Applications of ARMPS (Version 6) to Practical Pillar Design Problems

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ABSTRACT

The Analysis of Retreat Mining Pillar Stability (ARMPS) program has been used to evaluate room and pillar retreat mining layouts since it was first released in the mid 1990s. After the Crandall Canyon mine disaster focused attention on the importance of pillar design, ARMPS became an essential component in most Roof Control Plans developed by mine operators. In 2010, NIOSH released ARMPS version 6, which features a "pressure arch" loading model for deep cover room and pillar mining. NIOSH has also provided general guidance for using ARMPS, including design criteria based on statistical analyses of an extensive case history data base.

Many real-world retreat mining scenarios entail mining configurations that ARMPS does not directly address. Some of these situations that the MSHA Roof Control Division (RCD) has encountered in the course of its reviews of more than 100 "complex and non-typical" plans are

- Unmined pillars are left at the mouth of a retreat panel that function as a "composite barrier pillar"
- The floor is extracted on retreat, increasing the mining height
- More than one row of bleeder pillars is left in an adjacent, previously mined panel
- A retreat panel is located above or below a gob area in a previously mined seam
- Bleeder pillars are partially extracted on retreat

RCD has developed solutions that allow these situations to be fitted into the ARMPS framework, and these are presented in this paper. Also discussed are some of the rules of thumb that have been developed for various input parameters, such as the treatment of in-seam rock and slab cuts into solid coal.

INTRODUCTION

The Crandall Canyon disaster was an unfortunate reminder of how important pillar design is to mine safety. The MSHA report on the disaster (Gates et al., 2008) concluded that "it was obvious, at the most fundamental level, that the accidents at Crandall Canyon Mine were precipitated by pillar failures….The South Barrier [pillar] was the last substantial block of coal supporting the mountain and, as it was removed, the mountain was simply too heavy for the remaining pillars."

U.S. mining regulations require that "pillar dimensions shall be compatible with effective control of the roof, face and ribs and coal or rock bursts" (30 CFR § 75.203(a)). In the wake of the Crandall Canyon disaster, MSHA distributed Program Information Bulletins (PIBs) aimed at encouraging mine operators to use engineering procedures to prepare their roof control plans (Stricklin and Skiles, 2008; Skiles and Stricklin, 2009). A separate Procedure Information Letter (PIL) defined the characteristics of "complex, non-typical" plans that are to be sent to MSHA Technical Support, Roof Control Division (RCD) for further review (Skiles and Stricklin, 2008).

In many cases, the NIOSH Analysis of Retreat Mining Pillar Stability (ARMPS) computer program is the simplest and most reliable engineering technique that is available for pillar design. The program is flexible and can model a broad range of mining geometries, as shown in Figure 1. For these reasons, ARMPS has become an essential component in most of the roof control plans developed by mine operators. In some cases, however, the mining geometry does not readily fit into the ARMPS model scenarios. In the course of its review of more than 100 "complex, non-typical" pillar designs, RCD has developed procedures that allow some of these unusual geometries to be modeled. The purpose of this paper is to present these procedures to the mining community.

BACKGROUND TO ARMPS

ARMPS was first released by NIOSH in the mid 1990s (Mark and Chase, 1997). Updated versions were released in 2002 and 2010. During the same period, the size of ARMPS database has increased from 150 case histories to almost 650 (Mark, 2010).

The purpose of ARMPS is to help prevent three types of pillar failures:

- *Squeezes*, which are non-violent events that may take hours, days, or even weeks to develop. Squeezes are the most common type of pillar failure, and they commonly cause roof instability, floor heave, and rib falls. Because they develop slowly, however, no fatalities have been associated with pillar squeezes for at least 25 years (Mark, 2010).

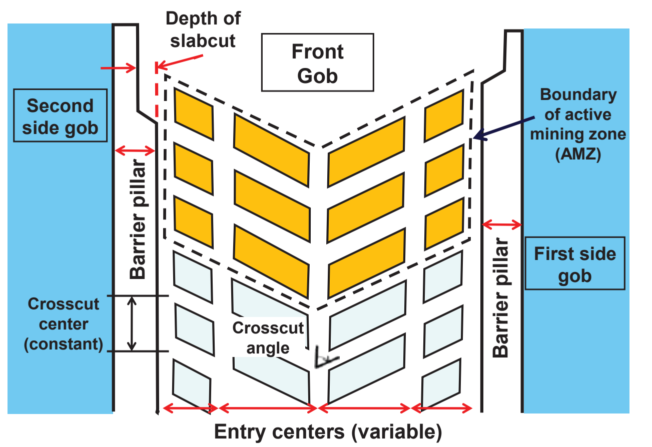

Figure 1. Geometry of typical retreat mining panel showing the ARMPS input parameters.

- *Collapses*, which occur when a large number of overloaded pillars fail almost simultaneously, usually resulting in a destructive airblast. Most collapses in the U.S. have occurred under low cover (< 500 ft (152.4 m)), and they have been associated with the slender pillar remnants that have been left in worked-out areas after partial pillar recovery operations.
- *Bursts*, which are violent events that can affect a small portion of a single pillar or may destroy many pillars at once. While bursts (sometimes referred to as "bumps" or "bounces") have many causes, and not all of them can be eliminated by pillar design, the likelihood of large bursts affecting multiple pillars can be greatly reduced when properly sized pillars are used.

