# Analysis of Multiple Seam Stability

**Christopher Mark,** Principal Research Engineer
**Frank E. Chase,** Research Engineer
**Deno M. Pappas,** Research Engineer
NIOSH-Pittsburgh Research Laboratory
Pittsburgh, PA

## ABSTRACT

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 primary concern, and;
- Overmining, where previous full extraction in an underlying seam can result in stress concentrations and rock damage from subsidence.

The National Institute for Occupational Safety and Health (NIOSH) has completed a major study aimed at helping to identify the location and likely severity of these interactions.  In the course of field visits to mines throughout the U.S., more than 300 multiple seam case histories were assembled into the largest data base of multiple seam case histories ever collected.  These data were analyzed with the multivariate statistical technique of logistic regression.  The study also employed LaM2D to estimate the multiple seam stresses, ALPS and ARMPS to determine pillar stability factors, and the CMRR to measure roof quality.

The study resulted in the development of a computer program, called Analysis of Multiple Seam Stability (AMSS), which can help mine planners to evaluate each potential interaction and take steps to reduce the risk of ground control failure.  AMSS first evaluates pillar design by calculating the single seam Stability Factor ($SF_{SS}$) using ALPS or ARMPS.  It also automatically generates a LaM2D analysis that provides the additional multiple seam stress so that the final, multiple seam $SF_{MS}$ can be determined. The second part of the AMSS procedure builds upon the statistical findings that overmining is much more difficult than undermining, isolated remnant pillars cause more problems than gob-solid boundaries, and weaker roof significantly increases the risk of multiple seam interactions.  AMSS quantifies these effects and predicts the outcome in terms of three levels of risk:  GREEN (where a major multiple seam interaction is considered unlikely), YELLOW (where adding a pattern of cable bolts or other equivalent supplemental support could greatly reduce the probability of a major interaction.), or RED (a major interaction should be considered likely, and it may be desirable to avoid the area entirely).

## INTRODUCTION

Studies have estimated that 156 billion tons of coal, representing two-thirds of the mineable reserves in the U.S., are subject to multiple seam mining influences (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, floor heave, and bumps 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, most 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 U.S. and internationally.  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 NIOSH has been conducting research with the goal of developing better techniques to predict the location and severity of multiple seam interactions.  In the course of this investigation, more than 40 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 Akinkugbe, 2004).

## MULTIPLE SEAM MINING IN THE U.S.

Figure 1 shows the 5 major regions for underground coal mining in the U.S. From the standpoint of multiple seam mining, by far the most significant is the Central Appalachian region of southern WV, eastern KY, and southwestern VA. 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 (DOE-EIA, 2006). Mining has been ongoing in Central Appalachia for nearly 150 years, and recent studies have indicated that perhaps 70% of the ultimate reserve base in the region has already been mined out (Bate and Kvitovich, 2004).
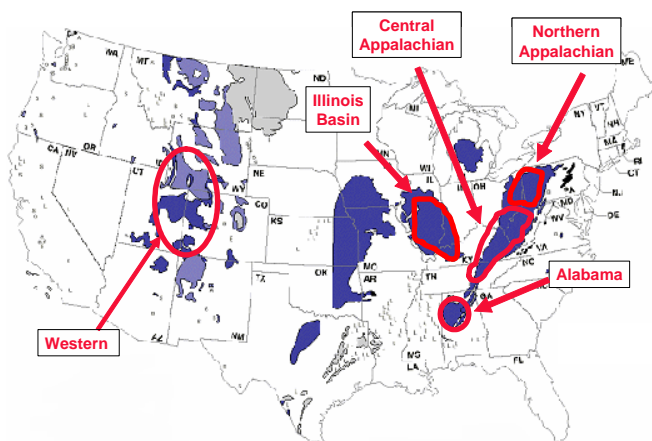


Figure 1. The five major underground coal mining regions in the United States.

One consequence of the maturity of the central Appalachian coal fields 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. Full-extraction is also widely practiced in the Central Appalachian coalfields. While only 8 mines currently employ the longwall method (Fiscor, 2007), 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 U.S. is the next most significant area for multiple seam mining. Here, in the states of UT, CO, WY, and NM, nearly 95% of underground production comes from 13 longwall operations (DOE-EIA, 2006; Fiscor, 2007). 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).

In none of the other three underground mining regions are multiple seam interactions currently a major factor, though all three

have historically 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:

- Most longwall production in the Northern Appalachian and Alabama coalfields is from a single seam (the Pittsburgh and the 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, and;
- Very few room and pillar mines engage in full-extraction pillar recovery in the Illinois Basin, and 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 classed into four major categories, depending on the mining method, the mining sequence, and the thickness of the interburden. Other potential hazards are associated with inflows of water, gas, or 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 remnant structures associated with full-extraction mining in the overlying seam. For significant load transfer to occur, the interburden must be relatively thin, and the seams must be relatively deep.
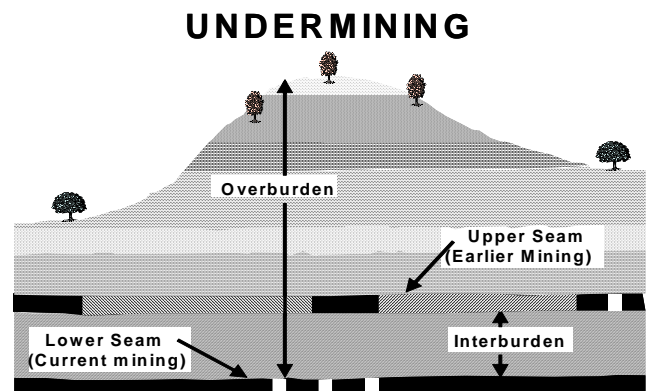
## UNDERMINING



Figure 2. Undermining

Two types of remnant structures can cause undermining interactions (figure 3). A gob-solid boundary carries a single, distributed abutment load, while an isolated remnant pillar is subjected to two, overlapping abutments. 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 proportionally greater.

