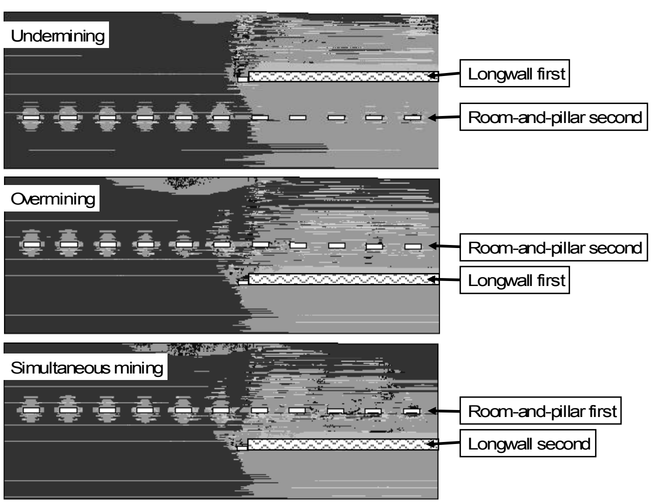

Figure 7.—Multiple-seam mining interaction models for three interaction types. In undermining, a longwall is mined in the upper seam first, followed by room-and-pillar mining in the lower seam. In overmining, a longwall is mined in the lower seam first and the upper seam subsides fully, followed by room-and-pillar mining in the upper seam. In simultaneous mining, the upper seam is developed first and then a longwall mines the lower seam, causing subsidence of the existing workings in the upper seam. Dark shading indicates intact rock; lighter shading indicates matrix failure or slip along bedding planes.

The models consider a slice of the rock mass 160 m wide and up to 75 m high. Each model contains 450 elements along the width and up to 515 elements along the height. Coal seam thickness is 2 m, entry width is 6 m, and entry height is also 2 m. The thickness of each geologic layer is about 0.15 m on average and ranges from 0.05 to 0.25 m. Most of the rock mass layers are assigned properties corresponding to CMRR unit ratings of 45 to 60, which is equivalent to a moderate strength rock mass. However, as discussed later, the immediate roof of the affected seam is considered separately. The stratigraphy used in the model is extracted from a detailed core log similar to that shown in Table 1. Weak, moderate, and strong sections from this log were assembled as needed. While the models are artificial, they have a basis on a real geologic log.

Following recent work on horizontal stress by Dolinar [2003], an average horizontal stress of 10 MPa is applied to the model via the equivalent horizontal strain. Thus, horizontal stress varies according to the relative stiffness of each geologic layer. Stiffer layers have higher horizontal stress than softer layers. Vertical stress is applied at the top of the model to simulate cover load.

The full-extraction area is approximated as a strain-hardening material using the DY, or double yield, constitutive model that can simulate irreversible compaction. Thus, a gob layer replaces the mined coal seam over a height of three times the coal seam thickness. This approximation leads to subsidence over the full-extraction area of about 50% of the seam thickness.

As shown in Figure 8, each model type examined the effect of three factors on the mechanics of multiple-seam mining interaction. Each variable in the matrix has just two values. Vertical stress is either 3 MPa or 9 MPa, which implies an overburden depth of 120 m (shallow) or 360 m (deep). Interburden thickness is either close (7 m) or intermediate (24 m). Finally, the immediate roof quality is either weak (CMRR unit rating of 30–45) or strong (CMRR unit rating of 60–80).

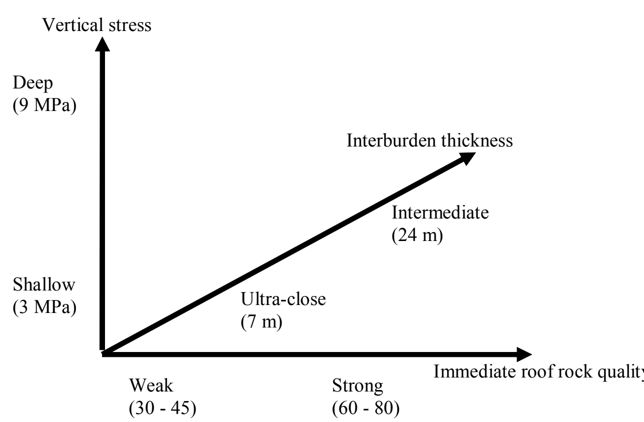

Figure 8.—Three variables for numerical modeling matrix of multiple-seam mining interactions.

Preliminary analysis of case history data presented by Ellenberger et al. [2003] suggests that multiple-seam mining interactions are possible when the OB/IB thickness ratio exceeds 7 for both undermining and overmining cases. By implication, this modeling matrix considers three OB/IB ratio values, namely, 5 where no interaction is expected, about 15–17 where an interaction is possible, and 51 where an interaction is likely.