Like most pillar design methodologies, ARMPS consists of three basic steps:

- Estimate the load bearing capacity of the coal pillars.
- Estimate the applied loads, including any abutment loads.
- Compare the load to the capacity, and employ engineering criteria to determine whether the design is adequate. ARMPS assigns as "Stability Factor" (SF) based on the ratio of bearing capacity divided by applied load.

ARMPS employs relatively simple models of the pillar loads and load-bearing capacities. Over the years, most of the equations used in the ARMPS models have changed only slightly (one major exception is the "pressure arch" loading function that was added when Version 6 was released in 2010).

To calculate the strength of the pillars within the "Active Mining Zone" (AMZ; see Figure 1), ARMPS uses the Mark-Bieniawski formula (Mark and Chase, 1997). Each pillar's load bearing capacity is simply its strength multiplied by its load bearing area. A key assumption of the ARMPS model is that the pillars within the AMZ behave as a *system*, sharing load with one another. Failure occurs when the overall system is overloaded. ARMPS does not evaluate the stability of individual pillars.

To estimate the development loads, ARMPS starts with the "tributary area" approximation, which assumes that each pillar supports the rock directly above it, all the way to the surface. The "abutment angle" concept (Figure 2) is used to estimate the loads transferred to the pillars during the various stages of the pillar extraction process. Figure 3 shows the loads that are initially applied to the AMZ. For many shallow cover situations, where the depth of cover is less than the panel width, no further adjustment of the load is necessary.

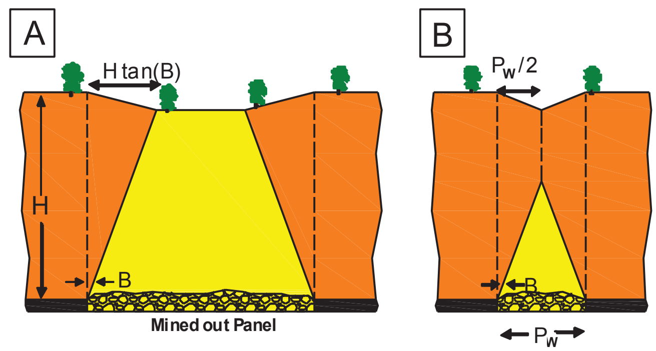

Figure 2. The "abutment angle" concept used to estimate loads in ARMPS. (A) Supercritical panel. (B) Subcritical panel.

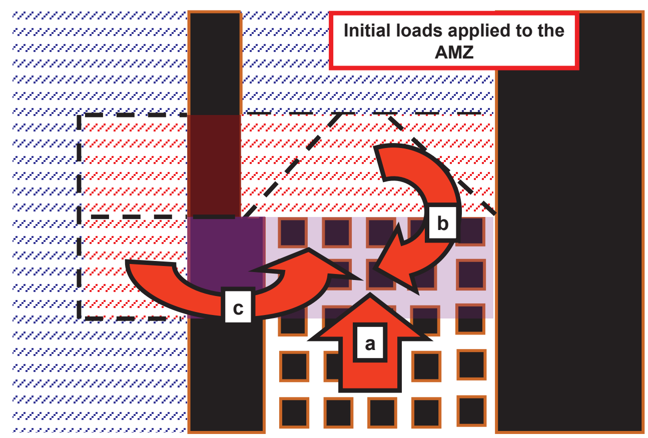

Figure 3. The initial loads applied to the Active Mining Zone (AMZ) by ARMPS are the development (tributary area) load (a), the front abutment load (b), and the side abutment load (c).

Where the panel width is less than depth of cover, however, a pressure arch may be formed. In this case, ARMPS shifts some of the load from the AMZ to the barrier pillars on either side (Figure 4A). The quantity of load that is shifted is calculated by multiplying the initial AMZ loads by the "pressure arch factor" (Fpa):

$$\mathrm{Fpa} = 1 - \left[0.28\left(\ln\left(\frac{H}{Pw}\right)\right)\right] \quad (1)$$

