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Integrating the LaModel and ARMPS Programs (ARMPS-LAM)

Peng Zhang
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Integrating the LaModel and ARMPS Programs (ARMPS-LAM)

Peng Zhang

Dissertation submitted
to the Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in
Mining Engineering

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Morgantown, West Virginia
2013

Keywords: ARMPS-LAM, ARMPS, LaModel, Ground Control, Pillar Design

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ABSTRACT

Integrating the LaModel and ARMPS Programs (ARMPS-LAM)

Peng Zhang

Over the years, the various versions of the ARMPS and the LaModel programs have been widely used in the U.S. coal fields. In a recent deep-cover database analysis, LaModel was found to more accurately classify a small deep-cover database than ARMPS. However, the LaModel analysis of each case study required several days to complete, as compared to a requirement of only several minutes for each ARMPS analysis. If the LaModel analysis of an ARMPS-type mine design, could be made as easily and quickly as an ARMPS analysis and calibrated against a large database, the potential exists to improve the quality of overall mine design.

In this research, a computer code (ARMPS-LAM) has been developed to effectively integrate the LaModel and ARMPS programs. This program takes the basic ARMPS input for defining the mining plan and then automatically develops, runs, and analyzes a full LaModel analysis to output the stability factor and other data for mine design analysis, all without further user input. This new program allows an ARMPS-type LaModel analysis to be developed and run in just a few minutes. The ARMPS-LAM program consists of three primary modules: pre-processing, numerical solution and post-processing. The pre-processing module includes the component subroutines to import data, develop and calibrate the laminated overburden model. The numerical solution module solves the laminated overburden model. The post-processing module can automatically extract and calculate the stability factor and output other important data. The program can also be run in batch mode to quickly analyze a large database.

To initially evaluate the ARMPS-LAM program, it was used to analyze the entire 645 case histories of the ARMPS database and compared to the ARMPS output. It was found that the ARMPS-LAM SF is generally about 8% higher than the ARMPS SF. Further, the laminated overburden model (as implemented in ARMPS-LAM) distributes less load on the AMZ for shallow cover (< 1,000 ft) and more load for deep cover (>1,000 ft) than ARMPS.

Next, the ARMPS-LAM classification accuracy was determined. This analysis involved a multi-variable regression using the five most significant input variables of the ARMPS-LAM program (AMZ SF, depth, seam height, barrier pillar SF and pillar width-to-height ratio). Based on this statistical analysis, the ARMPS-LAM program was seen to be slightly more accurate than ARMPS by a factor of 72% versus 63%. In the future, this classification accuracy may yet increase with additional research on improving the accuracy of the calibrated laminated overburden model.

In this dissertation, the ARMPS-LAM program has been successfully developed and validated. In the future, it is planned to be implemented into ARMPS as an effective tool to help engineers perform pillar design, and the batch version will also serve as a platform to assist researchers in evaluating new ground control approaches.

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Chapter 1. Introduction

1.1 Background

Accurately analyzing the stability of underground coal mine openings and pillars is critical to designing safe and economic mining activities. Over the years, the various versions of the Analysis of Retreat Mining Pillar Stability (ARMPS) and the LaModel programs have been widely used in the U.S., and undoubtedly, they have improved the safety of room-and-pillar retreat mining operations.

The original version of ARMPS was developed by the National Institute for Occupational Safety and Health (NIOSH) in the mid-1990s (Mark & Chase, 1997) to aid in the design of room-and-pillar retreat mining operations in underground coal mines. ARMPS was created with a very user-friendly interface, and it was simple, easy and fast to use. This ease of use and associated adoption in the mining industry greatly improved the efficiency of room-and-pillar retreat mine design.

In the ARMPS program, the stability factor (SF) of the Active Mining Zone (AMZ) is determined by comparing the load bearing capacity of the pillars in the AMZ against the development loads and abutment loads applied to those pillars. During the stability factor calculation, the strength of the pillars is determined using the Mark-Bieniawski pillar strength formula; the development loads are determined using a combination of the tributary-area and pressure-arch methods (Mark et al., 2011); and the abutment loads are determined using the abutment angle concept. The value of the calculated pillar stability factor is then compared against a large database of successful and unsuccessful case histories to determine the chance of success of the chosen design. This large database of case histories is the real strength of the program and provides very solid empirical support for the application of the ARMPS method. The ARMPS program has become so universally accepted in the U.S. that it is often integrated into roof control plans for the mines. The ARMPS program is very fast and accurate for “conventional” room and pillar retreat mining scenarios; however, it cannot be used to analyze complex mine plans,

variable topography, multiple-seams and many other more complex, but ever more common situations.

In contrast to the empirical ARMPS program, the LaModel program is a numerical mechanics-based program which is based on simplified overburden and seam mechanics. It simulates the overburden as a stack of homogeneous, frictionless plates (Heasley, 1998) and within the seam horizon, the elements are simulated with various stress-strain behaviors (elastic, elastic-plastic, strain-softening and strain-hardening) intended to model the various behaviors of the in-seam coal and gob. It has a number of features to help calibrate the overburden, coal and gob materials based on observed behavior (Heasley, 2008; Heasley et al., 2010), which is intended to help improve its accuracy in stress analysis. LaModel is capable of accurately modeling complex mining geometries, variable topography, multiple-seams and many other situations and/or detail beyond the capability of ARMPS (Wang & Heasley, 2005). The integrated mechanical calibration models and its flexibility make it extensively used throughout the coal mining industry (Akinkugbe & Heasley, 2004; Chase et al., 2005; Heasley & Chekan, 1999).

When the LaModel program is executed, it takes the user defined input properties of the overburden and balances it with the in-seam material behaviors and solves for the resulting displacements, stresses, pillar safety factors, etc. However, the LaModel program requires quite a bit more time, effort and complexity to run than the ARMPS program, typically hours instead of minutes.

The Crandall Canyon Mine collapse in August 2007 highlighted the fact that that further research was required to improve the pillar design in the U.S., especially for pillar recovery under deep cover. As part of the post Crandall effort to improve deep cover mine design, Tulu et al. (2010) investigated the deep-cover loading distributions and stability factors calculated from ARMPS and LaModel for 52 case histories. Based on the analysis of their loading mechanisms, it was shown that the laminated overburden model distributed the load from the active gob in a 3D 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. Compared with ARMPS, LaModel's mechanics-based loading

is assumed to be much closer to the actual overburden load distribution scenario. In Tulu's work (Tulu et al., 2010), it was found that the laminated overburden model more accurately classified the 52 deep-cover case histories than ARMPS by a factor of 60% versus 54%. This initial work indicated that there is potential to improve the current room-and-pillar mine design classification accuracy through application of LaModel and/or the laminated overburden model (Tulu et al., 2010).

1.2 Statement of Problem

The ARMPS program is easy and quick to use. Further, because its design criteria are based on analysis of a large database, it is confidently and widely used in coal industry. However, it is not very flexible for more complex mining situations. The LaModel program is very flexible in regard to complex mining situations and it is grounded in mechanics-based models and calibration with observations. However, a LaModel analysis is very time consuming.

In the previous comparison between ARMPS and LaModel based on the deep-cover database, LaModel showed significant promise for improving the accuracy of the ARMPS calculation; however, in this previous research, the LaModel analysis of each case study required several days to complete, as compared to a requirement of only a few minutes for each ARMPS analysis. Using LaModel, the input parameters and mine grid need to be entered by hand and the output needed to be manually analyzed to determine the stability factor of the AMZ. The user expertise and attention-to-detail for LaModel required considerable more time and effort than performing a simple ARMPS analysis.

Therefore, there appears to be the potential for improving mine design by developing a program to automate LaModel analysis of ARMPS-type mine design. Ideally, the automatic LaModel analysis would be as easy and quick as ARMPS and similarly calibrated against a large database. It would only need the basic ARMPS geometric inputs for defining the mining plan and then it would automatically develop and analyze a complete LaModel file with calibrated laminated overburden to calculate the stability factor of the AMZ (and barrier pillars), all without further user input.