Stemple (1956) conducted a landmark study of multiple seam interactions which involved the collection of 61 case histories from the eastern U.S. He found that in all the cases where undermining interactions occurred, the depth of cover exceeded 500 ft, and the interburden was less than 110 ft. Prof. Chris Haycocks and his
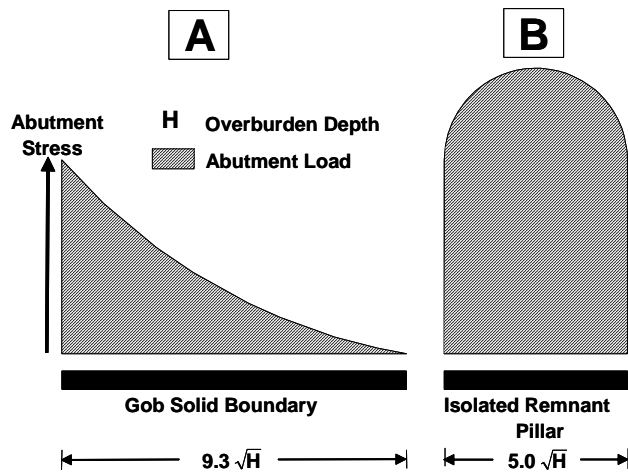
Figure 3. Stress concentrations in multiple seam mining. (A) gob solid boundary and (B) remnant pillar isolated in the gob.



Figure 4. Overmining.

students and colleagues at Virginia Polytech Institute built upon Stemple's work over a period of nearly two decades, beginning in the early 1980's. 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, Haycock's et al. (1982) proposed two relationships for predicting the critical interburden thickness (Icu) in "room and pillar mining":

$$Icu = 110 - 0.42\ Z \qquad (1)$$

$$Icu = 6.8\ N + 55 \qquad (2)$$

Where N is the number of interbeds, and Z is the percent of hard rock (sandstone) in the interburden.

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 1970's, the National Coal Board in the UK collected detailed data from 18 undermining case histories (Dunham and Stace, 1978). The study's authors 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 data base, 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.

*Overmining*, the second type of interaction, occurs when the upper seam is extracted after mining is complete in the lower seam (figure 4). 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 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 of overburden behavior can be identified (Singh and Kendorski, 1981; Peng and Chiang, 1984; Kendorski, 1993; Kendorski, 2006). 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
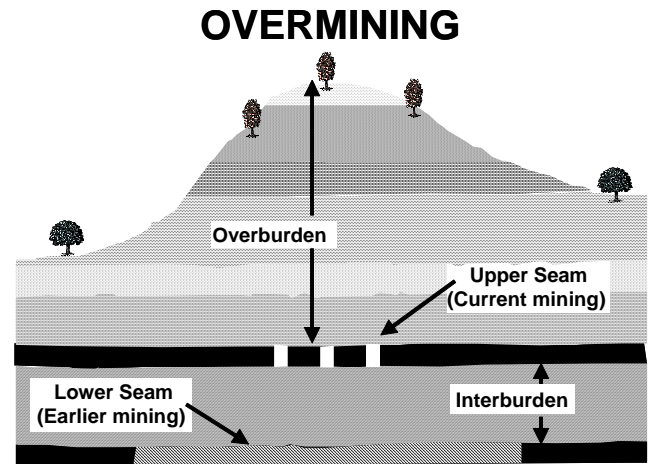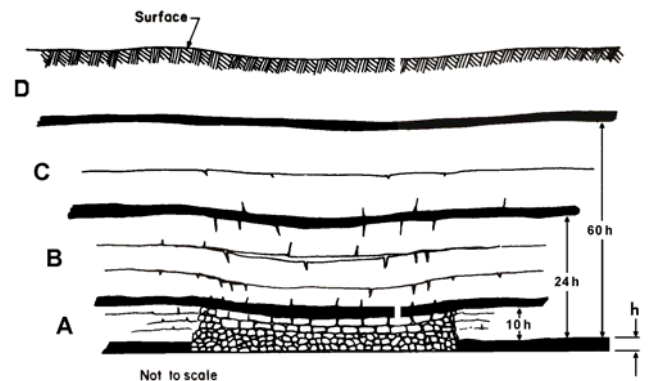


Figure 5. Overburden response to full-extraction mining: (A) caving zones, (B) fracture zone, (C) dilated zone, and (D) confined zone (after Kendorski, 1993; and Peng and Chiang, 1984).

upper seam should be largely intact, though the strata may be fractured or otherwise damaged.