where H is the depth of cover and Pw is the panel width

$$\frac{H}{Pw} > 1.0$$

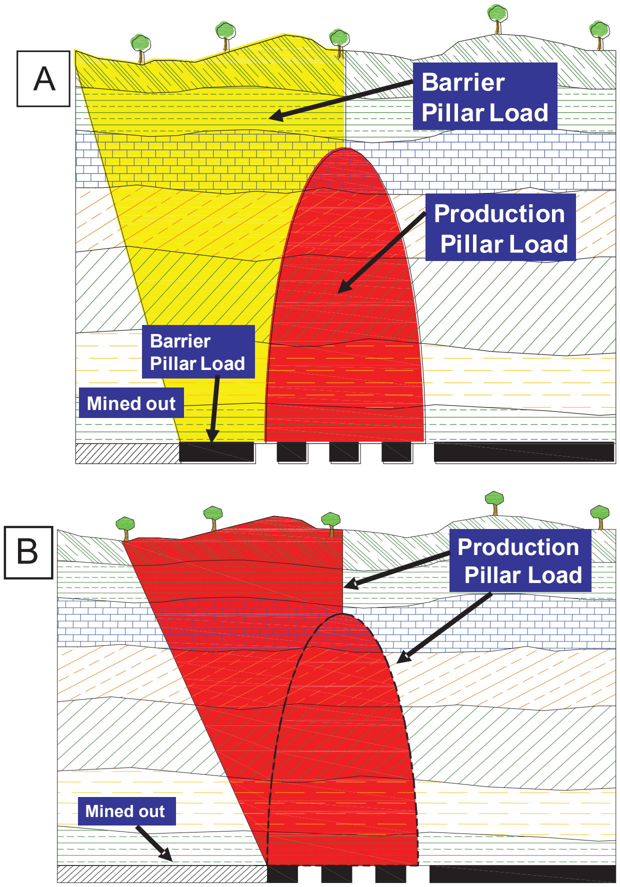

Figure 4. The pressure arch in ARMPS. (A) The initial pressure arch, showing the additional loads applied to the barrier pillars or solid coal. (B) The transfer of pressure arch loads back to the AMZ when the barrier pillar is not large enough to carry them.

ARMPS next checks if the barrier pillars are capable of carrying the entire load that has been assigned to them. If not, then some of the abutment and pressure arch loads may be shifted back to the AMZ (Figure 4B). This process begins with the inby remnant barrier pillars. If a slab cut has removed some of the inby remnant, or if the SF of the inby remnant is less than 1.5, then some excess loads are transferred to the outby barrier and/or the AMZ.

A very critical step is the evaluation of the outby, solid barrier pillar. The amount of load that is transferred depends upon the SF calculated for the barrier pillar (SF_{BAR}). There are three possibilities:

- If SF_{BAR} is greater than 1.5, then no load transfer occurs.
- If SF_{BAR} falls between 1.5 and 0.5, then a portion of the side abutment and pressure arch loads are transferred to the AMZ.
- If SF_{BAR} is less than 0.5, then the entire side abutment and pressure arch loads are transferred to the AMZ.

The maximum amount of load that can be transferred is the same as if the barrier was gob (in other words, equal to a full side abutment plus any pressure arch loads).

Finally, the SF for the AMZ is calculated by dividing the total load-bearing capacity of all the pillars within the AMZ by the total load applied to the AMZ.

The power of ARMPS is not derived from the accuracy of its calculations, but rather from the large database of retreat mining case histories that it has been calibrated against. The most important characteristic of each case history included in the database is the "outcome," which is that the design was either "successful" or "unsuccessful." A case history was considered "successful" only if no problems were reported and the mine map showed that all pillars were recovered as planned. If, on the other hand, the map showed that under deeper cover several rows of pillars were abandoned, then the knowledgeable mine officials were asked about the conditions encountered. If the description clearly implied a pillar failure had occurred, the case would be designated as "unsuccessful." If water, a steep dip (swag), too much rock in the coal, or some other non-ground control circumstance was responsible, then the case was not included in the database. More details on the data collection methods used to develop ARMPS have been provided elsewhere (Mark, 2010).

Figure 5 shows the ARMPS database and design criteria that were developed from the statistical analysis (Mark, 2010). The suggested design guidelines are shown in Tables 1 and 2. Figure 5 indicates that ARMPS does misclassify some pillar failure case histories (that is, it predicts success for some cases where the actual outcome was unsuccessful). All of these misclassifications were pillar squeezes; not the more hazardous collapses or multiple-pillar bursts. Still, the misclassifications are a reminder that pillar design remains an imperfect science, and much remains to be learned.

COMPOSITE BARRIER PILLARS

One of the most common non-standard ARMPS situations encountered by RCD occurs when one or more rows of intact pillars separates a worked out panel from a mains or submains. Typically the mains or submains either needs to be protected or will be retreat mined. In this situation, the "composite barrier pillar" usually consists of the intact pillars plus some portion of the unmined solid coal adjacent to the mains (Figures 6 and 7). Since the standard ARMPS model assumes that barrier pillars are solid strip pillars, a method is necessary to calculate the width of a strip pillar whose load-bearing capacity is "equivalent" to the actual composite barrier pillar system.

ARMPS determines the strength of the barrier pillars (S_{BAR}) using the Mark-Bieniawski pillar strength formula, assuming that the barrier's least dimension is W_{BAR}, the mining height is h, and that the barrier is a long strip pillar:

$$S_{BAR} = S1\left(0.64+\left(0.54\frac{W_{BAR}}{h}\right)\right) \tag{2}$$

where
h is the mining height
S1 is the "in situ coal strength" assigned as 900 psi

Table 1. ARMPS 2010 suggested design criteria.

Depth of cover, ft (m)	ARMPS SF	Barrier pillar SF
<650 (198)	1.5	No recommendation
>650 (198)	1.5	1.5

Table 2. Alternative ARMPS 2010 suggested design criteria when the panel width is less than 420 ft (128 m) and the barrier pillar SF is greater than 2.0.