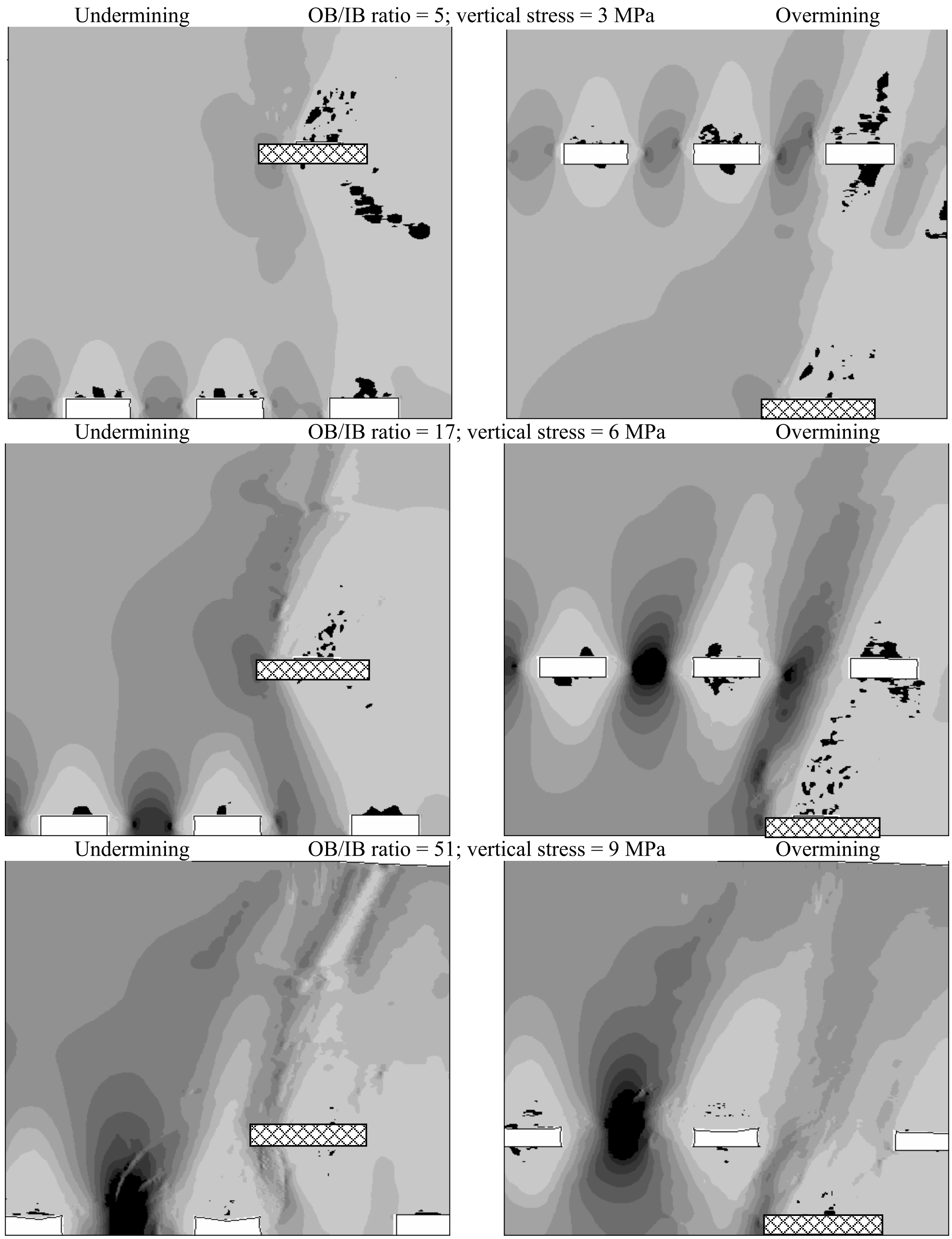

Figure 9.—Vertical stress comparison. Dark shading indicates high stress; light shading indicates low stress. Applied horizontal stress is 10 MPa. Hatching indicates longwall.