1.3 Statement of Work

The objective of this research is to enhance coal mine safety by improving the current technology of room-and-pillar coal mine design through integrating the ARMPS and LaModel programs and developing a new computer code, called ARMPS-LAM. ARMPS-LAM will combine the advantages of both the ARMPS and LaModel programs: it will be easy and quick to run and compatible with large database; this program will be implemented with mechanics-based material behaviors (laminated overburden, the elastic-plastic coal and strain-hardening gob models) to simulate the displacements and stresses of the overburden, in-seam coal and gob materials.

The ARMPS-LAM program will integrate the pre-processing, numerical analysis and post-processing components of LaModel into a single program. The ARMPS-LAM program will use the ARMPS input to build, calibrate, run and analyze a laminated overburden model to evaluate the stability factor of the given room-and-pillar mine design. Based on the mine geometry information in the user input, the ARMPS-LAM program will automatically develop a mine map and then grid the mine plan and develop the mine grids. According to the imported in-situ coal strength and abutment angle values, the program will automatically calibrate the rock mass, coal and gob materials based on the current recommended LaModel deep-cover calibration techniques. After running the model, it will automatically determine and extract the critical stability factor, pillar strength and other results, and save and present them to the user.

Once the ARMPS-LAM program has been developed, the mathematics, algorithms and coding will be validated and demonstrated with a case study. In particular, the results calculated with ARMPS-LAM will be compared with manually calculated results to make sure the various subroutines and the entire program are correctly coded.

Then, the ARMPS database will be analyzed using both ARMPS and ARMPS-LAM programs. Based on the results, the differences between the programs will be investigated, and any potentially significant variations will be analyzed. Ultimately, a statistical analysis will be performed to compare the classification accuracy of the case history database between the ARMPS and ARMPS-LAM programs.

Chapter 2. Literature Review

Performing an analysis of the pillar design in a mine with the use of computer program is a common practice in underground room-and-pillar design today. Both the empirical program ARMPS and numerical program LaModel have been widely used in the mining industry for decades.

2.1 ARMPS

The prevention of unplanned pillar failure is critical to the safety of pillar retreat operations. To help improve the underground safety of retreat mines, NIOSH developed the Analysis of Retreat Mining Pillar Stability (ARMPS) program. The ARMPS program can model many standard retreat mining layouts, including angled crosscuts, varied spacings between entries, barrier pillars, slab cuts in the barriers and pillars left to maintain bleeder systems. The program is widely used to evaluate room-and-pillar coal mine designs in the U.S. and around the world.

2.1.1 Original ARMPS

The original ARMPS program was developed by researchers from NIOSH in the mid 1990's (Mark & Chase, 1997). The goal of ARMPS program was to help minimize pillar failures due to pillar squeezes, massive pillar collapses and bumps on room-and-pillar retreat sections by ensuring that the pillars developed for future extraction are of adequate size for all anticipated loading conditions. In the program, the mining geometry and empirical concepts were used to estimate loads and pillar strength. Figure 2.1 shows a sample retreat mining layout in an ARMPS analysis. This sample mining layout has one retreating panel and two side gobs. As shown in Figure 2.1, in ARMPS program, users can define most features of the room-and-pillar mine design, such as front gob extent, side gob width, crosscut angle, entry spacing, crosscut spacing, barrier pillar width and slab cut depth.

Figure 2.1 A sample retreat panel layout in ARMPS (from Mark et al., 2011).

In ARMPS program, the stability factor is calculated to evaluate the mine design through comparing against a large database of successful and unsuccessful case histories. The stability factor is determined based on the estimates of the loads applied to and the load-bearing capacities of, the pillars during retreat operations.

2.1.1.1 Pillar Loads

In the original ARMPS program, the initial loads applied to the AMZ include: development load (a), front abutment load (b) and side abutment load (c), which are illustrate in Figure 2.2. The development loads are determined using the “Tributary Area” concept. The front/side abutment loads are calculated based on the “Abutment Angle.”

Figure 2.2 The initial loads applied to the AMZ in ARMPS (from Mark et al., 2011).

The “Tributary Area” used for the estimation of the development load assumes that each pillar supports the rock directly above it and half of the entry on each side, all the way to the surface (see Figure 2.3).

Figure 2.3 Tributary area schematic (from Bise, 2013).

In the above schematic, the plan view area of the pillar supporting the overburden weight is equal to the pillar width (w_p) times the pillar length (l_p):

$$\text{pillar area} = w_p * l_p \quad (2.1)$$

The tributary area theory assumes that the weight of overburden above half of the entry on each side of the pillar is carried by the pillar. Therefore, if half of the entry width (w_e) on each side of the pillar is added to the pillar width and half of the crosscut width (w_c) on each end of the pillar is added to the pillar length, it can be seen that the tributary area of the overburden load can be calculated as Equation 2.2.

$$\text{tributary area} = (w_p + w_e) * (l_p + w_c) \quad (2.2)$$

Therefore, in ARMPS program, the empirical formula for the pillar development load estimation is the volume of the overburden within the tributary area up to the surface for the given depth (H) times the density of the overburden (δ_r):

$$\text{pillar load} = \delta_r * H * (w_p + w_e) * (l_p + w_c) \quad (2.3)$$

In addition to the development loads imposed on coal pillars, there are often loads on the pillars due to adjacent areas of room-and-pillar retreat mining, including side abutment loads and front abutment loads. Figure 2.4 shows these types of abutment loads applied on pillars within the AMZ (Mark & Chase, 1997).

Figure 2.4 Schematic of applied loads on AMZ (from Mark & Chase, 1997).

The magnitude of the abutment load is commonly conceptualized and calculated using the “Abutment Angle” concept. This concept is based on the abutment load estimation in the Analysis of Longwall Pillar Stability (ALPS), which is widely used for longwall pillar design (Mark, 1990, 1992; Mark & Chase, 1997). Figure 2.5 shows two typical conditions of the “Abutment Angle” concept (supercritical and subcritical), where the total abutment load is considered to be the weight of the wedge of overburden defined by a vertical line at the edge of the panel and the line at the “abutment angle” (β) on the inside of the panel. The weight of the overburden within the abutment angle wedge is supported by the pillars and, as a corollary, the gob is assumed to support the remainder of the overburden weight over the full-extraction area. Using field measurements of abutment loading, a suitable average abutment angle for use in the United States was determined to be 21 °(Mark, 1990), and this is the default value used in ARMPS.

Figure 2.5 Schematic of abutment angle in ARMPS (from Mark et al., 2011).

There are two types of panels based on their relative dimensions (see Figure 2.5). A “supercritical” panel is wide enough that the abutment angle lines do not cross before they intersect the surface. Therefore, from geometry, the panel width (P) is greater than twice the distance of the abutment angle intercept on the surface, which equals to the depth (H) times the tangent of the abutment angle (β):

$$\text{Supercritical panel: } P > 2 H \tan(\beta) \quad (2.4)$$

For a supercritical panel, knowing the density of the overburden (δ_r), the magnitude of the abutment load (L_s) for a unit length of the panel can be calculated from the geometry as following:

$$L_s = H^2 \tan(\beta) (\delta_r / 2) \quad (2.5)$$

A “subcritical” panel is defined as a panel that is narrow enough that the abutment angle lines cross before they intersect the surface. Therefore, from geometry, the width (P) of a subcritical panel is less than twice the depth times the tangent of abutment angle (β):

$$\text{Subcritical panel: } P < 2 H \tan(\beta) \quad (2.6)$$

Based on the geometry, the abutment load for a subcritical panel (L_{ss}) can be calculated as:

$$L_{ss} = \left[\left(\frac{H * P}{2} \right) - \left(\frac{P^2}{8 * \tan(\beta)} \right) \right] * \delta_r \quad (2.7)$$

The abutment load stress distribution (σ_a) was found to be a square decay relationship given in the following formula (see Equation 2.8) and is related to the magnitude of the abutment load (L_s) and the distance from the edge of the panel (x).

$$\sigma_a(x) = \left(\frac{3L_s}{D^3} \right) (D - x)^2 \quad \text{for } 0 \leq x \leq D \quad (2.8)$$

Based on the abutment load distribution formula presented by Equation 2.8, the abutment load distribution can be determined and plotted in Figure 2.6. It shows the distribution of side abutment load stress. It indicates that the peak abutment stress at the edge of the panel ($x = 0$) is equal to $3L_s/D$ and then it decreases as a squared function of the distance from the edge of the panel until the stress reaches zero at a distance of D .