Depth of cover, ft (m)	Panel width, ft (m)	ARMPS SF	Barrier pillar SF
650-1,000 (198-305)	<420 (128)	1.5-[0.20x((Depth-650)/350)]	2.0
>1,000 (305)	<420 (128)	1.30	2.0

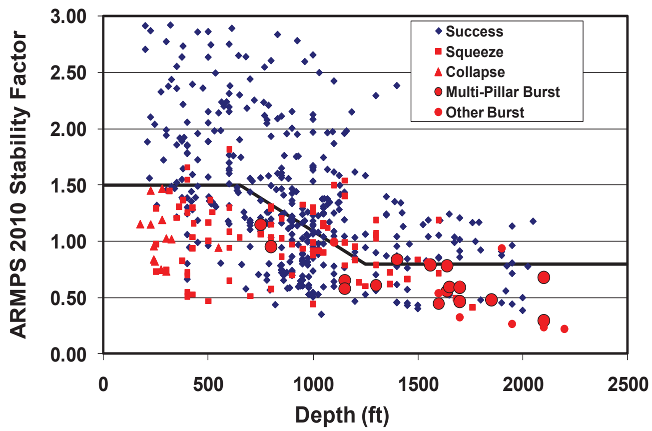

Figure 5. The ARMPS database, showing the Stability Factors (SF) calculated for each of the case histories, as well as the recommended design criteria.

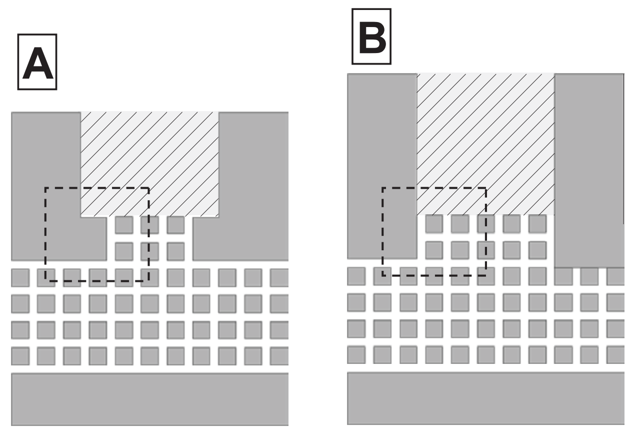

Figure 7. Typical mining geometries where a composite barrier analysis is helpful. (A) Panel mouth necked down (dotted line is area of close-up shown in Figure 8. A). (B) Panel mouth not necked down (dotted line is area of close-up shown in Figure 8. B).

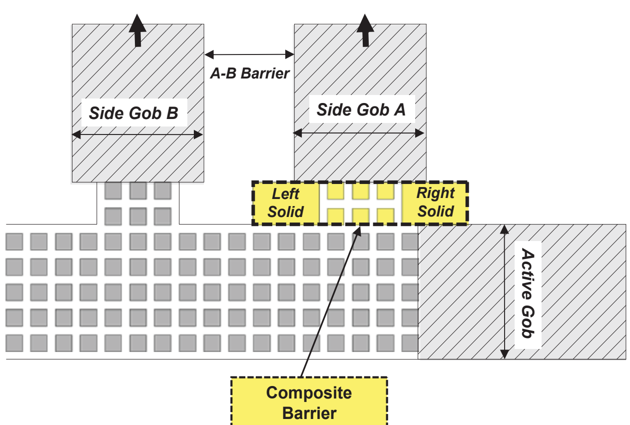

Figure 6. Overview of the composite barrier problem.

Since it can be shown that slab cuts have a negligible effect on the barrier pillar strength for most typical barrier pillar configurations, they are ignored in the barrier pillar strength calculation.

The load-bearing capacity of the barrier ($PLBC_{BAR}$) is then determined, assuming that relevant area of the barrier extends to the outby edge of the AMZ (see Figure 8a):

$$PLBC_{BAR} = (S_{BAR})\,(W_{BAR})\,(DepAMZ) \qquad (3)$$

where

DepAMZ is the distance from the pillar line to the outby edge of AMZ

$DepAMZ = 5\sqrt{H}$

H is the depth of cover

The evaluation of the composite barrier case begins by defining the lengths Ws, Ls, and L_b (see Figure 8a). The value of Lb is

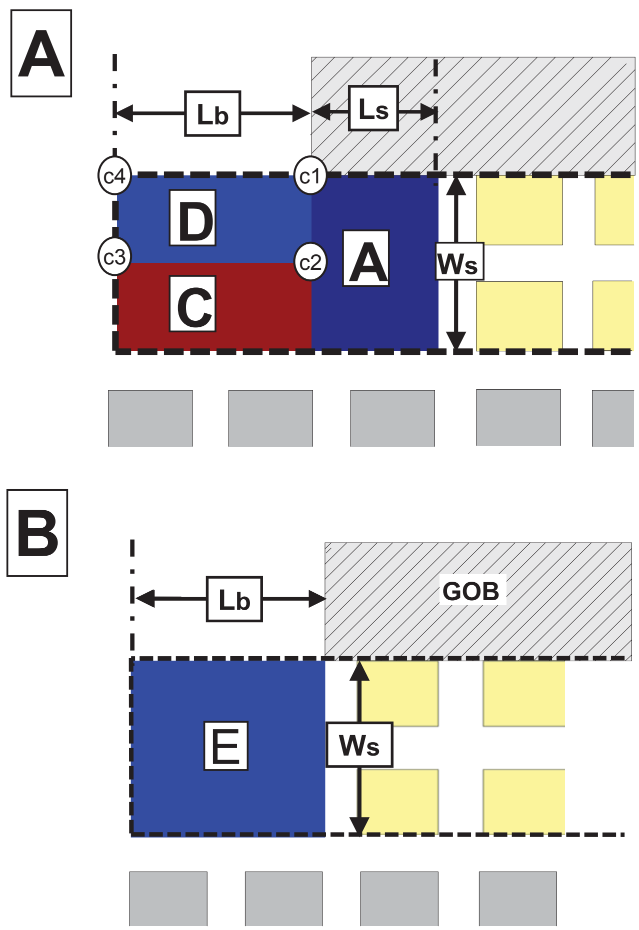

Figure 8. A close-up of the composite barrier, showing the different dimensions used in the derivation. (A) Case where the mouth of the panel is necked down. (B) Case where the mouth of the panel is not necked down.