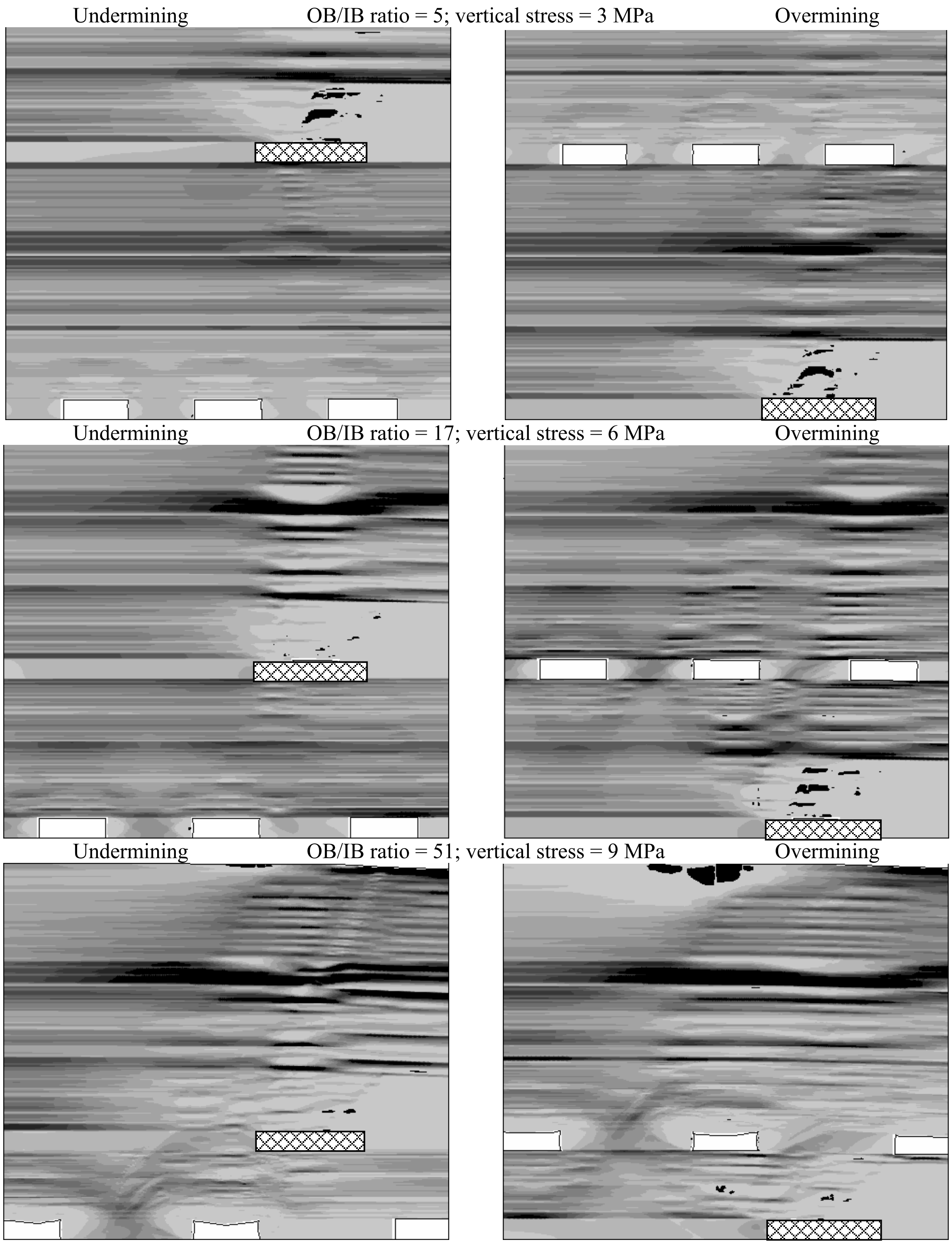

Figure 10.—Horizontal stress comparison. Dark shading indicates high stress; light shading indicates low stress. Applied horizontal stress is 10 MPa. Hatching indicates longwall.

