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A Comparison of the Overburden Loading in ARMPS and LaModel

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ABSTRACT

The Analysis of Retreat Mining Pillar Stability (ARMPS) and the LaModel programs have been used successfully in the U.S. for designing safe pillar recovery operations for many years. However, the recent Crandall Canyon Mine collapse showed that further research is required to improve the pillar design for recovery under deep cover. To this end, the National Institute for Occupational Safety and Health (NIOSH) and the West Virginia University (WVU) Mining Engineering Department have been working together to improve both the ARMPS and the LaModel programs.

This paper compares and analyzes the overburden loads calculated by ARMPS 2002, the new ARMPS 2010, and the LaModel program with regard to the retreat pillar line, the gob, and the barrier pillars. The analysis shows a number of distinct differences between the ARMPS and LaModel loading distributions. Ultimately, the programs, with their distinctive load distributions, are used to analyze a database of 52 deep cover pillar retreat case studies, and the ability of each program to discriminate between successful and unsuccessful retreat pillar plans is evaluated.

INTRODUCTION

The Analysis of Retreat Mining Pillar Stability (ARMPS) and the LaModel programs have been used successfully in the U.S. for designing safe pillar recovery operations for many years. However, the recent Crandall Canyon Mine collapse showed that further research is required to improve the pillar design for recovery under deep cover.

Pillar recovery accounts for less than 10% of the coal produced from underground coal mines; however, in the period between 1989 and 1996, it accounted for more than 25% of all ground fatalities (Mark et al., 2003). In the past 15 years, the safety of retreat mining operations has greatly improved. Mark (2009) explains three steps promoted by MSHA and NIOSH for safer pillar recovery:

- 1) Global stability through proper pillar design
- 2) Local stability through proper roof support
- 3) Worker safety through proper section management

The ARMPS and LaModel (Heasley, 1998) programs have been playing an important role in guiding mine operators in designing pillars to ensure the global stability of a retreat panel.

The ARMPS Program

Researchers from NIOSH developed the original ARMPS program in the mid-1990s (Mark and Chase, 1997). The original program uses the tributary area method to estimate the development loads on the "Active Mining Zone" (AMZ), and the "abutment angle" concept is used to estimate the loads transferred to the pillars during pillar extraction (see Figure 1). Then, the program calculates the strength of the pillars using the Mark-Bieniawski formula. Ultimately, the "Stability Factor" (SF) of the AMZ is calculated by dividing the load bearing capacity of the AMZ by the total estimated load applied to the AMZ (Mark, 2009). The loading assumptions used in the ARMPS program mirror those from the Analysis of Longwall Pillar Stability (ALPS) program, which was previously developed for longwall pillar design (Mark, 1992).

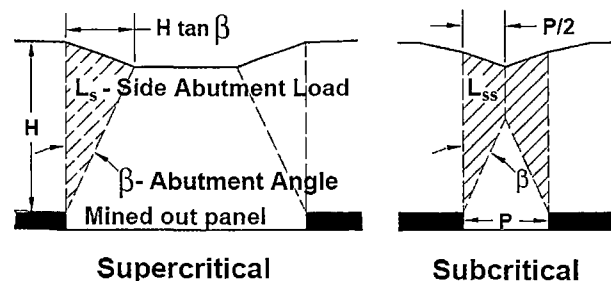


Figure 1. Abutment angle concept (Mark, 1992).

Mark (2009, 2010) states that the strength of the ARMPS program does not come from the accuracy of its load calculations, but rather, its strength comes from the large database from which ARMPS is calibrated. The original version of ARMPS (Mark and Chase, 1997) was calibrated with a database of 150 cases, and a stability factor of 1.5 was suggested when designing retreat panel

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pillars. However, it was also found that the ARMPS SF became less meaningful when the depth of cover exceeded 228 m (750 ft) and that there was a need for further research on pillar design for retreat mining under deep cover.

In 1997, NIOSH investigators initiated new research on deep cover pillar retreat by specifically collecting new data from deep cover mines. The goal of this research was to develop appropriate criteria for applying ARMPS to design pillars for deep cover pillar retreat panels (Chase et al., 2002). The result of this deep cover initiative was the ARMPS 2002, which was developed from 250 case histories. According to the ARMPS 2002 guidelines, a stability factor of 1.5 is satisfactory for the pillar retreat cases where the depth of cover is less than 198 m (650 ft). Between a depth of 198 and 381 m (650 and 1,250 ft), there is a linearly decreasing trend in the stability factor, and below a depth of 381 m (1,250 ft), a SF of 0.9 (0.8 for strong roof) is recommended (see Figure 2, Table 1).

Table 1. Recommended ARMPS Stability Factors (Chase et al., 2002).

| | Depth (H) | Weak and Intermediate Strength Roof | Strong Roof |
|-------------------|-------------------------|-------------------------------------|----------------------|
| ARMPS SF | H < 650 ft | 1.5 | 1.5 |
| | 650 ft ≤ H ≤ 1,250 ft | 1.5 - [H-650] / 1000 | 1.4 - [H-650] / 1000 |
| | 1,250 ft ≤ H ≤ 2,000 ft | 0.9 | 0.8 |
| Barrier Pillar SF | H > 1,000 ft | ≥ 2.0 | ≥ 1.5* (≥ 2.0**) |
| | H < 1,000 ft | No Recommendation | |

*Non-burst-prone ground

**Burst-prone ground

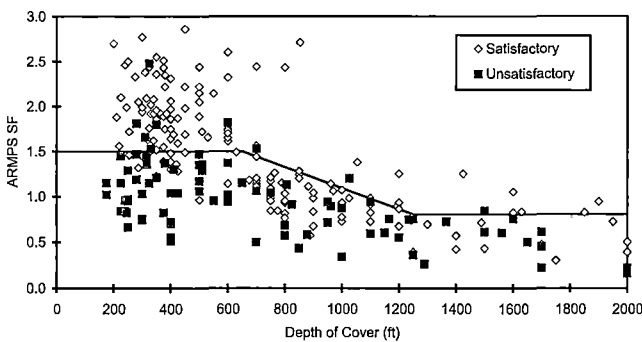


Figure 2. Recommended ARMPS SF from the 2002 deep cover study (Chase et al., 2002).