Figure 2.6 Schematic of side abutment load distribution extent (from Bise, 2013).

Then, through integration of Equation 2.8, the total side abutment load (L) within distance of the edge of the panel (W) can be calculated as Equation 2.9 (from Bise, 2013).

$$\begin{aligned}
L(W) &= \int_0^W \sigma_a(x) = \int_0^W \left(\frac{3L_s}{D^3} \right) (D-x)^2 dx \\
&= - \left(\frac{L_s}{D^3} \right) (D-x)^3 \Big|_0^W \\
&= - \left(\frac{L_s}{D^3} \right) (D-W)^3 + \left(\frac{L_s}{D^3} \right) (D-0)^3 \\
&= L_s^* \left[1 - \left(\frac{D-W}{D} \right)^3 \right]
\end{aligned} \tag{2.9}$$

Mark (1992) analyzed the stress distribution of the abutment load (L) based on field measurements of the side abutment load. It was found that the maximum extent of the abutment load (D) was a function of the depth (H) as shown in Equation 2.10.

$$D = 9.3\sqrt{H} \tag{2.10}$$

And 90% of the abutment load falls within a distance of $5\sqrt{H}$ (see Equation 2.11).

$$D_{.9} = 5\sqrt{H} \tag{2.11}$$

(It should be noted the depth (H) in Equations 2.10 and 2.11 needs to be in units of feet.) Figure 2.7 shows the schematic of the front abutment load distribution based on field observations (Mark & Chase, 1997).

Figure 2.7 Distribution of front abutment load (from Mark & Chase, 1997).

A distance of $5\sqrt{H}$ (contains 90% of front abutment load, see Figure 2.7) is often considered to be the “practical” extent of the abutment load and is used to define the extent of the AMZ in ARMPs. The AMZ is a significant term that was coined in the room-and-pillar mine design. Since experience has shown that the pillars within this range typically behave as a system, $5\sqrt{H}$ is employed as the breadth of the AMZ (Mark & Chase, 1997). Therefore, the AMZ includes all of the pillars in the extraction front and extends out by the pillar line a distance of five times the square root of the depth of cover ($5\sqrt{H}$), and contains 90% of the abutment load.

2.1.1.2 Pillar Load-Bearing Capacity

It is certainly not easy to determine the strength of a coal specimen and even more difficult to extrapolate this lab data to in-situ sized coal pillars. Numerous strength tests of

coal specimens have been performed to determine the strength of coal pillars. It has been found that coal strength is affected by both the size and the shape of the tested specimen (Bieniawski, 1968; Gaddy, 1956; Holland & Gaddy, 1957). Therefore the effects of pillar height and width have been incorporated into various pillar strength formulas (Bieniawski, 1992; Holland & Gaddy, 1957; Mark & Chase, 1997; Mark & Iannacchione, 1992; Salamon & Munro, 1967).

The ARMPS program uses the Mark–Bieniawski pillar strength formula (Mark & Chase, 1997) that can accurately consider the size and shape effects for rectangular pillars (see Equation 2.12). This empirical formula incorporates the length (l_p) of the pillar along with the pillar width (w) and height (h) into the strength of the pillar:

$$SP = S_1 \left[0.64 + 0.54 \frac{w}{h} - 0.18 \frac{w^2}{hl} \right] \quad (2.12)$$

where:

- SP = average pillar strength
- S_1 = in-situ coal strength, defaults to 900 psi
- w = pillar width
- h = pillar height
- l = pillar length

Then, the load-bearing capacity of each pillar can be determined by multiplying the average pillar strength by the load-bearing area.

2.1.1.3 AMZ Stability Factor

In ARMPS, the “Stability Factor” (SF) of the AMZ is determined as the ratio of bearing capacity of the pillars in the AMZ divided by load applied to the AMZ. Equation 2.13 shows the ARMPS SF calculation defined by Mark and Chase (1997).

$$\text{ARMPS SF} = \frac{\text{LBC}}{\text{LT}} \quad (2.13)$$

where:

LBC = estimated total load-bearing capacity of the pillars within the AMZ

LT = the estimated total load applied to pillars within the AMZ

ARMPS calculates the SF for the entire AMZ, rather than the stability factor or safety factor of individual pillars, because experience has shown that the pillars within the AMZ typically behave as a system. If an individual pillar is overloaded, it will normally transfer its excess load to adjacent pillars. Therefore, it is the strength of the entire AMZ that is important. Further, the factor is referred to as a “stability” factor as opposed to a “safety” factor, because the final determination of the suitability of a given design is based on the stability of the overall section (including roof and floor) as opposed to just the safety (or stability) factor of the pillars (Mark & Chase, 1997).

2.1.1.4 Suggested Design Criteria

The power of the ARMPS program is derived from the large database of retreat mining case histories that it has been calibrated against (Mark, 2010). The case histories in the database have been categorized as either success or failure (satisfactory or unsatisfactory) based on their ground conditions. Pillar failures responsible for the unsatisfactory ground conditions included:

- **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.
- **Collapses**, which occur when a large number of overloaded pillars fail almost simultaneously, usually resulting in a destructive air blast.
- **Bursts**, which can affect just 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.

A case history is considered “successful” or “satisfactory” when its entire panel was recovered without critical ground control incident (shown above); on the contrary, it is designated as “failure” or “unsatisfactory” (Mark, 2010).

The ARMPS design criteria were developed based on analyzing actual case histories. The original ARMPS database consisted of approximately 150 case histories (Mark & Chase, 1997). An additional 100 case histories were collected in a follow-up study, which focused on deep-cover pillar recovery (Chase et al., 2002). Then, a database with about 250 shallow, moderate and deep-cover case histories was formed. Chase et al. (2002) conducted a study, where the ARMPS 2002 design guidelines were derived through statistical analysis, a technique which was widely used in other scientific disciplines (Hosmer & Lemeshow, 2000). Table 2.1 and Figure 2.8 present the details of the design criteria recommended for use with ARMPS 2002 based on the analysis of the database at that time.

Table 2.1 Recommended design criteria of ARMPS 2002 (Chase et al., 2002).

	Depth of Cover (H)	Weak and Intermediate Strength Roof	Strong Roof
ARMPS SF	$H < 650 \text{ ft}$	1.5	1.5
	$650 \text{ ft} \leq H \leq 1,250 \text{ ft}$	$1.5 - [H - 650] / 1,000$	$1.4 - [H - 650] / 1,000$
	$1,250 \text{ ft} \leq H \leq 2,000 \text{ ft}$	0.9	0.8
Barrier Pillar SF	$H > 1,000 \text{ ft}$	≥ 2.0	$\geq 1.5^* (\geq 2.0^{**})$
	$H < 1,000 \text{ ft}$	No Recommendation	

Note: *Non-burst-prone ground; **Burst-prone ground.

Figure 2.8 The ARMPS 2002 database with the satisfactory and unsatisfactory cases and the recommended stability factor cut-off line (Chase et al., 2002).

It is obviously that this suggested room-and-pillar design criteria is highly related to the depth of cover (H): an ARMPS SF of 1.5 or greater is appropriate where the depth of cover is less than 650 ft; as the cover increases from 650 to 1,250 ft, there is a decreasing trend in SF for both the successful and the unsuccessful cases; however, deeper than 1,250 ft, there does not seem to be any clear trend. This correlation between the stability factor and depth was caused for some discussion (Tulu et al., 2010) but was not formally addressed until ARMPS 2010 (Mark, 2010).