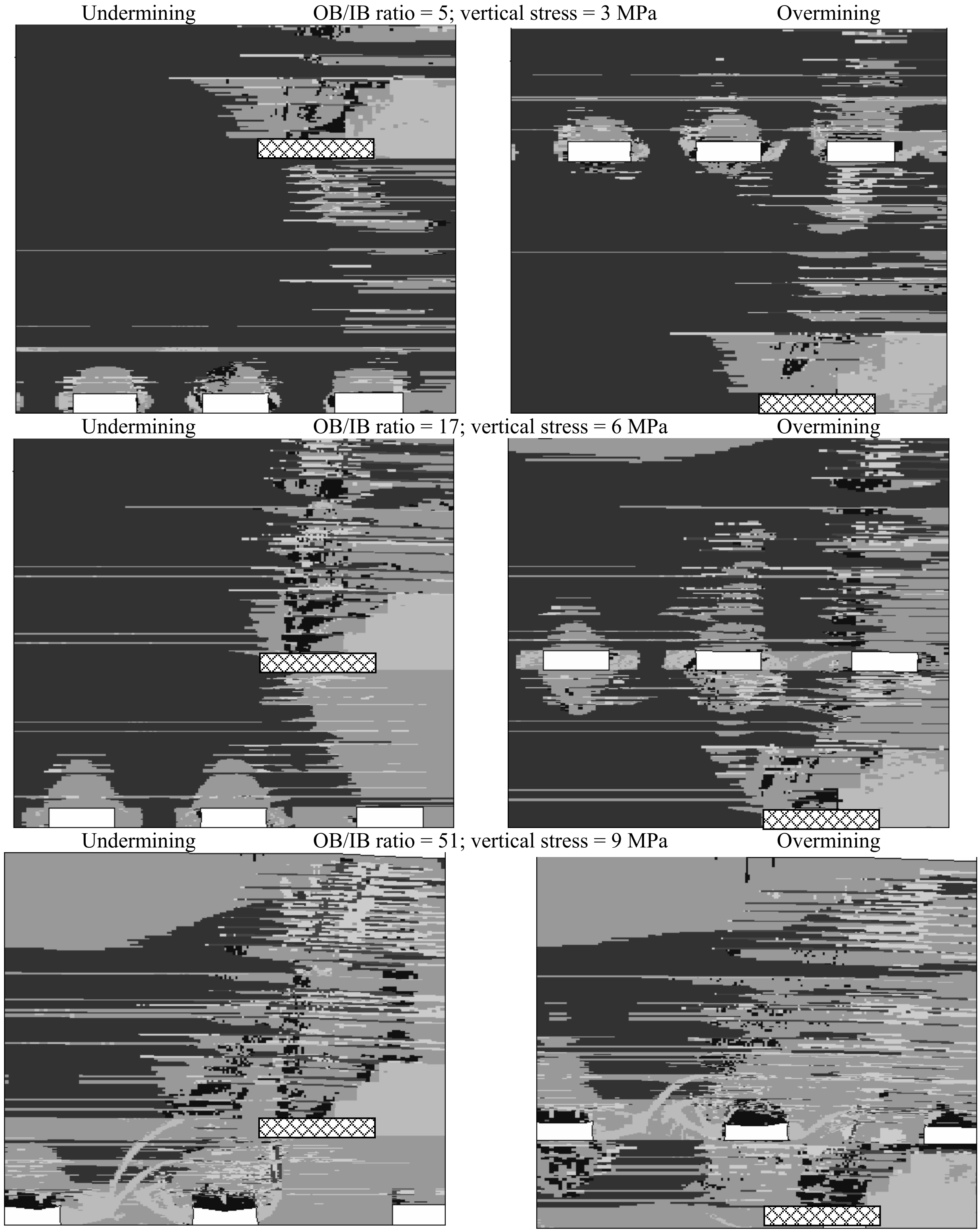

Figure 11.—Failure state comparison. Dark shading indicates intact rock. Lighter shading indicates matrix failure or slip along bedding planes. Applied horizontal stress is 10 MPa. Hatching indicates longwall.

COMPARISON OF MULTIPLE-SEAM MINING INTERACTION MODELS

Figures 9–11 compare vertical stress, horizontal stress, ,and failure state images, respectively, for the undermining and overmining type of multiple-seam mining interactions. The top image in each figure is for an OB/IB ratio of 5, where no multiple-seam mining interaction is expected. Vertical stress is low (3 MPa), and immediate roof rock quality is weak. These models lie near the lower left corner of the matrix shown in Figure 8. In the middle image, the OB/IB ratio is 17, so a multiple-seam mining interaction is possible. Vertical stress is medium (6 MPa), and immediate roof rock quality is medium. These models lie at the center of the matrix. Finally, the lower image is for an OB/IB ratio of 51, where an adverse multiple-seam mining interaction is highly likely. Vertical stress is high (9 MPa), and immediate roof rock quality is weak. These models lie at the upper left corner of the matrix shown in Figure 8.

The following general observations are noted.

1. Vertical stress concentrations occur in a narrow band above and below the gob-solid boundary. This band is inclined about 20° toward the gob both above and below the full-extraction seam. A vertical stress shadow occurs above and below the gob, and it diminishes slowly about 50 m from the gob-solid boundary where the gob has fully reconsolidated.
2. Full-extraction mining produces horizontal stress changes several tens of meters above and below the mined area. The horizontal stress changes occur much farther above and below the mined area than do the associated vertical stress changes laterally away from that mined area. The horizontal stress concentrations may in turn induce rock failure in select geologic layers well above or below the mined area that can further amplify horizontal stress concentrations in nearby layers.
3. Bedding plane slip and tensile failure through the rock matrix occur in a narrow band directly above and below the gob-solid boundary. This band is more extensive above the extracted seam; however, it also extends a considerable distance below it.
4. For coal mine entries in moderate strength immediate roof rock (CMRR unit rating of 45– 60), the extent of rock failure through bedding plane shear or tensile failure of the rock matrix is about 1 times the entry width.

With respect to undermining, the following additional observations are noted.

1. A zone of vertical stress relief occurs under the full-extraction mining area beginning past the gob-solid boundary and extending several tens of meters under the gob. This zone is well understood and correlates well with the best practice of offsetting gate roads under the gob for optimal stability in multiple-seam mining.
2. There is increased bedding plane slip in entries close to directly below a gob-solid boundary. The additional failure is slight and should not correspond to significant additional support requirements.
3. There is a small increase in the amount of pillar failure in the zone below the gob-solid boundary. This increase might correspond to additional pillar spalling and nothing more. As before, the additional pillar failure is slight and not indicative of severe ground control conditions.

With respect to overmining, the following additional observations are noted.

1. A significant increase in bedding plane slip and tensile failure occurs in the interburden and immediate roof rock along with pillar failure in the upper coal seam within a narrow band above the gob-solid boundary. This observation correlates with known decreases in entry and pillar stability in the transition zone above a gob-solid boundary [Rigsby et al. 2003].
2. There is no apparent increase in bedding plane slip or additional tensile failure in the immediate roof above coal mine entries developed in a coal seam that has subsided due to prior mining below. This numerical observation also correlates well with the good stability generally observed in entries driven in fully subsided coal seams. The failure zone induced by entry development in subsided ground is not substantially different from that of an entry in completely undisturbed ground.

With respect to simultaneous mining, the following additional observations are noted without showing the associated models.

1. The horizontal and vertical stress distribution is virtually identical to that shown for simple overmining.
2. The failure mode situation is completely different. When the longwall is created in the lower seam, calculations show a wave of tensile failure that propagates upward through the rock mass and completely envelopes the developed entries within this failure zone. Thus, these entries are likely to experience deteriorating ground control

conditions. This situation is completely different from the prior situation of entry development in a previously subsided coal seam.

Tables 2 and 3 compare notes about the undermining and overmining models within the modeling matrix described by Figure 8. These tables compare conditions around an entry not subject to any multiple-seam mining interaction to an entry subject to full interaction in the area directly above or below a gob-solid boundary. The comparisons examine relative changes on vertical stress, horizontal stress, and failure mode as the OB/IB ratio increases from 5 to 51. Figures 9–11 help illustrate this semi-quantitative comparison of changes in relative stress and failure zone size. As expected, the tables show interesting trends as the OB/IB ratio increases from 5, where no interaction is expected, to over 50, where a serious multiple-seam mining interaction is expected.