A significant outcome of this deep cover research was the realization of the significance of sufficiently strong barrier pillars. Out of 57 deep cover case histories, only one failure occurred when the SF was ≥ 0.8 and the barrier pillar stability factor was ≥ 2.0. Conversely, out of 30 case histories that had a SF < 0.8 and a

barrier pillar SF < 2.0, 60% were failures. This research did show that lower stability factors may be successful with deeper cover. Two possible explanations for this result were discussed:

- 1) The actual strength of the large pillars at depth might be higher than predicted by the Mark-Bieniawski formula
- 2) The pillar loads as predicted by ARMPS are higher than the actual pillar loads

It seemed most reasonable that ARMPS was over estimating the actual pillar loads. Heasley (2000) indicated that pillar loading was as important as pillar strength in panel design and there has not been enough research in this area. In his paper, he questioned the accuracy of the empirical abutment angle concept under deep cover by using elastic and laminated overburden models, and he concluded that ARMPS possibly over predicts the abutment load in the deep cover cases. Similar results were observed by Colwell et al. (1999), where they back calculated the abutment angle from the field measurements collected from Australian coal mines. In these measurements, they found that the abutment loading and therefore the abutment angle of the deep mines was considerably less than the default 21° abutment angle used in ARMPS.

ARMPS 2010

After the Crandall Canyon mine disaster, NIOSH started new research to improve the safety of retreat room and pillar mining under deep cover by further enhancing the ARMPS program (Mark, 2010). At the beginning of the research, 200 new case histories (primarily deep cover) from 35 different mines were added to the ARMPS database (Mark, 2010). Then, to reduce the overburden loads on the production pillars as estimated by ARMPS, a pressure arch concept was investigated. Initially, three different pressure arch loading functions (linear, elliptic, and logarithmic) with various parameters were analyzed. Ultimately, the pressure arch equation that allowed a constant stability factor with depth and which provided the optimum separation between the successful and unsuccessful cases in the database was the logarithmic function:

$$F_{pa} = 1 - \left(0.28 * \ln \left(\frac{H}{P_w} \right) \right) \quad (1)$$

where:

F_{pa} = the pressure arch factor

H = overburden depth

P_w = panel width

(This formula only applies when the overburden depth of cover is greater than the panel width plus 24 m (80 ft.))

The new version of ARMPS, which implements the pressure arch loading, is called ARMPS 2010. The new overburden loading algorithm takes the tributary area loading on the active mining zone (AMZ) and reduces it by the pressure arch factor shown above. The extra AMZ loads are then transferred to the barrier pillars. If the barrier pillars are too small to carry all of the applied loads,

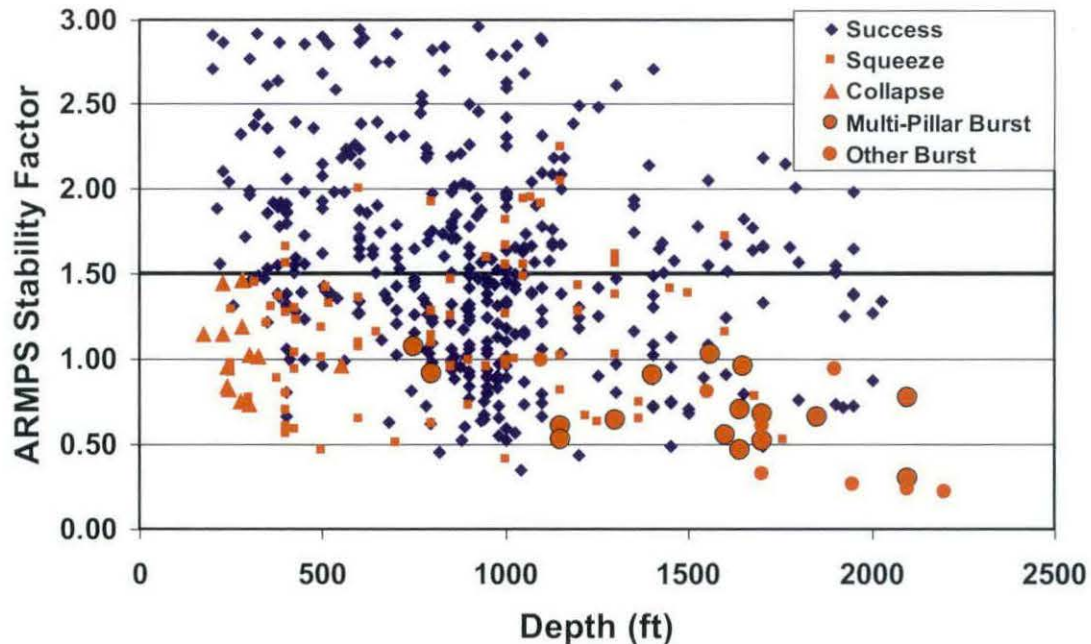


Figure 3. Recommended ARMPS SF from the 2010 deep cover study (Mark, 2010).

then the pressure arch loads are transferred back to the AMZ. With the addition of this new loading algorithm, the previous depth effect seen in ARMPS 2002 was eliminated (see Figure 3).

The LaModel Program

The LaModel program was originally developed in 1993. It is a boundary element program that simulates a laminated overburden as a stack of frictionless plates (Heasley, 1998). Within the seam, the different coal and gob areas are represented by elements with various stress-strain behaviors. Using the stiffness behavior of the seam elements and the prescribed flexure of the overburden, the LaModel program can calculate the displacements and loads throughout the modeled area of the seam.