assumed to be either DepAMZ or one-half the width of barrier pillar A-B, whichever is smaller.

The next step is to define the strengths and load-bearing capacities of the Areas A, C, and D shown on Figure 8a. Because Area A can be considered one-half of a rectangular pillar whose width (least dimension) is Ws and whose length is 2 *x* Ls,[1] its strength (S_A) is

$$S_A = S1\left[0.64 + \left(0.54\left(\frac{Ws}{h}\right)\right) - \left(\frac{Ws^2}{2(LS)(h)}\right)\right] \qquad (4)$$

Similarly, Area C can be considered a section of a half of a strip pillar whose length is Lb and whose width is Ws.

Area D does not lend itself to such a simple approximation. The "method of slices" (Mark and Zelanko, 2001) can be used to determine its strength, but this calculation can be cumbersome. A simple approximation is to use the Mark-Bieniawski pillar *stress* formula (Mark and Chase, 1997) to calculate the strengths of pillar elements located at the four corners of Area D:

- Corner 1: $Sc1 = 0.64\ (S1)$
- Corner 2 and Corner 3: $Sc2 = Sc3 = S1\left(0.64 + 2.16\left(\frac{Ws}{h}\right)\right)$
- Corner 4: Sc4 = the minimum of $S1\left(0.64 + 2.16\left(\frac{Ws}{h}\right)\right)$ or

$$S1\left(0.64 + 2.16\left(\frac{Lb}{h}\right)\right)$$

The strength of Area D is then taken as the average of Sc1, Sc2, Sc3, and Sc4. For most typical composite barrier pillar geometries, this approximation is within 10% of the strength obtained from the method of slices.

The load bearing capacities of the three areas (LBC_A, LBC_C, and LBC_D)] are then calculated by multiplying each area's strength by its load bearing area.

These calculations are then repeated for the solid portion of the composite barrier on the other side of the panel. If there is symmetry around the centerline of the panel, and both solid portions of the composite barrier are the same, then the load bearing capacity of the entire composite barrier ($PLBC_{BARComp}$) is:

$$PLBC_{BARComp} = 2(LBC_A + LBC_C + LBC_D) + Np(LBC_p) \qquad (5)$$

Where Np is the number of production pillars included in the composite barrier, and LBC_p is the load bearing capacity of each one.

Before $PLBC_{BARComp}$ can be substituted for $PLBC_{BAR}$ in Equation 3, it must be adjusted so that its length matches the length of the barrier pillar in ARMPS. The equivalent composite barrier pillar capacity, $PLBC_{BAREq,}$ is:

$$PLBC_{BAREq} = PLBC_{BARComp}\left(\frac{DepAMZ}{L_{BARComp}}\right) \qquad (6)$$

where $L_{BARComp}$ is the length of the entire composite barrier pillar as defined in Figure 6.

The final steps are to substitute Equation 2 for S_{BAR} in Equation 3, then substitute $PLBC_{BAREq}$ for $PLBC_{BAR}$ in Equation 3, and then rearrange Equation 3 so that the quadratic equation can be used to solve for the equivalent barrier pillar width W_{BAREq}:

$$0 = (S1)(0.54)\left(\frac{DepAMZ}{h}\right)(W_{BAREq})^2 + ((S1)(0.64)(DepAMZ))\,W_{BAREq} - PLBC_{BAREq} \qquad (7)$$

[1] Note that Equation 4 is only valid if Ws<2 x Ls.

The value of W_{BAREq} thus obtained can be input directly into the ARMPS program.

The solution derived above is appropriate when the panel has been "necked down" as shown in Figure 7a. When there is no neck and all of the panel entries extend into the submains (Figure 7b), then a slightly different approach is needed. This case is illustrated in Figure 8b. Area E can be considered as one-quarter of a rectangular pillar whose length is 2 *x* Ws, and whose width is either 2 *x* DepAMZ or the width of barrier pillar A-B, whichever is smaller. Its strength (S_E) is then:

$$S_E = S1\left[0.64 + \left(1.08\left(\frac{\text{DepAMZ}}{h}\right)\right) - \left(0.36\left(\frac{(\text{DepAMZ})^2}{\text{Ws h}}\right)\right)\right] \quad (8)$$

The load bearing capacity of area E, LBC_E, is calculated by multiplying the strength S_E by the load bearing area E. Assuming the same barrier width (A-B) on both sides of the panel, the load bearing capacity of the entire composite barrier ($PLBC_{BARComp}$) is:

$$PLBC_{BARComp} = 2\ (LBC_E) + (Np)\ (LBC_p) \quad (9)$$

The remainder of the solution for WBAREq is the same as the one employed previously.