2.1.2 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 (Mark, 2010). This research resulted in a new loading model in ARMPS based on the “Pressure Arch” concept was implemented into the latest version of ARMPS, called ARMPS 2010. Additionally, the case history database supporting ARMPS was updated and expanded to 692 case histories during this research.

2.1.2.1 Pressure Arch Model

In previous research (Chase et al., 2002) it was found that pillar designs under deep-cover could be successful with lower stability factors (SF), as indicated in Figure 2.8. With the increase of depth, the required ARMPS SF declined from 1.5 to 0.8. The most likely explanations for adjusting the SF with depth are either the pillar strength increases with depth or the pillar loading in ARMPS is overestimated at greater depths. There is no evidence or logical reason to believe that the strength of the pillars increases with depth (Mark, 2010). Therefore, for a deep-cover mine, the most likely explanation for the reduced safety factor is that, the loading on the AMZ is not as high as calculated by ARMPS using the complete tributary area and abutment loads. Apparently, some overburden load is transferred from the production pillars to the adjacent barrier pillars.

In ARMPS 2010, a “Pressure Arch” loading model was investigated and developed to improve the accuracy of deep-cover retreat mining by reducing the overburden loads on the production pillars as estimated by the original ARMPS (Mark, 2010). Equation 2.14 shows the empirical formula of this loading model, which has a logarithmic form. The pressure arch factor determined for ARMPS 2010 provides for a constant recommended SF with depth and empirically optimizes the separation between the successful and unsuccessful case histories in the database.

$$F_{pa} = 1 - \left[0.28 * \ln \left(\frac{H}{P_w} \right) \right] \quad (2.14)$$

where:

F_{pa} = pressure arch factor

H = overburden depth

P_w = panel width

It should be noted that instead of being mechanics based, this “Pressure Arch” loading model was purely derived from statistical analysis to improve the overall classification accuracy of ARMPS 2010. Therefore, this “Pressure Arch” formula (see Equation 2.14)

can best distinguish the successes and failures in the case history database. It helps standardize the mine design guidelines by bringing the recommended ARMPS SF to a constant value of 1.50 at any depth (see Figure 2.11), thereby to eliminate the depth effect previously seen with AMPS 2002 (see Figure 2.10).

For this “Pressure Arch” loading model, when the extraction panel width is less than the depth of cover, the model assumes that a pressure arch will be formed. Some of the load will be transferred from the AMZ to the barrier pillars or solid pillars on either side of the panel pillars. The amount of load transferred to the barrier pillars is calculated by multiplying the initial AMZ loads by the “Pressure Arch Factor” (see Equation 2.14 and Figure 2.9a). However, if the barrier pillars are inadequate or removed, their loads will be transferred back to the AMZ (see Figure 2.9b). The best threshold for implementing the pressure arch loading function was found to be when the depth of cover exceeds the panel width plus 80 ft (Mark, 2010).

a. Additional loads applied to the barrier pillars.

b. Pressure arch loads transferred back to the AMZ.

Figure 2.9 Pressure arch concept in ARMPS (from Mark, 2010).

2.1.2.2 Suggested Design Criteria

During the Crandall Canyon follow up study, the latest ARMPS database has expanded to 692 case histories from 127 different coal mines. The cases are from 42 counties in 10 states, covering all the U.S. coalfields. A total of 67 different coal seams are represented. It should be noted that the associated database analysis conducted by NIOSH (Mark et al., 2011) was based on 640 case histories extracted from the original 692 case histories by excluding the “borderline” and “floor heave” cases (where pillars are still intact). The database used for developing the ARMPS 2010 design guideline includes 520 successful and 120 unsuccessful case histories.

In order to investigate the performance of new “Pressure Arch” loading model in ARMPS 2010, a statistical analysis was initially conducted on the 640 case histories using ARMPS 2002 and its design criteria. The results are shown in Figure 2.10, where 82% of the failed case histories and 61% of the successful case histories were correctly classified at the original stability factor criteria, for an overall classification accuracy of 65% (Mark, 2010).

Figure 2.10 ARMPS 2002 guideline against 2010 ARMPS database (Mark, 2010).

Using ARMPS 2010 with the new “Pressure Arch” loading model, another statistical analysis was performed to derive the new design criteria and investigate the classification accuracy of the new loading algorithm. Based on the same 640 case histories, the ARMPS 2010 design guideline was determined to be an ARMPS SF_{2010} of 1.50, regardless of depth (Mark, 2010). Table 2.2 presents the complete suggested design criteria of ARMPS 2010.

Table 2.2 ARMPS 2010 suggested design criteria (Mark, 2010).

Depth of Cover	ARMPS SF	Barrier Pillar SF
< 650 ft	1.5	No Recommendation
> 650 ft	1.5	1.5

Figure 2.11 shows the 2010 ARMPS database with the ARMPS 2010 SF plotted against the depth, with the suggested design guideline of 1.50 marked (Mark, 2010).

Figure 2.11 Recommended ARMPS SF 2010 (Mark, 2010).

It should be noted that the ARMPS 2010 SF of 1.50 was not the optimum overall classification point; but rather, the recommended SF was increased to more accurately classify the critical unsuccessful case histories (Mark, 2010). However, based on the statistical analysis results, its discrimination ability between successes and failures is almost identical to that obtained using ARMPS 2002 program (61% successes and 82% failures can be accurately classified, with an overall classification accuracy of 65%).

2.2 LaModel

The frictionless laminated overburden model was originally introduced by Salamon in 1962 and implemented into the LaModel program by Heasley in 1993. LaModel uses the displacement-discontinuity (DD) variation of the boundary-element method with a laminated overburden, and is used to model the stresses and displacements on thin tabular deposits such as coal seams. What makes LaModel unique among boundary element codes is that the overburden laminations, which give the model flexibility for stratified

sedimentary geologies and multiple-seam mines. The mathematical basis of the model is the theory of thin plates and the formulations assuring that the displacements and stresses are continuous across the layers. Essentially, the rock mass in LaModel consists of a stack of strata laminations where the interfaces between beds are all horizontal and free of shear stresses and cohesion. Also, all of the layers have the same elastic modulus, Poisson's ratio and thickness. LaModel is able to analyze large areas of single or multiple-seam coal mines. Using LaModel, the total vertical stresses and displacements in the coal seam are calculated, and the individual effects of multiple-seam stress interactions and topographic relief can be separated and analyzed individually.

LaModel has continually been upgraded and modernized. The present program is written in Microsoft Visual C++ and runs in the windows operating system. It can be used to calculate convergence, vertical stress, overburden stress, pillar safety factors, intra-seam subsidence, etc., on single and multiple seams with complex geometries and variable topography. Presently, the program can analyze a $2,000 \times 2,000$ grid with 6 different material models and 52 different individual in-seam materials. The stress vs. strain curves of the 6 in-seam material models are shown in Figure 2.12. Figure 2.12 shows that in LaModel, there are three coal materials, including linear-elastic, strain-softening and elastic-plastic models; the three gob materials include: linear elastic, strain-hardening and bilinear hardening models.

Figure 2.12 In-seam material models in LaModel (Heasley et al., 2010).

For a full LaModel analysis, the following three steps are necessary:

- **Calibration:** define and calibrate the mechanical properties of the overburden rock mass, coal and gob using LamPre program.
- **Modeling:** as a boundary element method (BEM) solution for mine design, LaModel model the seam in a form of 2D grid with square elements. The seam grids can be built in LamPre program or using an advanced grid generator in AutoCAD.
- **Analysis:** after running the model using LaModel program, the results can be manually analyzed. The results can also be plotted in LamPlt program.

Each of the steps above is discussed in more detail in the following sections.