Recently, a calibration method has been developed for the LaModel program which essentially attempts to duplicate the abutment loading, gob loading, and pillar strength used in ARMPS 2002 (Heasley, 2010). Essentially, the calibration method does the following:

- 1) Adjusts the lamination thickness in LaModel to match the abutment extent used in ARMPS
- 2) Adjusts the gob modulus to match the magnitude of the gob/abutment loading (in two dimensions) used in ARMPS
- 3) Adjusts the coal properties to produce pillars with a Mark-Bieniawski strength as used in ARMPS

Using this calibration method, the first approximation of the overburden loads are calibrated to mirror the ARMPS 2002 program; however, the flexure of the laminated overburden and the relative stiffness/strength of the seam elements still determine the ultimate distribution of the overburden loads.

DEEP COVER CASE HISTORY DATABASE

As part of the research to improve the ARMPS and LaModel programs, a database of deep cover retreat mining case studies was developed (Heasley, 2010). In the database there are 52 deep cover pillar retreat case studies from 11 different mines. Seven of these mines were in the Central Appalachian coal fields and 4 were in the western coal fields. (These are presently the only areas in the United States where deep cover pillar retreat is being performed.) The depths at the case study sites ranged from 228 to 671 m (750 to 2,200 ft), with an average of 383 m (1,256 ft). The extraction thicknesses at the case study sites went from a low of 1.1 m (3.6 ft) to a high of 2.7 m (9.0 ft), with an average of 2.1 m (6.9 ft). (This is probably higher than the average seam thicknesses in the given mining areas, but for deep cover pillaring to be economically successful, a thicker coal is very helpful.) The number of entries in the sections ranged from 3 to 13, with an average of 6.2 entries. Pillar widths ranged from 15-30 m (50-100 ft) and crosscuts spacing ranged from 24-46 m (80-150 ft) (center-center), with the average pillar size being 24 x 31 m (78 x 101 ft). The panel widths ranged from 49 to 287 m (160 to 940 ft), with an average of 125 m (410 ft).

Thirty-five of the case studies included loading from a single side gob, while fourteen of the panels only had an active gob, two of the sections had loading from two side gobs and one situation was development loading. Sixteen of the case study sites were considered failures, 31 were considered successful, and 5 were considered marginal, or middling. NIOSH personnel made the determination of success or failure during their visit to the mine and conversations with the mine staff. A case study is considered a success when an entire panel was recovered without any significant ground incidents (Mark, 2009). Generally, the unsuccessful cases include squeezes, collapses, and bumps (Mark, 2009). The

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database analysis does not specifically consider the geology, the cut sequence, the specific coal strength, or the type and amount of roof support.

OVERBURDEN LOAD ANALYSIS

In order to investigate the functional differences between the loading mechanisms in the ARMPS 2002, ARMPS 2010, and LaModel programs, a detailed analysis of the magnitude of the overburden loads from each of the three programs on different areas associated with the retreat panel and at different stages during the retreat mining cycle was performed. For this analysis, the different areas were defined as follows:

- 1) The active mining zone
- 2) The active gob
- 3) The outby barrier pillar
- 4) The inby barrier pillar
- 5) The outby side gob
- 6) The inby side gob
- 7) The outby adjacent panel
- 8) The inby adjacent panel

The locations and dimensions of these areas are shown in Figure 4. Load analysis was performed at 4 different mining stages:

- 1) Development loading
- 2) Development and first side gob loading
- 3) Development, first side and active gob loading
- 4) Development, first side, active gob and the slab cut loading

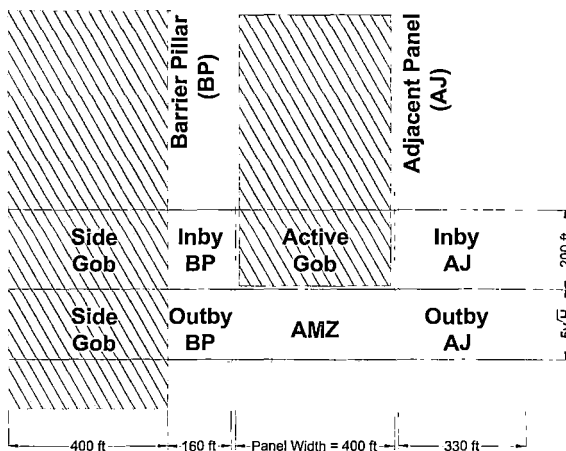


Figure 4. Different areas of the retreat panel where load is calculated.

In some of the detailed loading analyses, the case history database was used. In these instances, the pillar plan, seam thickness, seam depth, and adjacent mining conditions used for ARMPS and LaModel analyses were taken from the specific case history. To be consistent with the ARMPS analysis, an “idealized” LaModel geometry was used: the LaModel analyses had the exact same mine geometry, seam thickness, and overburden depth as the corresponding ARMPS analyses. Also, for these LaModel analyses,

the lamination thickness, gob stiffness, and coal strength were calibrated as recommended by Heasley (2009).

Average Model

For further loading analysis and for more accurate comparison of the loading distribution between the three different programs, a pillar retreat section with average dimensions from the database of 52 case histories was used. This “average” model had 2-6 m (6- 20 ft) wide entries with pillars on 24 x 30 m (80 x 100 ft) centers. The seam was 2.1 m (6.9 ft) thick and 384 m (1,260 ft) deep. The barrier pillar between the active section and the first side gob was 49 m (160 ft) wide (center-to-center), the side gob was 122 m (400 ft) wide (center-to-center), and the slab cut was 12 m (40 ft) deep (see Figure 4). These geometric parameters were input into the ARMPS analyses along with the default parameters. For the “average” LaModel analyses, the exact same mine geometry, seam thickness, and overburden depth as the corresponding ARMPS analyses was used, and the material input parameters were calibrated as recommended.