Early studies of multiple seam interactions generally concluded that overmining could be successful with interburden distances of 20 ft or even less (Eavenson, 1923; AIMME, 1926; Holland, 1951). It seems that these studies described conditions over gob areas, however, and did not address the effects of abandoned remnant structures. Stemple (1956) observed that some evidence of subsidence-induced damage could be observed in nearly every overmining case he examined. Haycocks and Zhou (1990) proposed several equations for predicting the critical interburden thickness for successful overmining, but these have not proven to be very useful in practice (Mark et al., 2007; Luo et al., 1997).

*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. For this reason, experts have been warning for nearly a century that dynamic interactions should be avoided at all costs (Eavenson, 1923; Paul and Geyer, 1932; Stemple, 1956; Lazer, 1965). Unfortunately, at least three relatively recent cases have been reported in the literature, and the overlying entries were lost or severely damaged in every case (Su et al., 1986; Ellenberger et al., 2003; Mark, 2006). 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 two years. Then the roof began to deteriorate dramatically, and heavy supplemental support was required to prevent major roof collapses (Mark, 2006).

*Ultra-close mining* is the fourth type of interaction, and the only one in which development mining alone is significant. The primary 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 6). Ultra-close scenarios are most likely to occur near where a thick seam splits, or where a rider coalbed is of mineable thickness.
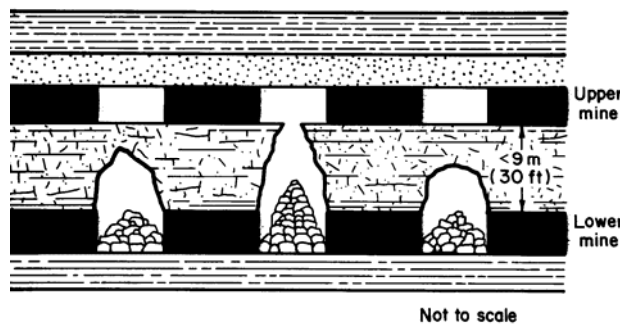


Figure 6. Ultraclose mining (after Chekan and Listak, 1994).

Ultra-close interactions are unlikely when the two seams are more than 20-30 ft apart (Haycocks and Zhou, 1990; Singh et al., 2002). Zhou and Haycocks (1989) determined that the minimum safe working thickness for a massive, unstratified sandstone was just 6 ft, while for shale it was 20 ft. Columnization of the pillars is considered the standard design practice when ultra-close interactions are a concern (Singh et al., 2002; Munsamy et al., 2004).

*Other multiple seam 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. MSHA regulations require that a permit be obtained prior to mining under a body of water (Michalek and Wu, 2000).

A review of MSHA data indicates that of the 201 inundation incidents that were reported between 1996 and 2005, only four 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. 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 Fractured and Dilated Zones (see figure 5) 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.

## NUMERICAL METHODS FOR MULTIPLE SEAM MINE DESIGN

Of the numerical techniques, the Displacement Discontinuity models are best suited for stress analysis of the complex three-dimensional geometries of many multiple seam situations. Displacement Discontinuity models have undergone continuous development and improvement over the past two decades (Heasley and Su, 2006). 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 non-linear 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, 2001). The most recent development is a simplified two-dimensional version of LaModel, called LaM2D, which is much easier to grid and which runs in a fraction of the time required for the full 3D model (Heasley and Akinkugbe, 2004).

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 the solid toward the gob than they are when retreating from the gob to the solid (figure 7);
- 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;
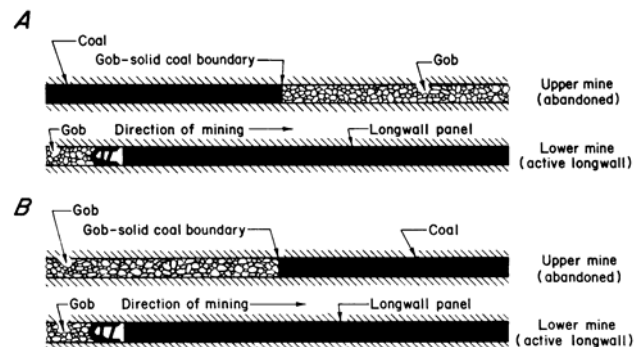


Figure 7. Influence of retreat direction on multiple-seam interaction: (A) retreating from solid to gob creates an unfavorable "stress window," while (B) retreating from gob to solid results in lower stress concentrations (after Chekan and Listak, 1993).

- Orientation relative to other seam remnant structures is not a major factor for development workings.

Hsuing and Peng (1987a) used finite element modeling to develop some rules-of-thumb for undermining. They concluded that if the interburden thickness is 2-3 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. Hsuing and Peng (1987b) also indicated that it is best to retreat from the gob towards the solid, and that the best situation occurs when a longwall face maintains an approach angle of about 30 degrees to remnant structure.

Some recent examples of finite element and finite difference model applications to multiple seam mining include 2- and 3-D analyses of pillar and roof stability in overmining cases from northern WV (Zhang et al., 2004; Morsy et al., 2006). Zipf (2005) 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 4 pillar widths above and below a chain pillar, which would be approximately 400 ft for a typical Australian longwall design.

## FACTORS AFFECTING MULTIPLE SEAM INTERACTIONS

Nearly a century of research has identified a number of qualitative 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 do gob-solid boundaries. First workings are generally not a concern unless the seams are ultra-close.
- *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 towards the solid side of a gob-solid boundary, and a longwall should not be brought broadside into long remnant structure.

The goal of the NIOSH multiple seam study was to *quantify* the effects of these factors, so that they can be evaluated on a site-specific basis and used in design.