It is important to keep in mind that the validity of the "composite barrier" approach outlined here depends upon the all the components of the "composite barrier" working together as a system. In particular, the mouth of the panel cannot be so wide that the pillars within the neck cannot shed some load onto the solid barriers on either side. The ARMPS pressure arch formula (Equation 1) can be use to place reasonable limits on the applicability of the approach.

LEAVE BLOCKS (BLEEDER PILLARS)

A new feature in ARMPS Version 6 (2010) is that the user may leave "bleeder pillars" next to the barrier pillars within the active panel and/or in the previously mined panel(s). Up to four rows of blocks may be left (see Figure 9). The dimensions of blocks left within the active panel (rows A and B) can be input directly in ARMPS. The width of the blocks left in the previous panel (rows C and D) can be input, but their length is assumed to be the same as that of the pillars in the active panel.

Leave blocks have several effects. The row A and B blocks that are within the active panel reduce the front abutment load because they reduce the width of the active gob. They also reduce the width of the AMZ for the active panel. [2] For example, if a panel is mined with 5 rows of 60-ft (18.3-m) pillars, and row A is left, the front gob width will be 240 ft (73.2 m). If there are no previous side gobs, the width of the AMZ will also be reduced to 240 ft (73.2 m).

The effect of the row C and D leave blocks in the previously extracted panels can increase the effective load-bearing capacity (LBC) of the barrier pillars. The model assumes that if the leave

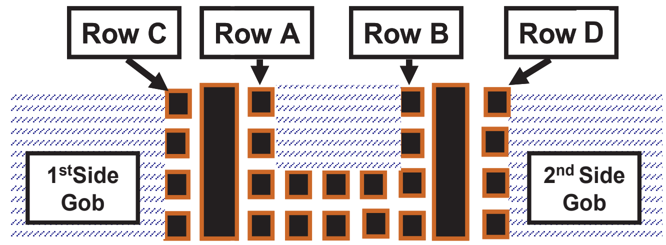

Figure 9. Leave blocks (bleeder pillars) in ARMPS.

pillars are large enough to carry the tributary area load that would be applied to them, then any "excess" load bearing capacity is added to the LBC of the barrier pillars.

One common situation is when there is not one, but two rows of blocks left adjacent to the barrier in the previous panel (Figure 10A). For example, if the previous panel was a longwall that used a three-entry gate system, then the two gate pillars would be left. In this case, it is possible to determine the "equivalent width" (w_{eq}) of a single pillar in row C or D that can replace the two actual rows of pillars.

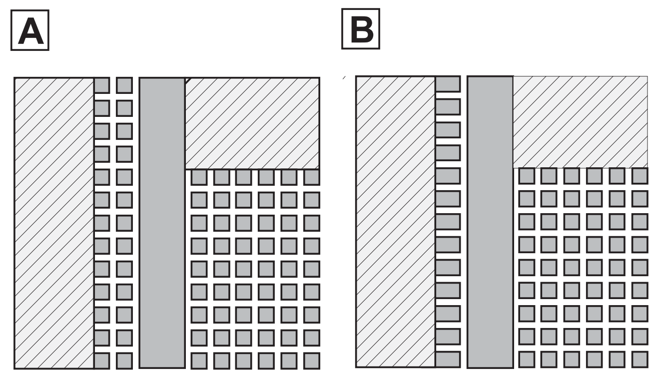

Figure 10. Substitution of a single row of leave blocks for two rows of pillars left in the gob. (A) Actual case with two pillars left in gob. (B) Equivalent single row of leave pillars.

The first step is to calculate the load bearing capacity of the two actual rows of pillars left in the previous panel (LBC_{actual})[3] using the Mark-Bieniawski formula and the actual load-bearing areas of the pillars. The load-bearing capacity of the equivalent pillar (LBC_{eq}) can be calculated as

$$LBC_{eq} = (W_{eq} L)\ S1\left[0.64 + \left(0.54\left(\frac{L}{h}\right)\right) - \frac{0.18L^2}{W_{eq} h}\right] \quad (10)$$

where

L is the length of the pillars

[2] If there is a side gob, the AMZ width is not reduced so that the side gob load is distributed over the full AMZ. In this situation, it is best to model the panel both with and without the side gob, and then use the ***minimum*** of the two SF obtained from the analyses.

[3] In this derivation, it is assumed that the length of the actual pillars in the previous panel (L) is the same as that in the active panel, and that L is less than the calculated equivalent pillar width (weq). Other solutions can be derived for different configurations.

After setting LBC_{eq} equal to LBC_{actual}, it is possible to solve for w_{eq}:

$$W_{eq} = \frac{\left[\frac{LBC_{actual}}{(S1)(L)}\right] + \left[0.18\left(\frac{L^2}{h}\right)\right]}{\left[0.64 + 0.54\left(\frac{L}{h}\right)\right]} \tag{11}$$

Another situation involving leave pillars occurs when they are partially extracted during retreat. Normally, it makes sense to treat partially extracted leave pillars as if they have been fully extracted, because the remnants normally have significantly less strength and load bearing capacity than the original blocks. However, if the original pillars are exceptionally large, and only a small portion is extracted, other approaches may be considered.