Development Loading

ARMPS 2002 calculates the development load based on the tributary area theory. For shallow depths (low depth/width ratios), the tributary area theory appears to provide a satisfactory estimate of the development load (Mark, 1992). However, the validity of the tributary area theory for estimating the development load under deep cover and narrow panel is questionable (Mark, 2009). In ARMPS 2010, in order to address the inadequacies of the tributary area approach, the pressure arch factor (Equation 1) is used to shed some development load from the production pillars to the barrier pillars for instances where the depth/width ratio is greater than one. In LaModel, the development load is determined by the bending stiffness of the laminated overburden and the relative stiffness (and failure strength) of the section and barrier pillars.

Figure 5 shows a comparison of the development loads calculated by each of the 3 programs for seven case histories from the deep cover database (with a selected range of depth/width ratios). In the figure, the vertical axis shows the magnitude of the development load on the AMZ as a percentage of the virgin in situ load, and the horizontal axis shows the panel depth/width ratios. It can be seen in Figure 5 that the development loads calculated by ARMPS 2002 (the green line) are exactly equal to the virgin in situ load and this 100% ratio stays constant with increasing depth/width ratio. In contrast, the development loads calculated by ARMPS 2010 are seen to decrease as the depth/width ratio increases above 1.0, a direct result of the applied pressure arch factor. Similarly, the development loads calculated by LaModel decrease as the depth/width ratio increases above 1.0, assumedly a result of more load shedding from the production pillars to the barrier pillars as the panel depth/width ratio increases. The amount of load shed from the AMZ with LaModel is roughly half of that seen with ARMPS 2010 for panel depth/width ratios greater than 1. (It should be noted that the LaModel results show some “random” variation as a result of different seam thicknesses and pillar dimensions in the chosen case histories, which affect the relative stiffness between the production pillars, barrier pillars, and the roof; and therefore affect the exact amount of load shedding.)

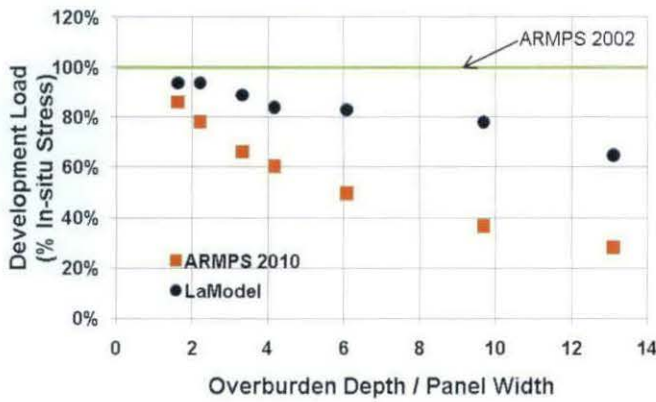


Figure 5. Development load calculated by ARMPS2002, ARMPS2010, and LaModel.

It can be concluded from Figure 5 that when the panel depth/width ratio is relatively small (< 2), ARMPS 2002, ARMPS 2010 and LaModel calculate similar development loads. However, when the panel depth/width ratio is large (> 2), the calculated development loads diverge quickly, with ARMPS 2002 staying constant and ARMPS 2010 shedding roughly twice as much load as the calibrated LaModel analyses.

In order to investigate where the overburden loads were being distributed by the three different programs, the “average” model (depth/width ratio of 3.15) was analyzed with each of the programs. In the case of development loading (see Figure 6), the percentage of in situ overburden load is calculated for the AMZ, outby barrier pillar, outby side gob, and outby adjacent panel. For this average scenario with development loading, it can be seen that ARMPS 2002 distributes the 100% of the total overburden load on each of the four areas. However, ARMPS 2010 distributed 68% of the in situ load on the development pillars and the remaining load is carried by the surrounding solid coal. Similarly, but to a lesser degree, LaModel distributes 94% of the in situ load on the development pillars, and the remaining load is carried by the surrounding solid coal.

| | Side Gob | Barrier Pillar | Development Panel | Adjacent Panel |
|------------|----------|----------------|-------------------|----------------|
| ARMPS 2002 | 100% | 100% | 100% | 100% |
| ARMPS 2010 | 100% | 146% | 68% | 123% |
| LaModel | 101% | 117% | 94% | 109% |

Figure 6. Overburden loads on the development panel.

Side Abutment Loading

Typically, a retreat mining panel has a previously mined panel (side gob) adjacent to it with a barrier pillar in between. In this layout, overburden load from the side gob is distributed between the side gob, the barrier pillar and the production pillars. ARMPS (2002 and 2010) predict the magnitude of the side abutment load/gob loading by using the abutment angle concept (see Figure 1), typically with the default 21° abutment angle. The distribution of the abutment stress (σ_a) within the abutment zone is then determined with this formula (Mark, 1992):

$$\sigma_a(x) = \left(\frac{3L_s}{D^3} \right) (D-x)^2 \quad (2)$$

where:

L_s = the total side abutment load (determined from the abutment angle concept)

D = the extent of the abutment zone (in ft)

x = the distance from the panel rib

and where the extent of the abutment zone is determined as (Peng, 2006)

$$D = 9.3\sqrt{H} \quad (3)$$

If the width of the barrier pillar in ARMPS is less than the extent of the side abutment zone, then some of the side abutment load will override to the active panel. In addition, if the barrier pillar yields, then ARMPS will shed additional load to the active panel.

In the calibrated LaModel, the magnitude of the side abutment load/gob loading is essentially determined using the abutment angle concept with the default 21° abutment angle, and the extent of the abutment stress is calibrated to essentially match Equation 3. Specifically, in the calibration process, the gob modulus in LaModel—for an idealized two dimensional gob with solid coal ribs—is determined such that the gob and abutment loading magnitudes exactly match those determined using the abutment angle concept. For calibrating the abutment extent, the lamination thickness is calibrated to provide 90% of the abutment load within exactly the same distance as 90% of the abutment load is distributed by equation 2; however, the distribution of the abutment stress between ARMPS and LaModel is somewhat different (Heasley, 2010).