## NIOSH MULTIPLE SEAM DATA BASE

In conducting the study, NIOSH relied primarily 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 data bases 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 the design of rib support (Colwell and Mark, 2005). While 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.

Past empirical studies of multiple seam mining have floundered because the data bases were too small for the large number of geologic and mining variables involved in multiple seam interactions, and because bi-variate analyses are inappropriate when there are so many variables involved. The key to the success of the NIOSH study was the assembly of the largest data base of multiple seam case histories ever collected.

The mines included in the NIOSH data base were identified through discussions with mining company personnel and MSHA Roof Control Specialists in each District. The study focused on those mines that had experienced the most difficulties with multiple seam interactions. A total of 44 mines were visited in the course of the study, nearly all from the Central Appalachian and Western coalfields (figure 8).
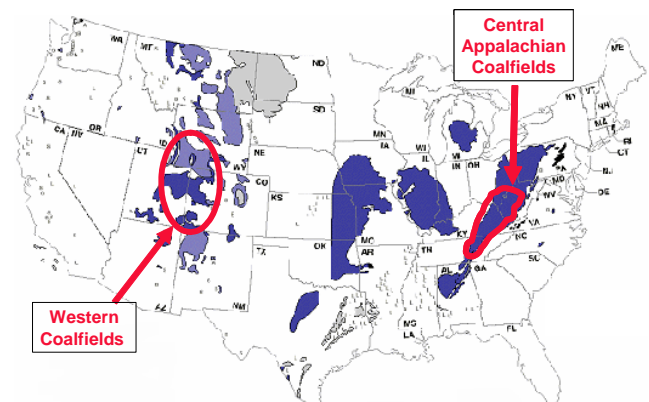


Figure 8. Location of mines included in the NIOSH multiple-seam data base.

The key goal of each mine visit was to develop a history of multiple seam interactions for the operation. Care was also taken to collect successful case histories as well as unsuccessful ones. 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. 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.

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, underground observations provided a sample of the ground conditions associated with interactions at that mine. Mapping of the conditions was only conducted in rare 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 the seams on the property, together with exploratory bore logs. These data were subsequently analyzed by NIOSH to complete the data base.

## PARAMETERS IN THE DATA BASE

In any empirical study, the most important parameter is the "Outcome" for each case history. The multiple seam study employed a combination of reported conditions and evidence from the mine map to rate the Outcome. For example, where a roof fall occurred above or beneath a remnant structure, but the map showed that nearby non-interaction areas encountered a similar density of roof falls, the case would be eliminated from the data base.

The two Outcomes were defined as follows:

- *Successful* cases were those where undermining or overmining had occurred, but no effect was reported in the seam currently being mined (the "target seam"). Successful cases also included those where the presence of past mining was noticed underground (for example, there was slightly more rib spall or an occasional roof crack), but the interaction was so minor that it did not have any effect on mining operations.
- *Unsuccessful* cases (Failures) were those where mining operations were abandoned, or in which mining was completed with significant difficulties, 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.

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 the NIOSH Analysis of Roof Bolt Stability (ARBS) method 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.

A remnant structure was judged to be an isolated remnant pillar if its SF indicated that it concentrated the abutment stress as shown in Figure 3. Equation (3) was used to determine whether a pillar was considered an isolated remnant or a gob-solid boundary:

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

(3)

where Wp is the maximum width (ft) for a remnant structure to be considered an isolated remnant pillar, and H is the depth of cover (ft). Equation (3) 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 (figure 9). Wider remnant structures were considered gob-solid boundaries, and very narrow pillars (those falling to the left of the shaded area in figure 9) were assumed to have yielded.
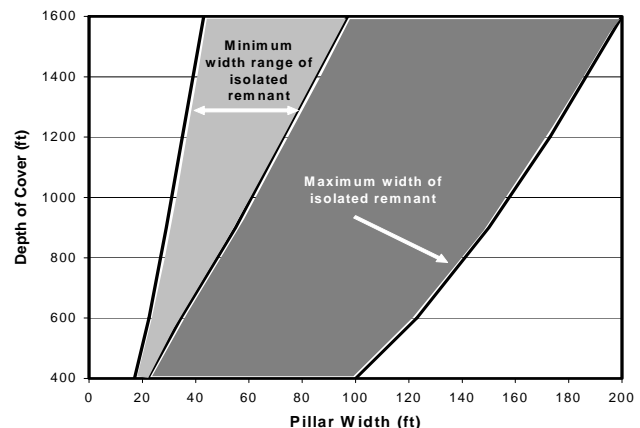


Figure 9. Upper and approximate lower limits for determining whether a remnant structure is an isolated remnant pillar or a gob-solid boundary.

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.

None of the case histories had a CMRR of less than 44, which means that truly weak roof conditions are not represented in the data base. For this reason, and because it was believed that

increasing the CMRR from 40 to 50 has a greater effect on stability than an increase from 80 to 90, the CMRR used in the analysis was:

$$lnCMRR20 = ln (CMRR-20) \qquad (4)$$

Since this logarithmic transformation implies that impact of a multiple seam interaction is amplified when the roof is weak, using the log version means that the ultimate design equation is more conservative for the lower CMRR values.

The Percentage of Competent Rock in the interburden was calculated at each borehole by summing the total thickness of sandstone, sandy shale, and limestone, and then dividing by the total interburden thickness. The number of beds in the interburden was also estimated from the core logs.