Vertical Stress Comparison

In Tables 2 and 3, the vertical stress comparison documents stress changes in pillars above or below a gob-solid boundary compared to a pillar far from the interaction area. As indicated in Table 2, when undermining with a low OB/IB ratio of 5 (Figure 9, top), there is little change in vertical stress within pillars near the gob-solid boundary compared to pillars far away, no matter whether the immediate roof rock is weak or strong. As the OB/IB ratio increases to 17 or 51 (Figure 9, middle and bottom), the relative vertical stress concentration increases significantly. Again, the strength of the immediate roof rock makes little difference in this increase.

Table 2.—Comparison of undermining models

OB/IB ratio	Weak immediate roof rock	Strong immediate roof rock
Vertical stress comparison		
5	Little change	Little change
15–17	Increases about 25% to 50%	Increases about 50%
51	Increase more than 50%	Increase more than 50%
Horizontal stress comparison		
5	Increases less than 10%	Increases about 25%
15–17	Decreases due to failure	Increases about 50%
51	Decreases due to failure	Increases more than 50%
Failure size comparison (remote entry and under gob-solid boundary)		
5	Slight increase in size	0.1 × entry width and no increase in size
15–17	0.5 to 1 × entry width to 1 to 1.5 × entry width	0.1 to 1 × entry width to 0.25 to 1 × entry width
51	1 × entry width to more than 2 × entry width	1 × entry width to 1.5 × entry width

Table 3.—Comparison of overmining models

OB/IB ratio	Weak immediate roof rock	Strong immediate roof rock
Vertical stress comparison		
5	Increases about 20%	Increases about 20%
15–17	Increases about 25% to 50%	Increases about 25% to 50%
51	Increase more than 50%	Increase more than 50%
Horizontal stress comparison		
5	Increases about 10%	Increases about 50%
15–17	Small increases and decreases due to failure	Increases about 50%
51	Decreases due to failure	Increases more than 50% and decreases due to failure
Failure size comparison (remote entry and under gob-solid boundary)		
5	0.3 × entry width to 1 × entry width	0.1 × entry width and no increase in size
15–17	0.5 to 1 × entry width to 1 to 1.5 × entry width	0.1 to 1 × entry width to 0.1 to 1.5 × entry width
51	1.5 × entry width to more than 2 × entry width	1 × entry width to 1.5 × entry width

When overmining, it seems there is more upward transmission of vertical stress concentration. As indicated in Table 3 and shown in Figure 9, at low OB/IB ratio, a significant relative increase in vertical stress does occur. At higher OB/IB ratios of 17 and 51, the relative vertical stress concentration increases, but it is not substantially different from that seen with undermining. Subsidence and the extent of the broken gob above the seam horizon may account for the difference at low OB/IB ratio. As with undermining, the strength of the immediate roof rock makes little difference with regard to the magnitude of the relative vertical stress changes in the pillars.

The overburden and interburden rock in all models is medium strength, with CMRR ranging from 45 to 60. Changing the physical nature of the interburden rock will change the vertical stress distribution; however, it will not change the relative vertical stress changes as noted in this comparison.

Horizontal Stress Comparison

The horizontal stress comparison documents stress changes in the immediate roof rock of an entry above or below a gob-solid boundary compared to an entry far from the expected interaction area. As shown in Tables 2 and 3 and Figure 10, at a low OB/IB ratio of 5, where no interaction is expected, horizontal stress does increase slightly above the background level and that increase depends on the strength of the immediate roof rock. A weak immediate roof rock sees a small increase, while strong immediate roof rock sees a much larger increase in horizontal stress. The relative increase in horizontal stress is more pronounced in overmining compared to undermining for reasons of subsidence and gob formation noted earlier.

As the OB/IB ratio increases, the change in horizontal stress from background depends on the strength of the immediate roof rock. With weak roof, horizontal stress decreases in the interaction area when the immediate roof rock fails and stress is distributed elsewhere. With stronger roof, horizontal stress in the interaction area can increase dramatically over background (50% or more). However, at sufficiently high OB/IB ratio, even strong immediate roof rock can be made to fail in the interaction zone, with a resulting decrease in horizontal stress. Table 3 for overmining shows this possibility.

The role of horizontal stress is crucial for further understanding of multiple-seam mining interaction. As seen in Figure 10, a full-extraction area induces horizontal stress changes many tens of meters above and below the mined seam. The magnitude of these changes depends on several factors, namely, OB/IB ratio, site-specific geology, the ratio of extraction area width to interburden thickness, and the ratio of horizontal stress to immediate roof rock strength.

The OB/IB ratio affects the geometry and the vertical stress level of the particular situation. Closer proximity of the affected seam to undermining and overmining has the expected effect on horizontal stress magnitude. With respect to geology, the major variable is the percentage of strong rock in the interburden and where that strong rock is located relative to the affected roof. A suitably placed strong bed can shield the immediate roof rock of a seam from adverse multiple-seam mining interaction. The ratio of extraction area to interburden thickness is another geometry factor that controls how far above or below a full-extraction area the horizontal stress might change. There are limits on this ratio that depend on whether the full-extraction area exceeds the "critical width" at which maximum subsidence is achieved and vertical stress in the middle of the full-extraction area returns to in situ value. Finally, the ratio of applied horizontal stress (in situ plus induced) to the strength of the immediate roof rock controls the degree of multiple-seam mining interaction. A higher ratio due to either high horizontal stress or low immediate roof rock strength increases the chance of an adverse interaction. Horizontal stress has been found to be a major factor in many ground control problems, especially in the Eastern United States [Mark and Mucho [1994].