In order to investigate the overburden loads calculated by ARMPS 2002, ARMPS 2010, and LaModel when there is a side gob adjacent to the development panel, the “average” model was again analyzed with each of the programs. Figure 7 shows the results of this analysis. By comparing Figures 6 and 7, it can be seen that when the adjacent panel is extracted all three programs exhibit the following results:

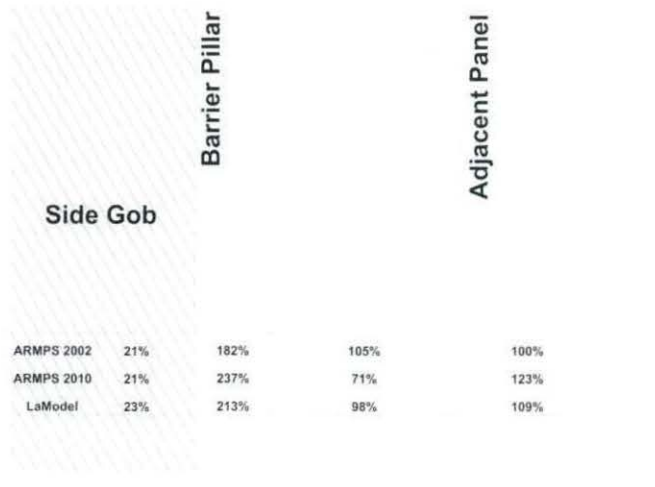


Figure 7. Overburden loads on the active panel with a side gob.

- 1) They have about the same amount of load on the side gob (21-23%).
- 2) They transfer the majority of the abutment load to the barrier pillar (95-97%).

They transfer some minor loading to the AMZ (3-5%) The gob loading between ARMPS and LaModel matches fairly well since the side gob loading is essentially two dimensional, and the LaModel gob loading is calibrated to the two dimensional abutment angle concept as used in ARMPS. In regard to the abutment loading, for this average model, the barrier pillar is very stable and the abutment load transferred to the AMZ is solely a result of the abutment stress overriding the barrier pillar. (From Equation 3, the abutment extent can be calculated as 101 m (330 ft) while the abutment pillar is only 49 m (160 ft) wide.) The difference in load transfer to the AMZ between the ARMPS programs (5%, 3%) and the LaModel program (4%) is simply a result of the slight difference in the shapes of the curves that each program uses to represent the abutment loading (Heasley, 2010). The difference in load transfer to the AMZ (and to the barrier pillar) between ARMPS 2002 and ARMPS 2010 is due to the application of the pressure arch factor in ARMPS 2010. Initially, both ARMPS programs calculate an identical 5% increase in the AMZ loading as a result of overriding side abutment load; however, ARMPS 2010 then applies a pressure arch factor equal to 0.68 ($H/P = 3.15$, Equation 1) to the 5% reducing it to 3.4% rounded to 3%. The load shed from the AMZ due to the pressure arch factor in ARMPS 2010 is then applied to the barrier pillar.

Barrier Pillars

To understand the differences in overburden load distribution between the ARMPS 2002, ARMPS 2010, and LaModel programs, it is important to understand the barrier pillar calculations. The three different programs calculate the outby barrier pillar strength and loading in very different ways. LaModel and ARMPS 2010 essentially determine the peak barrier pillar strength using the Mark-Bieniawski strip pillar formula. In contrast, ARMPS 2002 calculates the peak strength of the barrier pillar using the Mark-Bieniawski formula with an assumed pillar length equal to the

breadth of the AMZ. This essentially means that the barrier pillars in ARMPS 2002 are generally weaker than the equivalent barrier pillars in ARMPS 2010 or LaModel. The strength of the barrier pillars in ARMPS 2002 decreases with decreasing overburden depth (due to a decrease in the AMZ breadth, which decreases their assumed length), while the strength of the barrier pillars in ARMPS 2010 and LaModel is constant with depth (see Figure 8).

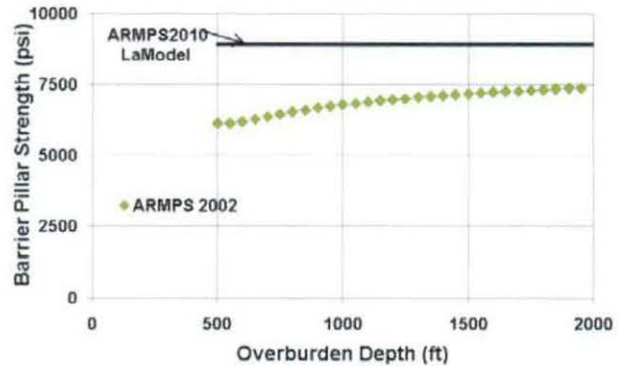


Figure 8. Strength of barrier pillars.

The loading and load shedding of the barrier pillars is also calculated very different among the programs (Mark, 2010). In ARMPS 2002, the outby barrier pillars are primarily loaded by 1) tributary area development load, 2) side abutment load, and possibly some 3) front abutment load from slab cuts. The inby barrier pillars are loaded by 1) tributary area development load, 2) side abutment load, and 3) front abutment load from the active gob. In ARMPS 2010, the outby barrier pillar also carries the loads transferred to it from the AMZ as a result of the pressure arch factor, and the outby barrier pillar may carry loads transferred from the inby remnant barrier pillar if the inby pillar yields (Mark, 2010).

In ARMPS, the outby barrier pillar starts shedding side abutment load (and pressure arch load for ARMPS 2010) to the AMZ when the stability factor is < 1.5 . This load is shed as a linear function of the stability factor until all of the side abutment load (and pressure arch load for ARMPS 2010) has been shed at a stability factor of 0.5. If the barrier pillar stability factor is below 0.5, the barrier pillar acts like a gob and distributes a full side abutment load on the AMZ. It is important to note that none of the load that was on a failing barrier pillar in ARMPS is ever transferred back to the surrounding gobs.