## LAM2D AND MULTIPLE SEAM PILLAR STABILITY FACTORS

An important difference between this study and past multiple seam studies is the use of LaModel to obtain estimates of the multiple seam stresses for all the case histories. Because of the large number of case histories, this study employed the two-dimensional LaM2D version of LaModel. Some simplifications were necessary in order to create 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 2D extraction ratio approximated the true 3D 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 (non-yielding) 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 2D.

Figure 10 shows a portion of a typical LaM2D model grid. The key stress output from LaM2D was the average multiple seam stress on the critical (most highly stressed) pillar. The results from the LaM2D analyses were then used to determine the multiple seam pillar stability factor (ARMPS $SF_{MS}$ or ALPS $SF_{MS}$) determined for the target seam, using the following formula (using either ARMPS or ALPS as appropriate):

$$ARPMS \ SF_{MS} = ARMPS \ SF \left[ \frac{single \ seam \ load}{(single \ seam \ load + multiple \ seam \ load)} \right] \qquad (5)$$

Finally, a SF Rating was calculated by comparing the ARMPS $SF_{MS}$ to the recommended ARMPS SF, which depends upon 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, and the others were rated 0.
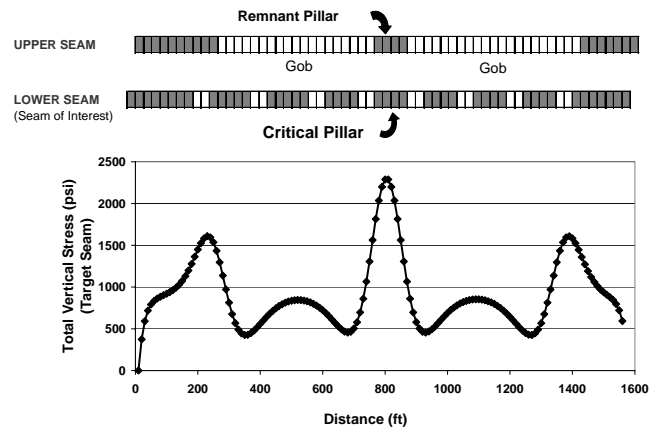


Figure 10. A portion of a LaM2D grid.

## DESCRIPTION OF THE DATA BASE

The final data base included 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 data base.

Figure 11 shows that more than half the cases in the data base 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 data base 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 data base, with a 68% success rate.
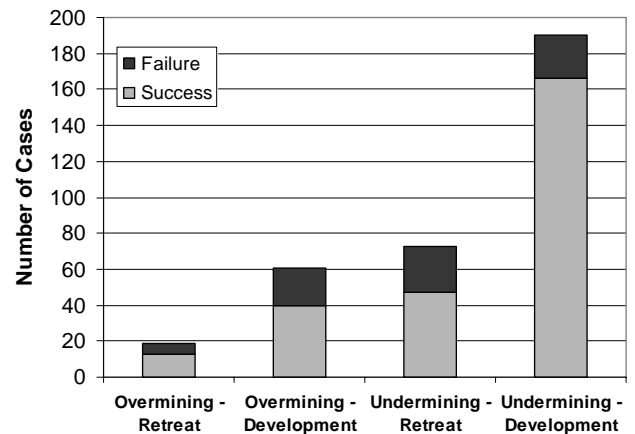


Figure 11. Histogram showing the case history data base by type of mining (development or retreat) and type of interaction (overmining or undermining).

Figure 12 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.
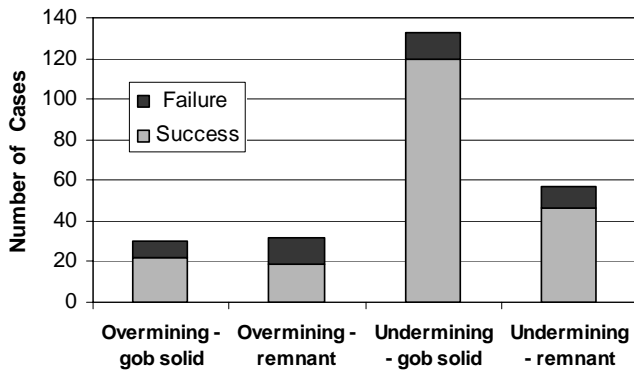
Figure 12. Histogram showing the case history data base by type of remnant structure and type of interaction.

Figure 13 shows the depth of cover and interburden thickness for the undermining cases. In about 90% of the cases, the depth of cover ranged between 400 and 1,200 ft. The interburden is less than 220 ft in all but 20 cases (and those 20 are all successes).
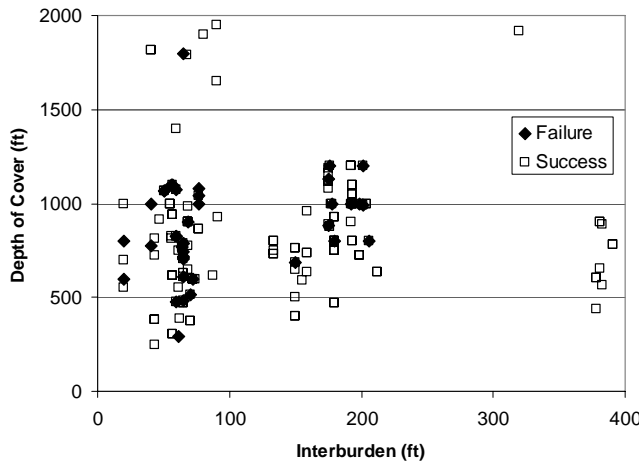