FLOOR MINING

Some room and pillar mines extract thick seams or, more commonly, two seams together with a parting. In these cases the total mining height (h_{tot}) can reach 15 ft (4.6 m). To minimize the miner's exposure to the high ribs, the preferred mining sequence is to extract only the top 8–10 ft (2.4–3 m) during development. The bottom portion of the seam is recovered by mining the floor when the pillars are recovered during retreat. This floor mining sequence has the additional advantage that smaller pillars can be used, because of the increased strength from the reduced width-to-height ratios for the intact pillars outby the pillar line. However, the mining height varies within the AMZ, because as each pillar is extracted it is necessary to ramp down from the upper seam area into the higher full seam area.

One approach for estimating the appropriate mining height for use in ARMPS is shown in Figure 11. If it is assumed that the ramps begin at the outby end of the last row of pillars and terminate at the inby end, then the average mining height within the AMZ (h_{avg}) is:

$$h_{avg} = \frac{\left[\left(\frac{h_{tot} + h_{dev}}{2}\right)L\right] + \left[(h_{dev})(DepAMZ - L)\right]}{DepAMZ} \tag{12}$$

where

h_{dev} is the mining height on development

L is the length of the pillars.

MULTIPLE SEAM INTERACTIONS

Today's pillar extraction operations are often conducted where previous mining has occurred in seams above or below the current mining. Evaluating the potential for multiple seam interactions is therefore an essential part of mine design. RCD uses the NIOSH empirical design method Analysis of Multiple Seam Stability (AMSS; Mark et al., 2007) for many of its evaluations.

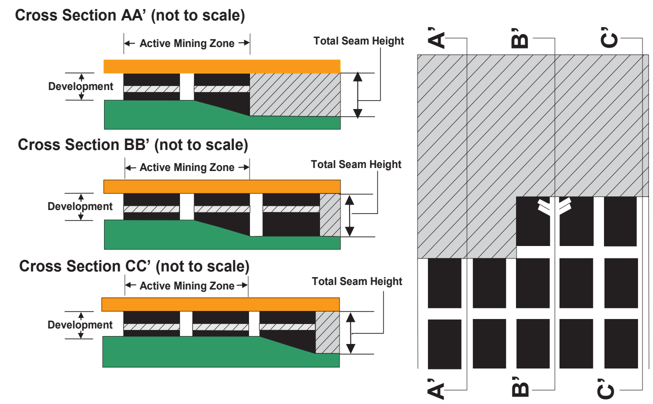

Figure 11. Determination of the average mining height when floor coal is extracted during retreat.

NIOSH developed AMSS after collecting more than 300 multiple seam case histories from 40 mines and then analyzing the database with the multivariate statistical technique of logistic regression. NIOSH found that many of the failed multiple seam cases involved pillars whose stability factors appeared inadequate when the additional multiple seam stresses were considered. Therefore, the first step in the AMSS procedure is to evaluate the pillar design. The AMSS computer program calculates the single seam ARMPS SF, and then it automatically runs a simple numerical model that provides the additional multiple seam stress. If the final, multiple seam stability factors appears inadequate, it can be improved by increasing the pillar width, increasing pillar length, or reducing the entry width.

Many other multiple seam interactions occurred even where the pillar SF was adequate. The intensity of these "pure" multiple seam interactions is not determined by pillar design, but rather depends upon the type of remnant structure in the previous seam, whether that previous seam was above or below the active mine, and the strength of the roof in the active mine, as well as on the total vertical stress. Based on the results of the statistical analysis, AMSS rates the likelihood of a multiple seam interaction as "green" (unlikely), "yellow" (likely unless a pattern of supplemental support is installed), or "red" (likely even with a pattern of supplemental support).

Since ARMPS is an integral part of AMSS, when NIOSH updated ARMPS it also modified AMSS. The new version of AMSS (version 2) calculates the single seam pillar SF using ARMPS version 6, and then uses the "pressure arch factor" to adjust the multiple seam loads in same way as the single seam loads. The final multiple seam SF calculated for the AMZ is then compared with the ARMPS version 6 suggested design criteria. This ensures that the AMSS pillar SF analysis is fully compatible with the standard ARMPS analysis.

However, in its evaluation of "pure" multiple seam interactions, AMSS version 2 does *not* use the pressure arch factor to calculate the total vertical stress. The explanation is that statistical analyses showed that applying the pressure arch factor to the case histories resulted in only slight changes to the relationships between the variables (in other words, it changed very few of the *predicted* outcomes of the case histories). But it did result in a new set of equations that would have required extensive changes to the program and might have needlessly confused the program's users. Therefore the determination of the "red-yellow-green" multiple seam interaction indicators for AMSS version 2 was left unchanged from that in version 1.

AMSS gives mine planners a tool that they can be use to evaluate multiple seam situations that cannot be addressed by a single seam ARMPS analysis. AMSS is limited to relatively simple multiple seam mining layouts, however. If a more detailed analysis is desired, or if the geometry is too complicated for AMSS, a numerical model (such as LaModel) may be an appropriate alternative (Heasley et al., 2010).