In LaModel, the barrier pillars are (presently) modeled with elastic, perfectly plastic elements. This means that once the barrier pillar reaches peak strength at a safety factor of 1.0, it will maintain that load as the elements continue to strain/yield with a plastic modulus of zero. This means that the LaModel barrier pillars never shed any load as the safety factor drops below 1.0. However, as the barrier pillar continues with post-failure strain, any additional overburden load that might have been applied to the pillar will be redistributed to the surrounding area, including both the AMZ and the side gob.

The practical result of the difference in calculating the barrier pillar strength and loading between the three programs can be seen

in Figure 9. To produce this figure, the width of the barrier pillar was varied in the “average” model for the case of side abutment loading only. The figure shows the amount of load transferred to the AMZ as a function of the outby barrier pillar stability factor for the three programs. When the barrier pillar’s stability factor and width are large, very little load is transferred to the AMZ for any of the programs. As the barrier pillar stability factor decreases, the load transferred to the AMZ increases. Initially, when the stability factor of the barrier is still greater than 1.5, ARMPS 2002 has the largest amount of side abutment override, because any override load transferred by ARMPS 2010 is reduced by the pressure arch factor, and because the side abutment distribution in LaModel has much less of a tail than in ARMPS (see Hoesly, 2010).

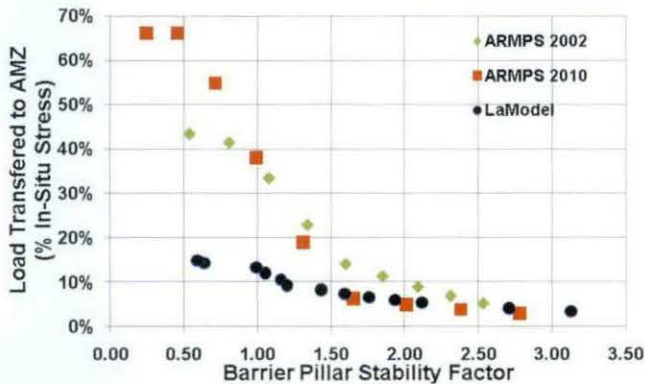


Figure 9. Overburden loads transferred to the AMZ.

As the width of the barrier pillar decreases and the barrier pillar stability factor drops below 1.5, both ARMPS 2002 and 2010 start to transfer considerably more load to the AMZ. At this point, ARMPS 2010 is transferring the most load because in addition to the side abutment loading in ARMPS 2002, it also has the additional pressure arch loading to transfer back to the AMZ. However, it should be remembered that ARMPS 2010 had by far the lowest initial loading on the AMZ (see Figure 6) due to the pressure arch factor. At the lower barrier stability factors, the LaModel program does transfer additional load to the AMZ, but considerably less than either ARMPS 2002 or 2010. This is partly due to the fact that the elastic-plastic pillars do not shed load after failure and partly due to the fact that any load transferred from the LaModel barrier pillars goes to all of the surrounding areas (as a function of stiffness), not just to the AMZ.

Front Abutment Loading

Retreat mining starts with the extraction of the panel pillars. When enough of the pillars have been extracted, the overburden strata above the extracted pillars start to cave. As a result of this roof caving, the “active” gob is formed. Some portion of the overburden load above the gob is carried by the gob, but a considerable amount of the original overburden load over the gob is transferred to the production pillars and barrier pillars as a front abutment load.

ARMPS (2002 and 2010) essentially predicts the magnitude of the front abutment load/gob loading by using the abutment angle concept and predicts the stress distribution of the front abutment loading by using Equation 2. Depending on the relative

dimensions of the width of the active gob, the extent of the active gob, and the overburden depth, three different geometries for the overburden loading consistent with the abutment angle concept can be developed (Mark, 2010). These loading geometries are used to determine the exact amount of the gob overburden load that is distributed to the gob, the active mining zone, and the inby barrier pillar. In ARMPS 2010, the front abutment loading on the AMZ is also adjusted by the pressure arch factor (if applicable), and any excess load is transferred to the outby barrier pillar. In the calibrated LaModel, the relative stiffness of the gob modulus (which was derived from matching the abutment angle concept in two dimensions) and the surrounding barrier and production pillars in conjunction with the flexibility of the overburden determines the exact distribution of the overburden load over the active gob.

Figure 10 shows the percentage of the overburden loads on the areas surrounding the AMZ for our average model as calculated by ARMPS 2002, ARMPS 2010, and LaModel.

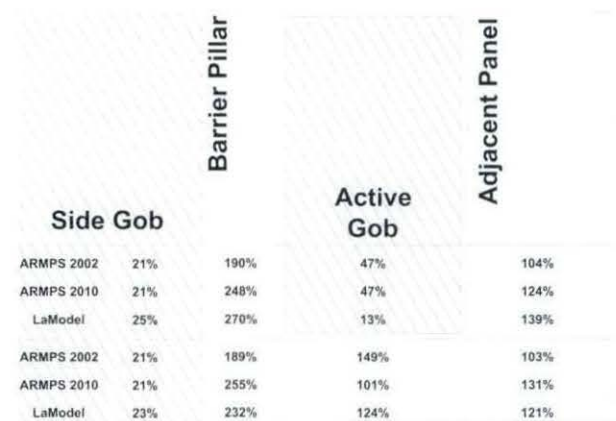


Figure 10. Overburden loads on the active panel with a side gob and an active gob.

In analyzing the results in Figure 10 and in comparing the results between Figures 7 and 10, there are two important concepts to understand:

- 1) LaModel is distributing stress from the active gob in a three dimensional manner.
- 2) ARMPS 2010 is shedding load from the AMZ to the outby barrier pillars as a result of the pressure arch factor.