Figure 13. Plot showing depth of cover and interburden thickness for the undermining cases in the data base.
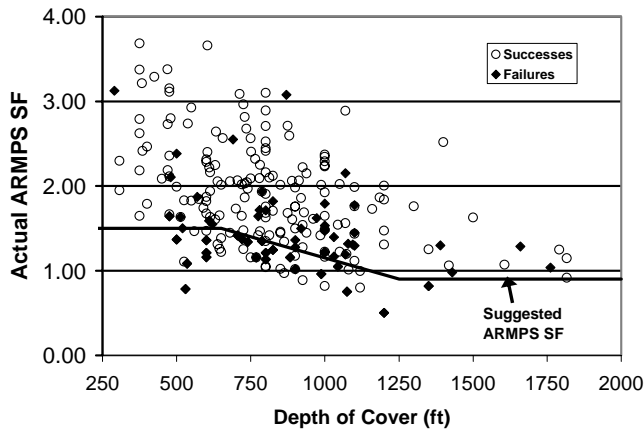


Figure 14. ARMPS SF for the case histories compared with the suggested values of the ARMPS SF.

Figure 14 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 SF that were below the recommended values. These included nearly one-half of the retreat cases. In contrast, more than 87% of the successful cases (including two-thirds of the retreat successes) had ARMPS SF 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 data base that cannot be explained by improper pillar design.

## STATISTICAL ANALYSIS

Logistic regression, the statistical technique employed in this study, is the most common multivariate statistical technique used when the outcome variable is binary (i.e., there are two possible outcomes). The goal of logistic regression analysis is to develop an equation that can predict the Outcome using a combination of the explanatory variables (Hosmer and Lemeshow, 2000). Further details on the logistic regression modeling of the multiple seam case histories can be found in Mark et al. (2007).

Of the 344 cases in the data base, the outcome in 9 of them was considered "borderline," and these were excluded. An additional 26 failed cases were excluded because their ARMPS (or ALPS) $SF_{MS}$ 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 to multiple seam interaction per se. As a result, the final data base included 309 cases histories.

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

$$\text{case weight} = \frac{1}{\sqrt{N_m}}$$

(6)

where: Nm = 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.

In designing the analysis, a key issue was whether the undermining cases, overmining cases, development cases, 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 data bases would each be much smaller. The analyses showed that all four groups could be combined and analyzed together (Mark et al., 2007).

The final, best model is given below:

$$g(x) = -0.81*TVS + 1.79*UO + 0.0233*INT + 2.02*EX \\ - 1.80*REMPIL + 1.95*lnCMRR20 - 6.47 \qquad (7)$$

where: g(x) = A measure of the likelihood of a case being a success
TVS = Total vertical stress on the critical pillar (thousands of ksi)

| 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 |
| lnCMRR20 | = | ln (CMRR-20) |

All of the parameters in this model are statistically significant at well above the 99% confidence level (Mark et al., 2007). The ROC (a logistic regression analog to the r-squared used to measure goodness-of-fit in multiple regression (Hosmer and Lemeshow, 2000)) is 0.88 for this model.

For use in mine design, the "cut point" value separating predicted successes from failures was adjusted to g(x)=0.86 (Mark et al., 2007). Table 1 indicates that with this cut point, the model correctly classifies approximately 81% of the cases overall, including 79% of the failures.

Since equation (7) would be difficult to use directly in design, it was rearranged to predict the "critical interburden thickness" (INTcrit, ft) and the maximum allowable stress on the critical pillar (TVSallow, psi):

$$INTcrit = 35*TVS - 77*UO - 87*EX + 77*REMPIL \\ 83*(lnCMRR20) + 359 \tag{8a}$$

$$TVSallow = 1000 (2.21*UO+0.0288*INT+2.49 \\ *EX-2.22*REMPIL+2.41*(lnCMRR20)-10.33) \tag{8b}$$

One disadvantage of equation (8a) is that in some extreme cases it can predict a negative value of the critical interburden thickness. Therefore, a logistic regression model was determined using the log of the interburden in place of the interburden per se. The resulting lnINT model was very similar to equation 5, but its ROC was slightly less at 0.87. The lnINT model was used to derive a second pair of equations for the critical interburden thickness INTcritLN and the TVSallowLN.

$$INTcritLN = EXP(0.35*TVS - 0.74*UO - 0.99* \\ EX + 0.74*REMPIL - 0.91*(lnCMRR20) + 7.23) \tag{9a}$$

$$TVSallowLN = 1000 (2.11*UO+2.85*Ln(INT)+ \\ 2.83*EX-2.10*REMPIL+2.59*(lnCMRR20)-20.75) \tag{9b}$$

Figure 15 shows that in general INTcritLN>INTcrit 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, equation (8a) was preferred for most situations. The log interburden model is preferred only for the thinnest interburdens, where equation (9a) provides the most conservative value for the critical interburden.