Failure Size Comparison

The failure size comparison documents the extent of rock matrix or bedding plane failure in either shear or tension within the immediate roof of the affected seam. The entry itself induces a failure zone in the immediate roof whose extent depends on overburden depth and immediate roof rock quality. This comparison notes how much additional failure occurs due to nearby multiple-seam mining. Failure extent is gauged relative to the entry width.

When undermining at low OB/IB ratio (Table 2), the overlying gob-solid boundary is far away, and it induces little additional failure about an entry in the potential interaction area (Figure 9). For high OB/IB ratio, the overlying gob-solid boundary is close, and the size of the failure zone grows by more than a factor of 2 in weak rock, as shown in Figure 11. Strong rocks show a similar trend as indicated in Table 2. At low OB/IB ratio, the interaction is negligible, while at high OB/IB ratio, the added interaction is severe even with strong immediate roof rock.

At intermediate values of OB/IB ratio, induced changes in the failure zone extent due to multiple-seam interaction can vary greatly. For one case in weak roof, it changes from ½ to 1 times the entry width, while in another case, it changes from 1 to 1½ times the entry width. With stronger rocks, the variability is even more pronounced. In one case, failure zone size changes from one-tenth to one-fourth times the entry width, and in another it remained the same size at 1 times entry width.

Failure zone size in the overmining models (Table 3) showed a similar trend. At low OB/IB ratio in weak rock, failure size is somewhat larger initially and grows more than in the undermining models, while in stronger rock there is no difference. At high OB/IB ratio, failure size grows significantly in both weak and strong rock, which is indicative of a substantial multiple-seam mining interaction. At intermediate OB/IB ratio, failure zone extent and its changes vary greatly as in the undermining models.

The observed changes in failure zone size reflect similar trends as seen with horizontal stress. For an OB/IB ratio less than 5, the chance of a multiple-seam mining interaction is very low, even under a weak immediate roof rock. An adverse interaction is expected for a high OB/IB ratio greater than 50, even under strong immediate roof rock. For an intermediate OB/IB ratio of around 17, the chance of an adverse interaction depends on the vagaries of the interburden rock, in particular site-specific geology and the ratio of horizontal stress to rock strength, and geometric factors such as the ratio of full-extraction width to interburden thickness.

MECHANICAL FACTORS IN MULTIPLE-SEAM MINING INTERACTIONS

The simple modeling matrix reproduces successfully many practical observations of multiple-seam mining interactions, lending credibility to the numerical model and the NIOSH input parameters. Close inspection of the models considered here suggests four underlying factors controlling the failure mechanics of multiple-seam mining interactions:

1. Vertical stress concentration;
2. Horizontal stress concentration;
3. Stress redirection; and
4. Bedding plane slip bands.

Vertical stress concentrations (Figure 12) occur in the vicinity of gob-solid boundaries, pillar remnants, and similar structures as vertical stress is diverted around full-extraction areas. The lateral extent of these increases is indicated in Figure 12 along with stress relief areas. The degree of vertical stress concentration decreases quickly with lateral distance from this boundary. The extent of vertical stress relief above and below the full-extraction area depends on the width of that area. There is also an associated vertical stress gradient near a gob-solid boundary.

Horizontal stress concentrations (Figure 13) also develop around full-extraction areas; however, their behavior is much more complex. Horizontal stress concentration depends on both distance above and below the full-extraction area and the relative stiffness of the geologic layers. Furthermore, horizontal stress concentrations can