RETREAT PANEL ENTIRELY BENEATH LONGWALL PANEL GOB

One unusual situation analyzed by RCD involved a retreat panel that was to be mined entirely beneath a previously extracted longwall panel. It was believed that the result would be a "pressure arch within a pressure arch," with loads on both the barrier pillars and the production pillars reduced due to the stress relief zone provided by the longwall gob (Figure 12). Obviously ARMPS could not model this situation directly, and AMSS could not either because it only provides estimates of the stress *concentrations* at the edges of gob areas, not the stress relief beneath them.

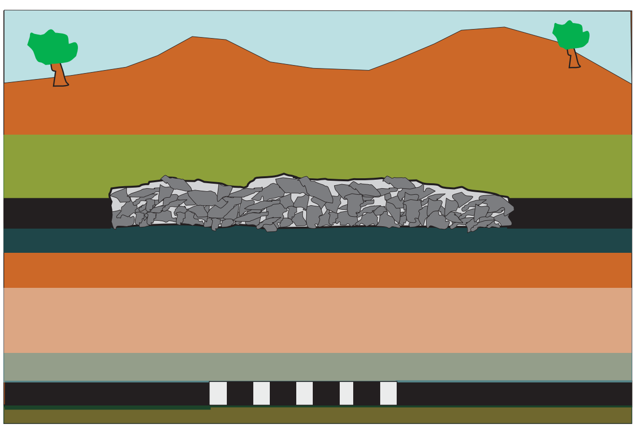

Figure 12. Pillars developed for retreat mining within the stress shadow provided by an overlying longwall.

The solution was to use an "adjusted depth of cover" as input to ARMPS that reflected the reduced load in the stress relief zone. Two LaM2D models (Heasley and Akingube, 2004) of the retreat panel were run, one with the overlying gob in place (the multi-seam case) and the other without (single seam). Then the average stress was determined in each case for the entire cross section, including the barrier pillars. Finally, the ratio of the multi-seam to the single seam average stress was calculated. In the actual case, the ratio was about 0.9. The depth of cover entered into ARMPS was therefore reduced by 10% to account for the stress relief. It should be noted that by using a *ratio* of the two LaM2D analyses, rather than directly entering the average LaM2D multiple seam stress into ARMPS, it was not necessary to ensure that the LaM2D stresses are quantitatively comparable with the ARMPS stresses.

Of course, the stress relief only occurred in the pillars located beneath the gob. A stress concentration did occur where the access entries crossed the longwall stop line. The pillars within the stop line crossing zone were evaluated using standard AMSS procedures.

SLAB CUTS

During retreat mining operations, slabs cuts are often taken from the barrier(s) or solid coal to increase the production and recovery ratio (Figure 1). The ARMPS program can model slab cuts, and they have a number of effects. First, they reduce the width, strength, and load-bearing capacity of the inby (remnant) barrier pillar. Second, they increase the effective panel width, which causes additional front abutment load to be transferred to the AMZ (modified by the pressure arch factor). Finally, they cause some portion of the front abutment load to be applied to the outby barrier pillar.

In ARMPS, the slab cut depth is entered into the program in the same portion of the input menu as the barrier pillar width. If the slab cut is to be taken from solid coal, the only way to model it is by "tricking" the program by entering an imaginary, 1,000-ft (304.8-m) -wide barrier pillar. However, this approach is considered unnecessarily conservative. Numerical model results presented by Tulu et al. (2010) indicated that when ARMPS models a slab cut, it transfers approximately twice as much load to the AMZ as LaModel does. The LaModel results show that when there is no nearby gob, the solid coal is generally strong and stiff enough to absorb most of the load that is transferred when the slab cut is made. It therefore seems that slab cuts should only be modeled in ARMPS when a previously mined gob is adjacent to the barrier pillar.

MINING HEIGHT

The mining height is a key ARMPS input parameter, because it has a large effect on the pillar strength. Today, many mines extract in-seam and/or roof rock with the coal. In some cases, it is justified to adjust the mining height to account for the rock. The basic guideline is that when the strength of the rock is approximately the same as the coal, then the full mined height should be entered. Where some of the rock is significantly stronger than coal, some reduction in the mined height may be justified.

Much of the rock that is mined with the coal is weak claystone, including most in-seam rock, most floor rock, most draw rock associated with a rider seam, and other draw rock that falls when the coal is mined. The exception is usually competent roof rock that is mined solely for equipment clearance. The thickness of such competent "cap rock" can be reduced by 50% in the entry height calculation. In other words, if 12 in (30.5 cm) of competent cap rock is mined, only 6 in (15.2 cm) should be added to the seam thickness to obtain the entry height.

A special case might be a thick parting that includes some strong rock. In that case, the strong portion of the parting could be subject to the "50% rule" described above. A geologist or ground control professional should help determine how much of the parting is actually competent rock. A thorough evaluation of such a parting would include a geotechnical description, a geologic section, unconfined compressive strength (UCS) or point load tests, and moisture sensitivity tests. Photographs showing the in situ structure of the rock parting are also helpful. The sampling and testing process of any specimens sent to the lab should also be thoroughly documented with photographs.

CONCLUSIONS

The ARMPS program continues to be a valuable tool for developing successful roof control plans. The solutions presented in this paper are just a few of the ways in which ARMPS can be adapted to non-standard situations. MSHA looks forward to working with our stakeholders to continue to expand the mine design capability of ARMPS.

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