When the actual interburden thickness exceeds the INTcrit determined by equation (8a), there is a very good likelihood that conditions will be satisfactory. The data in Table 1 and Figure 16 indicate that within the NIOSH data base, only 4.3% of the cases (9.6 of 221.8 weighted cases) where the interburden exceeded the critical value defined by equation (8a) were failures. Of the cases where the actual interburden was less than the critical value, the multiple seam interaction resulted in unsatisfactory conditions 41.5% of the time.
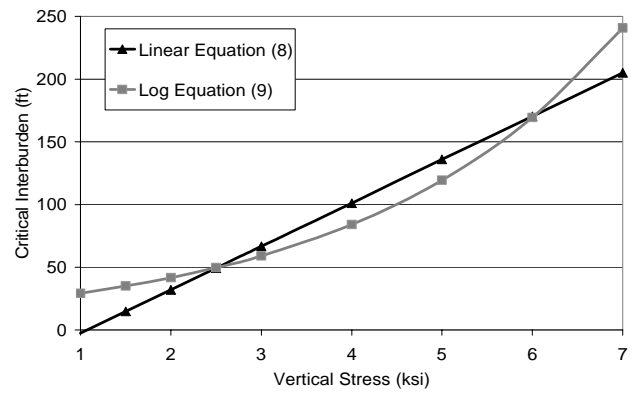


Figure 15. Comparison of Equations 8 and 9, showing that the logarithmic version (Equation 9) can yield the most conservative value of the critical interburden when the calculated interburden is less than about 50 ft.

Table 1. Performance of the Design Equation against the NIOSH data base.

| Model predictions | No. of cases[1] | % 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 success | 9.6 | 3.1 |
| Successes predicted as failures | 51.0 | 16.5 |
| Total cases incorrectly predicted | 60.6 | 19.6 |
| Total cases | 309 | 100% |

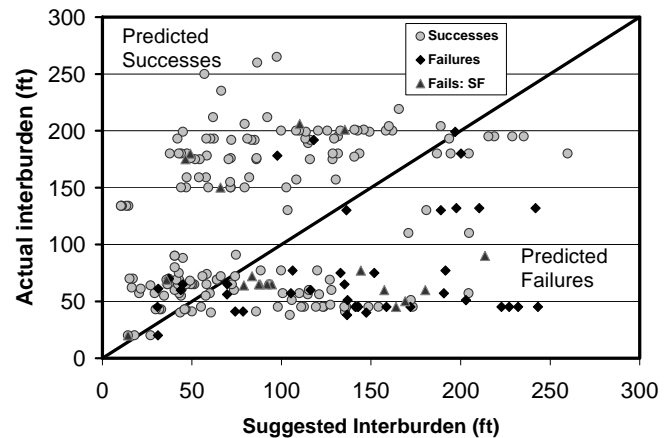[1]Weighted using equation (6).



Figure 16. Performance of the design equation, comparing the suggested critical interburdens with the actual interburdens in the case histories.

Equation (8a) also indicates that to maintain the same outcome when other factors are held constant:

- In order to compensate for an additional 1,000 psi of vertical stress on the critical pillar, an additional 35 ft of interburden would be required;
- Overmining requires 77 more ft of interburden (or a 2,200 psi reduction in the total vertical stress) than undermining;
- An isolated remnant pillar requires 77 more ft of interburden (or a 2,200 psi reduction in the total vertical stress) than a gob solid boundary;
- A CMRR = 45 roof requires approximately 50 more ft of interburden (or 1,580 psi less total vertical stress) than a CMRR = 65 roof.

The analysis indicates that by installing a pattern of cable bolts or other heavy supplemental support it may be possible to mine with 87 ft less of interburden than would be the case without the extra support. 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 17, 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 "Green" region, 97% of the case histories that maintained an adequate pillar SF were successful. In the middle, "Yellow" region, success is predicted only if a pattern of supplemental support is installed. Within the Yellow zone, 93% of the cases that did install supplemental support were successful, while just 63% of those who did not succeeded. In the bottom, or "Red" region of the graph, where failure is predicted, only 52% of the cases were successful.
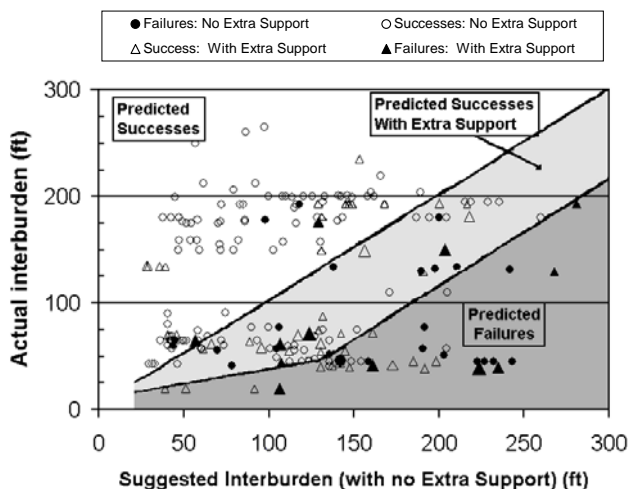


Figure 17. Suggested critical interburden values setting EX=0.

## VARIABLES NOT INCLUDED IN THE DESIGN EQUATION

The design equation does not include a number of variables that past studies had identified as being important to multiple seam analysis. This does not mean that these variables are not important, only that their influence was not identified in this study. For example, interburden competence was not significant in the NIOSH study. 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.

- Since the case histories are all from two coalfields where the rocks tend to be strong, there may not be sufficient variability in the data base to capture the effect of interburden competence.