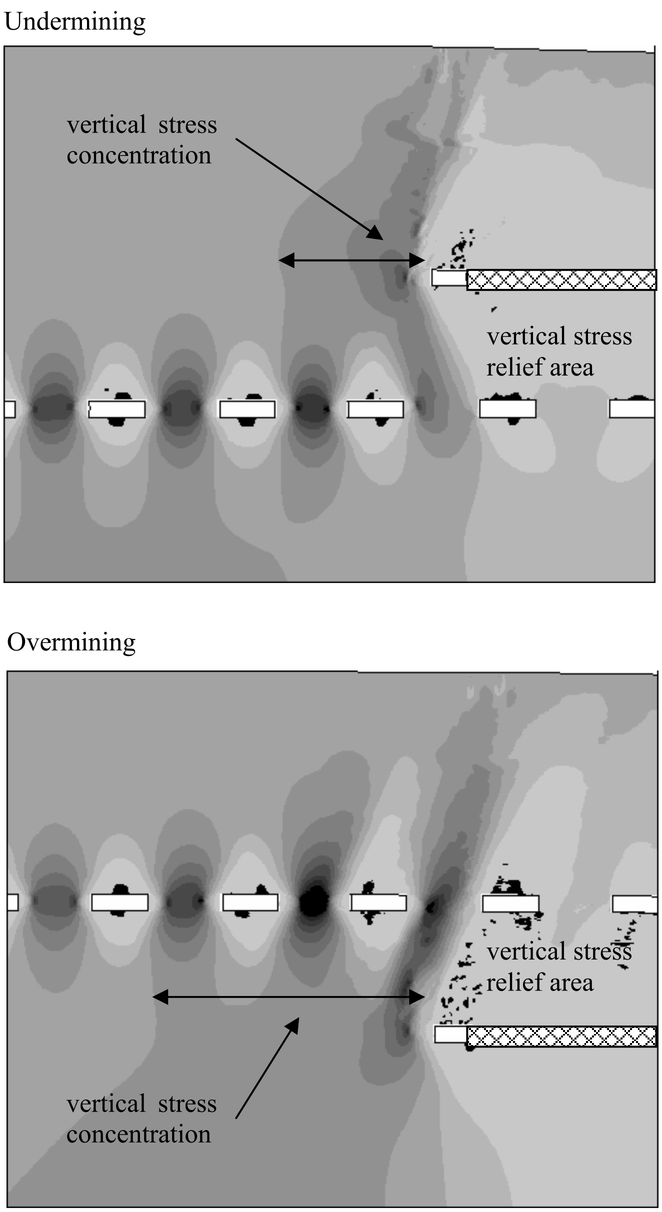

Figure 12.—Vertical stress concentration above and below gob-solid boundaries. Dark shading indicates high stress; light shading indicates low stress. Hatching indicates longwall.

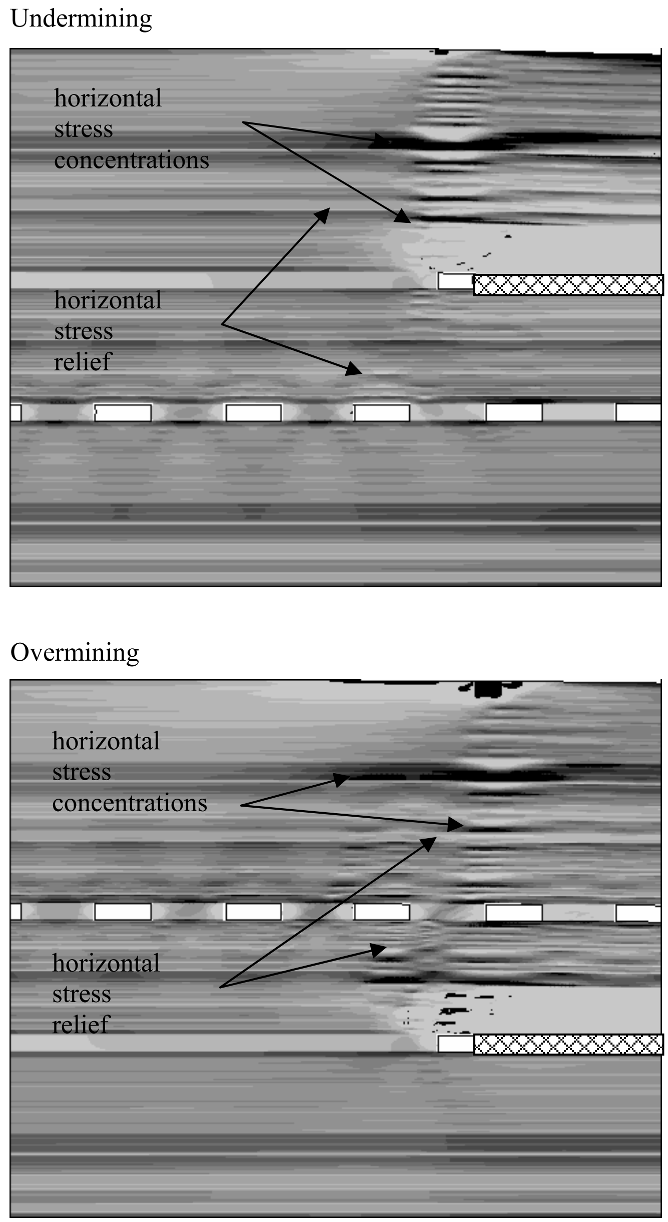

Figure 13.—Horizontal stress concentration above and below full-extraction areas. Dark shading indicates high stress; light shading indicates low stress. Hatching indicates longwall.

be expected much farther above or below a full-extraction area than vertical stress concentrations can be expected left or right of that area. Horizontal stress redistribution is seen much farther away, and it may induce failure in certain weaker layers, leading to even more horizontal stress redistribution. It seems that the effect of horizontal stress on multiple-seam mining interactions has not been explored in any prior studies. The extent of horizontal stress concentration and associated failure of select layers may explain certain cases of successful and unsuccessful multiple-seam mining in otherwise similar conditions.

The combination of vertical and horizontal stress increases in the vicinity of a full-extraction area and, in particular, stress gradients will reorient the principal stresses, as illustrated in Figure 14. This seemingly small stress reorientation has a profound effect on bedded rock. In the absence of mining, principal stresses are usually oriented parallel and perpendicular to geologic strata (Figure 14, top), which is a more favorable orientation for strength. Full-extraction mining reorients principal stresses to the weaker orientation shown in the bottom of Figure 14. Coal mine entries developed in nearby seams in this rotated stress field are much more likely to experience unfavorable ground control conditions. It is also noted without illustration that reorientation of the principal stress occurs in a fairly narrow vertical band adjacent to the gob-solid interface.