2.2.1 Calibration

The accuracy of a LaModel analysis depends entirely on the accuracy of the input parameters. Therefore, the input parameters need to be calibrated with the best available information, either: measured, observed, or empirically or numerically derived. However, in calibrating the model, the user also needs to consider that the mathematics in LaModel are only a simplified approximation of the true mechanical response of the overburden. And because of the mathematical simplifications built into the program, the input parameters may need to be appropriately adjusted to reconcile the program limitations. Recently, the calibration procedure for a number of the input parameters has been automated and the associated formulas and algorithms have been coded into the LamPre program (Heasley, 2008).

2.2.1.1 Critical Material Parameters

When building a model, the mine geometry and the topography are usually well known and fairly accurately discretized into LaModel. The most critical input parameters with regard to accurately calculating stresses and loads are (Heasley, 2008):

- Rock Mass Stiffness
- Coal Strength
- Gob Stiffness

These three parameters are always fundamentally important to accurate modeling with LaModel and particularly so in simulations analyzing abutment stress transfer (from gob areas) and pillar stability as in deep-cover pillar retreat. During model calibration, it is critical to note that these parameters are strongly interrelated and because of the model geomechanics, the parameters need to be calibrated in the order shown above. With this sequence of parameter calibration, the calibrated value of the subsequent parameters is determined by the chosen value of previous parameters and changing the value of any of the preceding parameters will require re-calibration of the subsequent parameters. The

calibration derivation and recommended calibration process as it relates to each of these parameters is discussed in more detail below.

2.2.1.2 Calibrating Rock Mass Stiffness

The stiffness of the rock mass in LaModel is primarily determined by two parameters, the rock mass modulus and the rock mass lamination thickness. Increasing the modulus or increasing the lamination thickness of the rock mass will increase the stiffness of the overburden. With a stiffer overburden, the extent of the abutment stresses will increase, the convergence and stress over the gob areas will decrease and the multiple seam stress concentrations will be smoothed over a larger area (Heasley, 2008).

When calibrating the rock mass stiffness, it has been found to be most efficient to initially select a rock mass modulus and then solely adjust the lamination thickness for the model calibration. Based on previous study and research, a recommended value of 3,000,000 psi is set as the default rock mass modulus (Heasley, 2008).

In the recommended calibration procedure for LaModel, the rock mass stiffness is calibrated to provide the required abutment stress extent. In calibrating the lamination thickness for a model based on the abutment extent, it would be best to use specific field measurements of the abutment zone from the given mine. However, often these field measurements are not available. In this case, visual observations of the extent of the abutment zone can often be used.

Without any measured or observed abutment extent, the recommended abutment extent in LaModel is set to be the same as that determined for ALPS and ARMPS, $5\sqrt{H}$ (see Equation 2.11). Once the desired abutment extent is known, LaModel can calculate the lamination thickness that will match that abutment extent.

In the original development of LaModel program, Equation 2.15 was developed which gives the abutment stress magnitude (σ_1) for the laminated overburden model as a function of the distance (x) from the panel rib, which was shown in Figure 2.13 (Heasley, 2008).

$$\sigma_1(x) = q \frac{P}{2} \sqrt{\frac{2 E_s \sqrt{12(1-v^2)}}{Eht}} e^{-\sqrt{\frac{2 E_s \sqrt{12(1-v^2)}}{Eht}} x} \quad (2.15)$$

where:

- σ_1 = abutment stress magnitude
- q = the in-situ stress
- P = the width of the panel
- E_s = the elastic modulus of the seam
- E = the elastic modulus of the overburden
- h = the seam thickness
- t = the lamination thickness in the overburden rock mass

Figure 2.13 Comparison of abutment stresses between ALPS and LaModel (Heasley et al., 2010).

In LaModel, for a given percent (n) of the side abutment load, Equation 2.16 can be derived based on the integration of the abutment stress Equation 2.15. For the field measurements of the abutment load extent, its value obviously included the distance of the yielding zone (d). However, in the derivation of Equation 2.15, the coal was assumed to be linear elastic. In reality, there is some distance of coal yielding (d) at the edge of the panel. Therefore, to calibrate the lamination thickness (t) using a given abutment load extent measured in the field, the actual yield zone (d) is subtracted from the desired abutment extent (see Equation 2.16). Finally, the lamination thickness (t) can be determined to match the desired side abutment load extent of $5\sqrt{H}$ (Heasley, 2008):

$$t = \frac{2 E_s \sqrt{12(1 - \nu^2)}}{E h} \left(\frac{5\sqrt{H} - d}{\ln(1 - n)} \right)^2 \quad (2.16)$$

where:

- E = the elastic modulus of the overburden
- ν = the Poisson's Ratio of the overburden
- E_s = the elastic modulus of the seam
- h = the seam thickness
- d = the extent of the coal yielding at the edge of the gob
- H = the seam depth
- n = given percent of the side abutment load, 90%

To simplify applying the above protocols and equations in LaModel, the lamination thickness wizard has been implemented into the new LamPre 3.0 to calibrate the rock mass stiffness.

2.2.1.3 Calibrating Coal Strength

Accurate in situ coal strength is another value which is very difficult to obtain and yet is critical to determining accurate pillar safety factors. It is difficult to get a representative laboratory test specimen for the coal strength and then scaling the laboratory values to

accurate in-situ coal pillar values is not very straightforward or precise (Mark & Barton, 1997).

In the LamPre program, users can choose the coal materials and set the coal properties. The most accurate calibration method for the coal is to determine the coal strength through back analysis consistent with the actual field measurements (Heasley, 2008). However, when the back analysis method is not applicable (no data is available), a default 900 psi in-situ coal strength is recommended. This value comes from the databases used to create the ALPS and ARMPS program and is supported by considerable empirical data (Mark, 1992; Mark & Barton, 1997; Mark & Chase, 1997). If the default 900 psi coal strength is used, the coal properties can be determined the stress gradient equation (see Equation 2.17) implied by the Mark-Bieniawski pillar strength formula (Mark, 1999).

$$\sigma_p(x) = S_i \left(0.64 + 2.16 \left(\frac{x}{h} \right) \right) \quad (2.17)$$

where:

- $\sigma_p(x)$ = peak coal stress, psi
- S_i = default in-situ coal strength of 900 psi
- x = distance into pillar
- h = seam thickness

To numerically simulate a yield zone in LaModel, concentric rings of different materials are used against the openings and the material properties of the ribs are set such that the pillar yields from the rib inward (see Figure 2.14). This type of yielding behavior matches that observed in the field. A systematic technique used in MULSIM (Zipf, 1992) for calculating these yielding coal properties based on the Mark-Bieniawski coal strength formula (Equation 2.12) and associated stress gradient (Equation 2.17) has been used in LamPre program.

Figure 2.14 Schematic of pillar loading and material code representation (Heasley et al., 2010).

Essentially, for an element at the side of a pillar (such as A, C and E in Figure 2.14), the element average peak strength is equal to the stress at the midpoint of the element as determined by Equation 2.17. For the corner elements, (such as B, D, F in Figure 2.14) which are needed to accurately approximate the Mark-Bieniawski pillar strength, the “pyramid-like” geometry produces an element average peak stress that is equal to the stress at the point one third of the distance across the element as determined by Equation 2.17.

A wizard for defining the coal properties in LamPre 3.0 can automate the coal strength calibration. The wizard assumes an elastic, perfectly-plastic material model and uses the Mark-Bieniawski pillar strength formula to produce sets of realistic coal material properties for the yield zone at the edges and corners of a pillar.

2.2.1.4 Calibrating Gob Stiffness

In a LaModel analysis with gob areas, an accurate stiffness for the gob (in relation to the stiffness of the rock) is critical to accurately calculating the overburden load distribution and therefore the pillar stresses and safety factors. The relative stiffness of the gob determines how much overburden weight is carried by the gob; and therefore, not carried by the surrounding pillars. This means that a stiffer gob carries more load and the

surrounding pillars carry less, while a softer gob carries less load and the surrounding pillars carry more. In LaModel, the stiffness of the gob is primarily determined by adjusting the “Final Modulus” of the strain-hardening gob model. A higher final modulus gives a stiffer gob and a lower modulus value produces a softer gob material (Heasley, 2008).