The time lag since mining the bottom seam was another variable that was not statistically significant. The data base 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 data base. It seems quite likely, in this instance at least, that the settling time was important.

The lack of influence of the lower coal bed to interburden thickness ratio may also be due to the small number of relevant cases in the data base. There were 30 cases (21 development and 9 retreat) in which the interburden thickness was 7.5-10 times the lower coal bed 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 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 (see figure 11). It may be that once the upper seam is above the caving zone, the lower coal bed to interburden thickness ratio may not be significant. However, since all of these cases (but one) came 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. The effect of retreat mining is indirectly included in the total vertical stress variable, however. On average, the total vertical stress was 20% greater in the retreat cases than in the development cases.

## ANALYSIS OF MULTIPLE SEAM STABILITY (AMSS)

The results of this study have been implemented in a software package called "Analysis of Multiple Seam Stability" (AMSS). AMSS requires only that the user input a variety of easily-obtained geometric and mining parameters. The program automatically runs the necessary LaM2D and ALPS or ARMPS analyses. The primary output from AMSS is a three-level (green/yellow/red) prediction of the intensity of the multiple seam interaction that is likely to be encountered. The step-by-step procedure for using AMSS 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 these AMSS input parameters using the maps and core logs:

   • 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 AMSS data base. If the roof of the active seam is very weak (CMRR<45) or the stress is very high (>5,000 psi) then AMSS 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 ultra-close interaction should be the primary consideration. AMSS will help with this by printing a "warning" if the data entered falls at the margins of the data base.

4. Determine whether the remnant structure is a gob-solid boundary or an isolated remnant pillar. Figure 9 may be used if the structure is a pillar. If the remnant pillar is so small that it may have failed completely, it may be helpful to determine its ARMPS SF.

5. Enter the AMSS parameters on the first input page of the program. These parameters include:

   • Whether the active mining is longwall or room and pillar;
   • Whether the case is undermining or overmining;
   • The interburden thickness;
   • The type of remnant structure;
   • The active seam CMRR;
   • The previously mined seam thickness;
   • The width of gob areas, and;
   • The width of the isolated remnant pillar (if present).

6. Enter the mining parameters for the active seam into the ARMPS or ALPS module for the proposed section in the target seam. AMSS then automatically conducts a single seam ALPS or ARMPS analysis, as appropriate.

7. AMSS automatically creates a LaM2D grid, and conducts a LaM2D analysis of the remnant structure crossing. It then determines the multiple seam stress applied to the critical pillar in the target seam.

8. AMSS determines the ARMPS or ALPS multiple seam pillar stability factor ($SF_{MS}$) for the target seam using equation (5), and compares it to the recommended ARMPS or ALPS SF. If the calculated $SF_{MS}$ is lower than the recommended value, then AMSS will print a "warning" suggesting that the pillar size should be increased.

9. AMSS will use the design equations (equations 8 and 9) to determine the critical interburden thickness (INTcrit) and the maximum allowable total vertical stress on the critical pillar (TVSallow), both with and without supplemental support.

10. AMSS compares the actual interburden and stress with the INTcrit and TVSallow values determined in step 9. Three predicted outcomes are possible:

    a. GREEN: If INTcrit is significantly less than the actual interburden without supplemental support, then a major multiple seam interaction can be considered unlikely.

    b. YELLOW: If the actual interburden is less than INTcrit without supplemental support, but greater than INTcrit with supplemental support, then adding a pattern of cable bolts or other equivalent supplemental support could greatly reduce the probability of a major interaction.

    c. RED: If INTcrit even with supplemental support is greater than the actual interburden thickness, then a major interaction should be considered likely, and it may be desirable to avoid the area entirely.

If desired, the pillar design in the target seam can be adjusted before running the program again. Changing the pillar size changes the value of the TVS, which can reduce it below the TVSallow (reducing the TVS also reduces the INTcrit.). Finally, if the case still falls within the "Yellow" range, it might be desirable to conduct a more detailed analysis using LaModel 3D.

## CONCLUSIONS

To conduct this study, NIOSH collected the largest data base 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 stability factors, 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 for protective mine design.

The study found that pillar design is a critical component of multiple seam mine planning. Many of the failed cases involved pillars whose SF appeared 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 coal bed to interburden thickness ratio, and the angle between the active mining and the remnant structure.

The study resulted in the development of a computer program, called Analysis of Multiple Seam Stability (AMSS), which can help mine planners to evaluate each potential interaction and take steps to reduce the risk of ground control failure. The first step in the AMSS procedure is to evaluate the pillar design. The AMSS program calculates the single seam $SF_{SS}$ using ALPS or ARMPS, and then it automatically generates a Lam2D analysis that provides

the additional multiple seam stress. If the final, multiple seam $SF_{MS}$ appears inadequate, the $SF_{MS}$ can be improved by increasing the pillar width, dropping crosscuts, or reducing the entry width.

The second part of the AMSS procedure is embodied in an equation that predicts the critical thickness of the interburden, and/or the maximum allowable pillar stress, required to minimize the likelihood of a multiple seam interaction. The program predicts the outcome in terms of three levels of risk: GREEN (where a major multiple seam interaction is considered unlikely), YELLOW (where adding a pattern of cable bolts or other equivalent supplemental support could greatly reduce the probability of a major interaction.), or RED (a major interaction should be considered likely, and it may be desirable to avoid the area entirely).

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