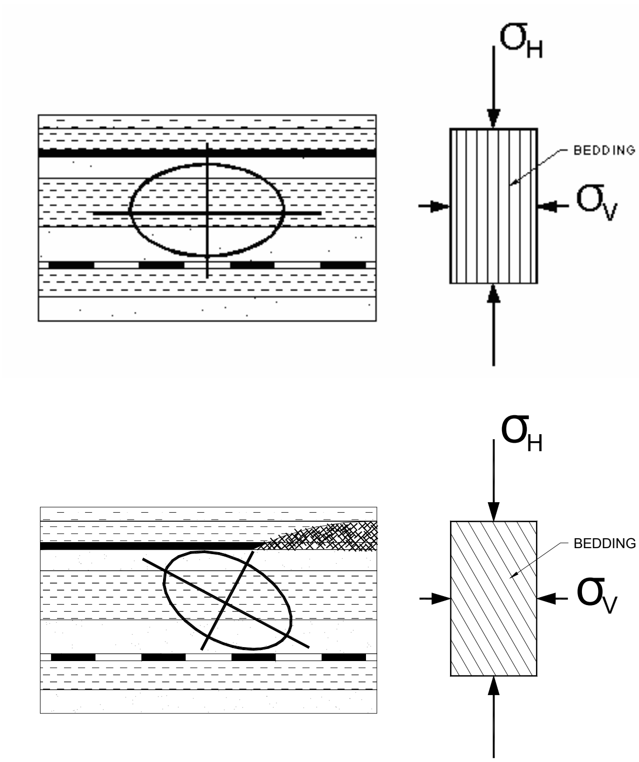

Figure 14.—Reorientation of principal stresses leads to failure due to multiple-seam mining interaction. In single-seam mining, far-field principal stresses are generally aligned parallel to the bedding planes in which a test specimen is relatively strong. If the far-field principal stresses are rotated due to nearby multiple-seam mining, the bedding planes are oriented in an unfavorable direction in which a test specimen is relatively weak.

The rotated stress field also leads to bedding plane slip in narrow, subvertical zones above and below gob-solid boundaries, as seen in the failure state plots in Figures 9–11. These zones of bedding shear are also more likely areas for unfavorable ground control conditions.

TOWARD DESIGN GUIDELINES FOR MULTIPLE-SEAM MINING

This research seeks to provide design guidelines that enable mine planning engineers to correctly assess the safety risk of an adverse multiple-seam mining interaction based on mine geometry factors, mine layout factors, and site-specific geologic conditions. Preliminary analysis of case studies by Ellenberger et al. [2003] suggested that for both undermining and overmining, when the OB/IB ratio was less than 7, there was little risk of adverse interaction. For an OB/IB ratio above 16, there was a possibility of extreme interaction; however, it became evident that other factors in addition to OB/IB also became important.

Numerical studies conducted during this research examined the effect of OB/IB ratio and the immediate roof rock quality of the affected seam on the degree of multiple-seam mining interaction. The numerical models utilized contain great geologic detail and the proper constitutive behavior and are able to capture the essential failure modes of the rock mass, in particular, shear or tensile failure through the rock matrix or along bedding planes.

The numerical models confirm aspects of the initial multiple-seam mining interaction guidelines above. When the OB/IB ratio is less than 5, the models clearly show little, if any, interaction between mining in nearby seams. When the OB/IB ratio exceeds 50, the models clearly show an extreme interaction, even with strong roof conditions in the affected seam. For the intermediate OB/IB ratios considered (15–17), the models show that an adverse interaction is possible, and they provide some insight into the controlling factors.

Numerical models show how vertical stresses divert around a full-extraction area in a seam above or below an active mining seam. The lateral extent of vertical stress increase is relatively narrow compared to the width of the full-extraction area. In addition, a zone of vertical stress relief occurs above and below the full-extraction area. It will extend to a distance up to the "critical width" of the extraction area. Horizontal stresses also divert around the full-extraction area; however, the distance that such stresses increase above or below the seam is much larger than the lateral extent of vertical stress increase. This distance may be approximately equal to the minimum width of the full-extraction area up to the "critical width." Thus, the size of this zone of vertical stress relief in conjunction with horizontal stress increase defines the extent to which adverse multiple-seam mining interaction could occur.

Numerical modeling suggests four factors that control multiple-seam mining interactions and should be considered explicitly in design guidelines:

1. OB/IB thickness ratio;
2. Gob width-to-interburden thickness ratio;
3. Site-specific geology; and
4. Horizontal stress to rock strength ratio.

As mentioned earlier, the OB/IB ratio affects the geometry and the vertical stress level of the particular situation. Greater depth or closer proximity of the affected seam to undermining and overmining are both known to increase the chance of an interaction. The minimum gob width of the extraction area relative to the interburden thickness is another geometric factor that controls how far above or below a full-extraction area the horizontal stress might change. There are limits on this ratio that depend on whether the full-extraction area exceeds the "critical width" at which maximum subsidence is achieved and the vertical stress in the middle of the full-extraction area returns to its original in situ value. With respect to geology, the major variable is the percentage of strong rock in the interburden and where that strong rock is located relative to the affected roof. A suitably placed strong bed can shield the immediate roof rock of a seam from adverse multiple-seam mining interaction. Finally, the ratio of applied horizontal stress (in situ plus induced) to the strength of the immediate roof rock strength controls the degree of multiple-seam mining interaction. A higher ratio due to either high horizontal stress or low immediate roof rock strength increases the chance of an adverse interaction. Although horizontal stress has been found to be a major factor in many ground control problems, especially in the Eastern United States [Mark and Mucho 1994], the role of horizontal stress in multiple-seam mining interactions has received little attention in prior investigations.

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