LaModel only has 13% of the in situ stress in the active gob area as opposed to 47% for both of the ARMPS versions. We know that LaModel was originally calibrated to match the two dimensional gob loading in ARMPS as demonstrated by the similarities of the loading in the side gob areas (see Figure 10). However, at the face line where the gob is surrounded on three sides by coal pillars and the loading condition is distinctly three dimensional, LaModel calculates considerably less load on the gob than the abutment angle concept. In this three dimensional situation, LaModel distributes the gob overburden load to the following areas:

- 1) The inby barrier pillar and inby adjacent panel, which show more load than from ARMPS
- 2) The outby barrier pillar and outby adjacent panel, which show more load than from ARMPS (except for ARMPS 2010, which also has the pressure arch load transfer on the outby barrier pillars). In fact, the ARMPS programs do not “directly” transfer load from the active gob to the outby barrier pillar or outby adjacent pillar. Rather, the active gob load only gets to the outby barrier area when the inby barrier sheds load due to a safety factor < 1.5 and/or by the pressure arch stress transfer from the AMZ in ARMPS 2010.
- 3) The AMZ, which shows that LaModel has less load than ARMPS 2002 since more of the overburden load from the active gob is being transferred to the inby and outby barrier pillar and adjacent panel

The difference in loading between ARMPS 2002 and ARMPS 2010 in Figure 10 is a result of ARMPS 2010 shedding load from the AMZ to the adjacent outby barrier pillars because of the pressure arch factor. With ARMPS 2010, the AMZ loading is less than with ARMPS 2002 and the outby barrier pillar and outby adjacent pillar loading is greater than with ARMPS 2002.

Slab Cut Loading

During the retreat mining operations, slabs are often taken from the barriers to increase the production and recovery ratio. In the ARMPS programs, this of course reduces the width and strength of the inby barrier pillar. Furthermore, the slab cut causes the ARMPS loads to be recalculated, and the calculation process is a bit different between ARMPS 2002 and ARMPS 2010. In ARMPS 2002, the slab cut has two effects on loading: 1) The portion of the front abutment load that was originally carried by the inby barrier pillar is transferred to the AMZ, and 2) the additional front abutment load from the area of the slab cut is transferred to the outby barrier pillar (see Figure 11). In ARMPS 2010, the slab cut also has two effects on the load calculations: 1) It increases the effective panel width, which causes additional front abutment load to be transferred to the AMZ (modified by the pressure arch factor), and 2) some portion of the front abutment load is now applied to the outby barrier pillar (see Figure 11). In LaModel, consistent with what has been previously discussed, when the slab cut is removed the loads it was carrying are redistributed to the surrounding areas, including the inby barrier pillar, the outby barrier pillar, and the AMZ, as well as the active gob, the inby side gob and the outby side gob (see Figure 11). Again, it is important to note that the ARMPS programs do not distribute any of the slab cut loading back to the gob areas.

STABILITY FACTOR COMPARISON

The final analysis performed with ARMPS 2002, ARMPS 2010, and LaModel was to use each program to calculate the stability factor for each case history in the deep cover database. The results of these calculations are shown in Figures 12, 13, and 14. (In the following analysis, the “middling” cases are considered to be the same as failures.) The stability factor results for the ARMPS 2002 program are shown in Figure 12. Using just the stability factor part of the ARMPS 2002 deep cover criteria, 8 of the 21 unsuccessful case histories (38%) and 20 of the 31 successful case histories (64%) are correctly classified for an overall classification accuracy of 54% (28 correct out of 52 cases). The results for the ARMPS

| | | Barrier Pillar | Slab Cut | Active Gob | Adjacent Panel |
|------------|-----|----------------|----------|------------|----------------|
| Side Gob | | | | | |
| ARMPS 2002 | 21% | 214% | 47% | 104% | |
| ARMPS 2010 | 21% | 332% | 47% | 139% | |
| LaModel | 28% | 302% | 20% | 140% | |
| | | Barrier Pillar | Slab Cut | Active Gob | Adjacent Panel |
| Outby Gob | | | | | |
| ARMPS 2002 | 21% | 217% | 160% | 103% | |
| ARMPS 2010 | 21% | 258% | 106% | 133% | |
| LaModel | 25% | 244% | 127% | 121% | |

Figure 11. Overburden loads on the active panel after a slab cut.

2010 program are shown in Figure 13. Using a cut-off stability factor of 1.5, 11 of the 21 unsuccessful case histories (52%) and 17 of the 31 successful case histories (55%) are correctly classified for an overall classification accuracy of 54%. The results of the stability factor analysis for LaModel are shown in Figure 14. Once again, using a cut-off stability factor of 1.5, 16 of the 21 unsuccessful case histories (76%) and 15 of the 31 successful case histories (48%) are correctly classified for an overall classification accuracy of 60%.

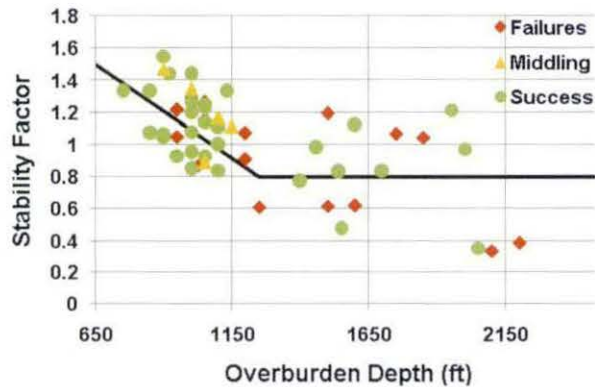


Figure 12. Stability factor analysis of the database with ARMPS2002.

There is not a very decisive difference between the stability factor analyses of the three programs. However, for this relatively small database, LaModel may be considered to classify the case histories slightly better than either ARMPS 2002 or 2010, since the overall classification is slightly better (60% to 54%) and the classification of the unsuccessful case histories is also better (76% to 52% or 38%). In addition, ARMPS 2010 may be considered to classify the case histories slightly better than ARMPS 2002, since the classification of the unsuccessful case histories is slightly better (52% to 38%), although the overall classification accuracy is identical.