For a calibrated LaModel analysis, it is imperative that the gob stiffness be calibrated with the best available information on the amount of abutment load (or gob load) experienced at that mine. It would be best to use specific field measurements of the abutment load (or gob load) from the mine in order to calibrating the gob stiffness. However, these types of field measurements are quite rare and often of questionable accuracy. For estimating abutment loads or gob loads, visual observations are not very useful; and therefore, general historical measurements and/or empirical information are quite often the only available data.

In order to calibrate the gob stiffness for a practical situation, it is best to consider a number of general guiding factors. First, the critical depth should be known. Based on the “Abutment Angle” concept used in ALPS and ARMPS programs (Mark, 1992; Mark & Chase, 1997), the critical depth (H_c) for a given gob width (P) and abutment angle (β) can be calculated as Equation 2.18. Once the overburden density and the abutment angle (β) were know, the overburden load transferred to the gob can be determined based on the abutment angle concept illustrated in Figure 2.5.

$$H_c = \frac{P}{2 \times \tan(\beta)} \quad (2.18)$$

where:

H_c = critical depth

P = panel width

β = abutment angle

In both of the ALPS and ARMPS programs, an average abutment angle of 21 °was determined from an empirical database (Mark, 1992; Mark & Chase, 1997), and this is the default value which is also employed in the LamPre program (Heasley, 2008). Using an

abutment angle of 21° ; the average gob stress in the laminated overburden model at the actual seam depth (H) can be calculated (see Equations 2.5 and 2.7). Finally, the gob stiffness can be adjusted to match the desired average gob stress calculated through the “Abutment Angle” concept. To simplify this procedure, the above formulas were coded in LamPre 3.0 program to assist users to calibrate the gob stiffness through adjust its “Final Modulus.” As part of this calibration process, the program actually produces a two dimensional laminated model with the site specific geometry (depth, seam thickness, gob width, etc.) and geo-mechanical properties (rock mass stiffness, coal properties, etc.) and iteratively determines the “Final Gob Modulus” which will provide the desired overburden load on the gob.

2.2.2 Modeling

Once the material properties are defined and calibrated, the material grid can then be built by using the visual grid editor in LamPre program. Figure 2.15 shows the user-interface of the grid editor for defining and building a particular mine plan. When the basic mine layout is built, including pillars, gob areas and entries, the pillar yield zones can be applied automatically using the coal properties defined previously and the location of the element within the pillar.

as gob. The tricky part comes when a grid element overlaps different areas in the mine plan. In this case, the element is assigned to a material based on one of two algorithms explained below.

Figure 2.16 shows the AutoCAD grid generator user interface which contains two tabs, “Grid Dimension” and “Build Grid.” The “Grid Dimension” tab has two sections, “Grid Location” and “Grid Geometry.” In the “Grid Dimension” tab, users can set the grid origin, rotation angle and cell size and grid size.

Figure 2.16 Interface of advanced grid generator.

Figure 2.17 shows the “Build Grid” tab, which contains the specifications for “Output File,” “Pillar Layer,” “Gob Layer,” “Element Code” and “Algorithm.” As you can see, two

algorithms were implemented to accomplish the gridding task: the middle point method and the area-based method (Wang, 2005).

Figure 2.17 Gridding method options in advanced grid generator.

The middle point algorithm uses the center point of the grid element as the critical element point. If this center point is inside one of the polygons in the AutoCAD mine map, the algorithm assumes that the whole element consists of the material associated with the given polygon. This middle point algorithm is very fast, but can be inaccurate in complex geometries. This middle point algorithm uses the classic ray crossing algorithm (Žalik & Kolingerova, 2001). The ray crossing algorithm is one simple way of finding whether a point is inside or outside a complex polygon by counting how many times a ray, starting from the point and going any fixed direction, intersects the edges of the polygon. If the

number of intersection points is an even number, the point is outside the polygon; if the number of intersections is an odd number, the point is inside the polygon.

The area-based algorithm examines the overlap area between the feature boundary and the rectangular element. The element is considered to be inside the polygon when the overlapped area is larger than a specified percentage (typically 50%) of the element area. The intersection polygon is defined by clipping each grid element polygon with the geological feature boundaries. In general, a polygonal boundary would be clipped against each edge of the element polygon one at a time. The cell/edge intersections, if any, kept after clipping against one cell edge are saved for clipping against the remaining edges.

The clipping algorithm applied in the module is similar to the Sutherland-Hodgman polygon clipping algorithm (Foley et al., 1996). It works by extending each line of the convex clip polygon in turn and selecting only vertices from the subject polygon that are on the visible side. The algorithm begins with an input list of all vertices in the subject polygon. Next, one side of the clip polygon is extended infinitely in both directions, and the path of the subject polygon is traversed. Vertices from the input list are inserted into an output list if they lie on the visible side of the extended clip polygon line, and new vertices are added to the output list where the subject polygon path crosses the extended clip polygon line. This process is repeated iteratively for each clip polygon side, using the output list from one stage as the input list for the next. Once all sides of the clip polygon have been processed, the final generated list of vertices defines a new single polygon that is entirely visible. The area-based algorithm takes longer, but is generally more accurate than the middle point algorithm, especially in complex geometries.

2.2.3 Analysis

Once the input for the numerical model is defined and built, it needs to be saved in a LaModel compatible input file (.INP file). This file is then imported into the LaModel numerical calculation program to run and solve the model. After solving the model, the results are extracted and saved in a LaModel compatible output file (.f1 file), which can be viewed in the LamPlt program. Figure 2.18 shows the user interface of the LamPlt program.

It is a powerful graphic solution providing several graphic plotting options: colored-square, cross section, history and 3D Fishnet.

Figure 2.18 User interface of the LamPlt program.

2.3 Recent Comparison between ARMPS and LaModel in Deep-Cover Mining

Recent research conducted by Tulu et al. (2010) compared and analyzed the overburden loading and stability factors calculated by the ARMPS 2010 and the LaModel 3.0 program. A number of distinct differences in loading distributions between the ARMPS 2010 and LaModel 3.0 programs were found and discussed. Further, a small database of 52 deep-cover case histories (Heasley et al., 2010) was used for evaluating the ability of each program to discriminate between successful and unsuccessful retreat pillar plans.

To investigate the functional differences between the loading mechanisms in ARMPS 2010 and LaModel 3.0 programs, the magnitude of the overburden loads from the programs on different areas during retreat mining cycle was analyzed. Figure 2.19 shows the analyzed areas including the AMZ, active gob, barrier pillar, side gob and adjacent panel. The loading cycle included four mining stages: development loading; development and first side gob loading; development, first side and active gob loading; development, first side, active gob and slab cut loading. To be consistent with the ARMPS analysis, the LaModel analysis had the exact same mine geometry, seam thickness, and overburden

depth. Also, the overburden lamination thickness, gob stiffness and coal strength were calibrated as recommend by Heasley (2008).

Figure 2.19 Retreat panel used to analyze loading mechanisms (Tulu et al., 2010).

The analysis of the overburden loads between ARMPS 2010 and LaModel 3.0 indicated that for the ARMPS 2010 program, the pressure arch factor has resulted generally lowering the load on the AMZ and therefore generally increasing the stability factor and eliminating the depth effect on the stability factor in ARMPS 2010 (as designed). Moreover, 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.

Compared with ARMPS 2010, the LaModel program distributes more load to the inby and outby barrier pillars as well as to the adjacent panel. The slab cut causes additional

front abutment load to the AMZ and outby barrier pillar; however, it was noted that ARMPS 2010 did not distribute any of the slab cutting loading back to the gob areas whereas the LaModel 3.0 program did. In general, any perturbation in the loading in LaModel is distributed throughout the mining area as a function of the relative stiffness of the various mining structures. In contrast, ARMPS 2010 redistributes loads to specific areas based on empirically determined approximations. In general, for the critical loading on the AMZ in this deep-cover analysis, LaModel predicts more load than ARMPS 2010. However, it was noticed 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.