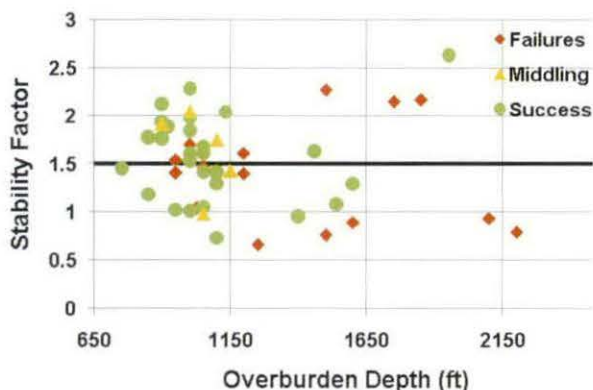


Figure 13. Stability factor analysis of the database with ARMPS2010.

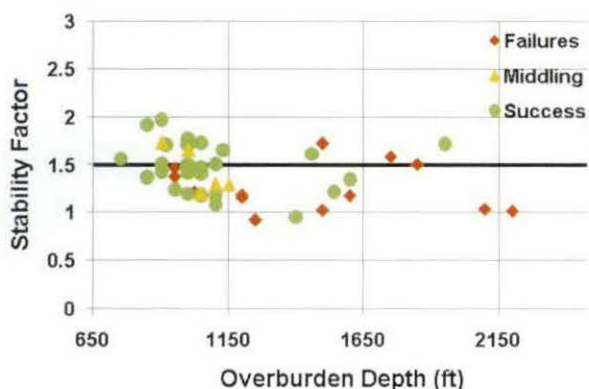


Figure 14. Stability factor analysis of the database with LaModel.

SUMMARY AND CONCLUSIONS

In this paper, the overburden load distributions calculated by ARMPS 2002, ARMPS 2010 and LaModel are analyzed and compared. The ARMPS 2002 program uses the tributary area method to estimate the development loads on the active mining zone, while the ARMPS 2010 uses the pressure arch factor to modify the tributary area stresses. Both programs use the abutment angle concept (see Figure 1) to estimate the abutment loads transferred to the AMZ and barrier pillars during pillar extraction. In both ARMPS programs, if the stability factors of the barrier pillars are too small (< 1.5) to carry all of the applied loads, then the loads are generally transferred back to the AMZ. In addition, ARMPS 2010 uses a new pressure arch factor (see equation 1) to reduce the loading on the AMZ and redistribute it to the barrier pillars when the depth/width ratio of the panel is greater than one.

The addition of the pressure arch factor to ARMPS 2010 has resulted in improved estimation of both AMZ and barrier pillar loads. First, for deep cover panels, it has generally lowered the load on the AMZ and therefore generally increased the stability factor and eliminated the depth effect on the stability factor as previously seen with ARMSP 2002 (see Figures 2 and 3). Furthermore, since the excess load due to the pressure arch factor

originally goes to the outby barrier pillar, but then comes back to the AMZ if the barrier pillar fails, ARMPS 2010 has implicitly incorporated the importance of the barrier pillar stability factor into the stability factor of the AMZ. This eliminates the need for a dual barrier pillar – AMZ stability factor criteria as shown in Table 1.

The LaModel program essentially simulates the overburden as a stack of frictionless plates, models the coal and gob areas with input stress-strain behaviors, and then uses these prescribed stiffness behaviors to calculate the displacements and loads throughout the modeled area of the seam. If LaModel is calibrated with the new procedures (Heasley 2010), then the extent of the abutment zone and the 2-D magnitude of the gob/abutment loading in LaModel are set to match those used in ARMPS. However, as seen in Figure 10, in the 3-D scenario at the active face line, LaModel overburden calculations distribute the load from the active gob in a 3-D-like manner with more load on the inby and outby barrier pillars and adjacent panel, and less load on the AMZ, than the abutment angle concept used in ARMPS would calculate.

In general, for the critical loading on the AMZ in this deep cover analysis, ARMPS 2002 predicts the greatest load, ARMPS 2010 predicts the least load and LaModel falls somewhere in between (see Figures 5, 6, 7, 10 and 11). Also, it should be noted that as the load on the AMZ increases and the stability factor decreases, the AMZ loading in LaModel gets closer to the AMZ loading in ARMPS 2010. Ultimately, in the stability factor comparison of the relatively small deep-cover database (see Figures 12, 13, and 14) there is not a decisive difference between the classification accuracy of the three programs. However, LaModel may be considered to classify the case histories slightly better than either ARMPS 2002 or 2010, and ARMPS 2010 may be considered to classify the case histories slightly better than ARMPS 2002.

This analysis of the overburden loading in the ARMPS and LaModel programs has certainly highlighted a number of areas for further research and improvement. In the ARMPS programs, the shedding of load from the different mining areas due to the formation of a pressure arch and due to barrier pillar failure seems to be reasonable. However, the three-dimensional load distribution produced by LaModel provides a better classification of the case histories and indicates that the ARMPS programs may benefit from further research into load shedding during retreat mining. In the LaModel program, the elastic, perfectly-plastic behavior of the barrier and production pillars is certainly not accurate for narrower pillars that probably soften as they yield, or for wide pillars that may strain-harden after failure. A more accurate strain-softening/strain-hardening pillar model may provide more accurate stability factors. Finally, none of the overburden loading calculations in the three programs (if LaModel is calibrated with the “standard” method) considers the site-specific geology. Certainly, a better understanding of how the immediate roof geology affects the gob formation and magnitude of gob/abutment loading, and/or how the major geologic features of the overburden affect the distribution of abutment load would lead to more accurate stability factor calculations.

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