Another analysis performed with ARMPS 2010 and LaModel in this previous research was to compare the stability factors calculated for each case history in the deep-cover database. In this comparison, the cut-off stability factor of 1.50 was employed for both ARMPS 2010 and LaModel 3.0 programs. The results of the database analysis are presented in Figure 2.20 (Tulu et al., 2010). For ARMPS 2010, 52% of the failed case histories and 55% of the successful case histories were correctly classified for an overall classification accuracy of 54% (see Figure 2.20a). While for LaModel 3.0, 76% of the failed case histories and 48% of the successful case histories were correctly classified for an overall classification accuracy of 60% (see Figure 2.20b). There is not a very decisive difference between the stability factor analyses of these two programs. However, for this relatively small database, LaModel may be considered to have better performance in classifying the deep-cover case histories. To be specific, the LaModel 3.0 program more accurately classified the 52 case histories than the ARMPS 2010 by a factor of 60% versus 54%. The LaModel 3.0 program also more accurately classified the unsuccessful case histories than the ARMPS 2010 by a factor of 76% versus 52%.

a. Stability factor analysis with ARMPS 2010.

b. Stability factor analysis with LaModel 3.0.

Figure 2.20 Comparison between ARMPS 2010 and LaModel 3.0 (Tulu et al., 2010).

In summary, in ARMPS 2010, the shedding of load due to the formation of a pressure arch and barrier pillar failure seems to be reasonable. However, the 3D load distribution produced by the LaModel program provides a better classification of the case histories in

this study. If the same improvement is seen for the entire ARMPS database, then there is a considerable potential to improve current room-and-pillar design classification accuracy using the laminated overburden model. In this previous research, the LaModel analysis of each case study required several days to complete. Most of the time and effort was spent on developing the mine grid and analyzing the stability factor within the AMZ. However, it is possible to greatly automate the LaModel analysis of these ARMPS-type mine designs, which will greatly improve the speed of room-and-pillar mine design analysis using LaModel.

Chapter 3. Integrating the Laminated Overburden Model and ARMPS

In this research, a computer code, ARMPS-LAM, has been developed to effectively integrate the laminated overburden model into the ARMPS program. ARMPS-LAM functions as an automated solution for a LaModel analysis of an ARMPS-type mine design. Basically, ARMPS-LAM program takes the basic ARMPS geometric input and empirical parameters for defining the mining plan and loading condition; and then automatically conducts a complete LaModel analysis to calculate the stability factor on the AMZ (and barrier pillars), all without further user input. The program contains the necessary modules for covering all aspects and procedures of a full LaModel analysis, from pre-processing to post-processing. From the user perspective, only the traditional ARMPS input is required. And, similarly to ARMPS, the output contains the AMZ SF, barrier pillars SF and other loading and strength data; however, these output values are now calculated using the laminated overburden model. In this chapter, the program structure, primary modules and their internal subroutines are introduced and discussed.

3.1 General Program Structure

The ARMPS-LAM program consists of three primary modules: pre-processing, numerical solution and post-processing. To further illustrate the above modules and their subroutines, the general program structure is presented in Figure 3.1 (Details of the flowchart symbols are presented in Appendix C). The pre-processing module includes the necessary subroutines to import data, develop, and calibrate the laminated overburden model. The numerical solution module solves the laminated overburden model. The post-processing module contains the subroutines to automatically extract and calculate the stability factors and pillar loadings and then output the important data.

Figure 3.1 General flowchart of the ARMPS-LAM program structure.

To completely automate the model building and analysis process, numerous complex algorithms and mathematical formulas needed to be developed and implemented into the ARMPS-LAM program. Fortunately, many of these algorithms and formulas associated with material property calculation and calibration, and the mathematical solution had already been developed and implemented in previous work (Heasley, 1998, 2008; Heasley et al., 2010). However, to completely automate the calibration, mine map gridding and post-processing for ARMPS-LAM, quite a number of new and unique algorithms needed to be developed. The major steps in the automatic development and analysis of the laminated overburden model (LaModel) in ARMPS-LAM are listed below and further detailed in the following sections:

Required Pre-processing Modules

- **Data Import:** Read the input file containing the ARMPS 2010 like data, which is in MS Excel compatible format.
- **Property Calibration:** Determine the appropriate properties for the overburden, coal and gob materials based on the LaModel calibration procedures (as discussed in Chapter 2).
- **Boundary Buffer Sizing:** Based on the input mine geometry and calibrated overburden properties, determine the radius of displacement and stress influence, thereby defining the required size for the boundary pillars around the edge of the model.
- **Mine Model Sizing:** Based on the input mine geometry and the required boundary pillar sizes, determine the overall physical size for the model grid.
- **Mine Map Generation:** Based on the input mine geometry and the required boundary pillar sizes, generate the exact boundary lines for all of the mine pillar and gob areas and output as an AutoCAD file.
- **Element Sizing:** Based on the overall model dimensions and the dimensions of the entries and pillars, determine an optimum element size.

- **Grid Generation:** Insert the coal and gob materials into the mine grid based on the pillar and gob locations.
- **Yield Zone Application:** Apply the yield zones to the pillars based on the Mark-Bieniawski stress gradient.
- **Input File Generation:** Generate and output the LaModel input file based on the final material properties and mine grid. (This input file is a fully compatible LaModel 3.0 input file). Save the imported data and calculated results to a debugging file generated by the post-processing module.

Required Numerical Solution Module

- **Run the Model:** Solve the model using LaModel and generate the output file (The solution is identical to LaModel 3.0 and the output file at this phase is a fully compatible LaModel 3.0 output file). Save the numerical calculation information to a debugging file generated by the post-processing module.

Required Post-processing Module

- **Calculate Stability Factors:** From the LaModel output file, determine and save the stability factors of the AMZ and barrier pillars and other important data to a text file. This module will also generate another text file for debugging, which includes the information of pre-processing, numerical calculation and post-processing.

3.2 Pre-processing Module

3.2.1 Data Import

For importing data to the ARMPS-LAM program, the necessary parameters for a single case history are entered on a single line (see Appendix A) in a text formatted file. For ARMPS-LAM, the import subroutine will general read a single case history from a single line. However, in order to run a large database of multiple case histories using this program, the “Data Import” subroutine is also designed to read multiple input lines from the ARMPS

input (each line represents a single ARMPS case). The general flowchart for this subroutine is presented in Figure 3.2. Before reading the ARMPS input data, the subroutine will check whether the MS Excel file (CSV file) actually has valid data in order to eliminate unpredictable errors later on. Then, it will start an iteration to read and save the case history data line by line. During this process a counter (i) will count the lines. The saved case history data will be used by the other subroutines to automatically develop and analyze the laminated overburden model. The subroutine will end when the last line is read into the program.

Figure 3.2 Flowchart of data import.

The ARMPS-LAM program is designed to extract the geometry and empirical input data from both the single case and the multiple case ARMPS database. Since the current ARMPS case history database is saved in a Microsoft (MS) Excel file which can easily be exported as a comma-separated (CSV) file, it was determined to use the CSV format for the ARMPS-LAM input file. A CSV file stores tabular data (numbers and text) in a plain text format with the columns separated by comma. No further interpretation or code libraries are needed for reading a CSV file, and its format will not change with updates to the underlying programs. It is believed that this CSV format will help maintain compatibility with the present (and future) ARMPS case history database and help minimize code maintenance requirements.

The import data structure for ARMPS-LAM is based on the ARMPS case history database (supplied in the installation directory of ARMPS 2010). However, the latest ARMPS 2010 program has upgraded the mine plan layout, where users can now configure bleeder pillars (leave blocks) in the AMZ (see Figure 3.3) (Mark, 2010). These bleeder pillars may be left next to the barrier pillars within the active panel and/or in the adjacent panel(s). Up to four rows of bleeder blocks can be left and their dimensions can be set in ARMPS 2010. As seen in Figure 3.3, rows A and B are within the active panel and rows C and D are in the adjacent side gobs. For rows A and B, the bleeder pillars' sizes are the same as that of the pillars in the active panel. However, for rows C and D, the width of bleeder blocks can be set in the input, but their length is assumed to be the same as that of the pillars in the active panel.

Figure 3.3 Bleeder pillars (leave blocks) in ARMPS 2010 (Mark et al., 2011).

The most current ARMPS case history database does not contain the new capabilities of bleeder pillars. Therefore, the ARMPS-LAM input data is designed to not only include all of the 37 items in the original ARMPS database, but also contain the 15 additional items listed in Table 3.1 to handle the bleeder pillars. For the current ARMPS database, the data of each case history includes: mine plan geometry (e.g., entry width, crosscut angle, crosscut spacing, entry spacing, gob extent, etc.), abutment angle, in-situ coal strength, breadth of AMZ, layout information (e.g., loading condition, bleeder pillar, etc.), serial number, mine information (e.g., name and region), roof strength rating, CMRR and outcome (successful or unsuccessful, only for case history). In addition to the items in the current ARMPS database, additional input items for ARMPS-LAM include: unit system, in-situ coal strength, overburden weight, breadth of AMZ, abutment angles, bleeder pillar sizes and element size. Therefore, the entire ARMPS-LAM input data line now contains 52 items as seen in Appendix A.

Table 3.1 Additional items in the ARMPS-LAM input data.

Item Name	Description
Unit	‘0’ represents “ft, lbs”; ‘1’ represents “m, kN”
Coal strength	In-situ coal strength, psi or MPa, based on unit
Overburden weight	Overburden weight, pcf or kN/m ³ , based on unit
Breadth of AMZ	Breadth of AMZ, default value is $5\sqrt{H}$
Abutment angle: Active gob	Abutment angle of active gob, default is 21 °
Abutment angle: 1st side gob	Abutment angle of 1st side gob, default is 21 °
Abutment angle: 2nd side gob	Abutment angle of 2nd side gob, default is 21 °
Bleeder pillar: Row A	Left bleeder pillar in AMZ, ‘0’ – No, ‘1’ - Yes
Bleeder pillar: Row B	Right bleeder pillar in AMZ, ‘0’ – No, ‘1’ - Yes
Bleeder pillar: Row C	Bleeder pillar in 1 st side gob, ‘0’ – No, ‘1’ - Yes
Bleeder pillar: Row D	Bleeder pillar in 2 nd side gob, ‘0’ – No, ‘1’ - Yes
Bleeder pillar: Width of Row C	Width of bleeder pillar in 1 st side gob, rib-to-rib
Bleeder pillar: Width of Row D	Width of bleeder pillar in 2 nd side gob, rib-to-rib
Element size value	‘0’ represents using ARMPS-LAM to determine element size; ‘1’ means using user defined value
User defined element size	Users defined element size, default is 0

3.2.2 Property Calibration

In ARMPS-LAM, the laminated overburden model is calibrated based on the ARMPS input, including the mine plan geometry and the empirical parameters used in ARMPS, i.e., the abutment angle and in-situ coal strength. In order to automate the calibration procedure in the ARMPS-LAM program, the pre-existing algorithms (discussed in section 2.2.1) in LamPre (Heasley, 2008; Heasley et al., 2010) were further coded in such a way that the calibration procedure and required parameters were based on the ARMPS input and some predefined default parameters. The specific automatic calibration procedure for the rock mass stiffness, coal strength and gob stiffness are discussed below.

3.2.2.1 Calibrating Rock Mass Stiffness

In previous research, the calibration of the rock mass stiffness has been developed and automated (Heasley, 2008). In the ARMPS-LAM program, the same algorithm discussed in section 2.2.1.2 was used: the rock mass modulus is fixed and then the lamination thickness is solely adjusted to get the desired default 90% abutment load extent of $5\sqrt{H}$. Some parameters are fixed in order to completely automate this calibration procedure based on the ARMPS input. Specifically, for the rock mass, the elastic modulus and Poisson's ratio use the default values of 3,000,000 psi and 0.25, respectively. The vertical stress gradient uses the default input value (162 pcf) from the ARMPS input. For the seam parameters, except for the elastic modulus (which defaults to 300,000 psi), all of the other parameters: seam thickness, seam depth, gob width and in-situ coal strength, come from the ARMPS input values.

3.2.2.2 Calibrating Coal Strength

The in-situ coal strength from the input file is used for calculating the Mark-Bieniawski coal strength. For most conditions, 900 psi is the default; however, users can change its value in the ARMPS-LAM input file. The generation of appropriate element strengths is the same as those previous discussed in section 2.2.1.3 (Heasley, 2008).

3.2.2.3 Calibrating Gob Stiffness

The gob stiffness calibration procedure has been previously developed and automated in LamPre 3.0 as discussed in section 2.2.1.4 (Heasley, 2008). The same automation algorithm was slightly adjusted to completely automate the gob stiffness calibration in ARMPS-LAM. This subroutine uses the values read from the ARMPS input to calibrate each gob area. An abutment angle of 21° is still the default but users can change it in the input file. Since the ARMPS input parameters don't contain any of the parameters for the gob material, default values are used. Specifically, the initial gob modulus, upper limit gob stress and gob height factor are set at the recommended default values of: 100 psi, 4,000 psi and 1.0, respectively.

In the ARMPS database (and when running ARMPS), it is very common that a large value, e.g., 1,000 ft, is used to represent a supercritical gob condition which may be much larger in reality. This is reasonable since a larger value than the supercritical distance will not contribute to additional loading on the AMZ. However, for the laminated overburden model, the gob width is critical for calibrating the final gob modulus. Moreover, an excessively large gob will unnecessarily increase the model size, and an extremely large model will greatly extend the program running time without necessarily improving the model accuracy (see section 3.2.4). Considering the above facts, ARMPS-LAM uses a threshold of gob width based on the model input to determine a reasonable gob size. Specifically, this threshold (or supercritical) gob width is set at two times the “Boundary Buffer Size,” which is described in detail in section 3.2.3. If the input gob width is greater than this threshold value, it will be shortened to the threshold value and then used to calculate the gob stiffness. Otherwise, if the input gob width is less than the threshold value, the original input width will be used for calibrating the gob stiffness.

Figure 3.4 illustrates the procedure for calibrating the gob stiffness. For each case history, the subroutine will access the ARMPS-LAM input and set the value of “threshold gob width” as two times of the “Boundary Buffer Size.” Then, the subroutine will start an iteration to calibrate the gob stiffness for individual each gob in the model. For each gob area, the subroutine will compare the gob width with the gob threshold width first. If the input width is greater than the threshold, its value will be substituted by the threshold; otherwise, its value will not be changed. Next, in the iteration, the gob stiffness will be calibrated. Based on the abutment angle concept, the average gob stress ($\sigma_{\text{Abut-gob-ave}}$) can be determined from the given abutment angle, β . Then, identical to the procedure discussed in section 2.2.1.4 (Heasley, 2008), the program will produce a 2D LaModel with same site geometry. Then, it iteratively determines the “Final Gob Modulus” which will provide the desired average gob stress determined by the abutment angle concept ($\sigma_{\text{Abut-gob-ave}}$). After calibrating the gob stiffness for all of the gob areas, the calculated “Final Gob Modulus” for each gob will be saved in the program for generating the LaModel compatible input file.

Figure 3.4 Flowchart of gob stiffness calibration.

3.2.3 Boundary Buffer Sizing

3.2.3.1 Buffer Zone Algorithm

For LaModel, stress and displacement effects from the boundary of the mine grid can cause errors in the numerical calculations at the center of the grid, if the grid boundary is too close. In order to help eliminate the boundary effect on the critical areas of the model, a sufficient buffer area is needed around the edge of the model. For the boundary buffer zone, it could be a solid pillar or a gob material. In the ARMPS program, the user can set the side gob width. However, in LaModel analysis, it should be noted that too narrow a side gob may not effectively eliminate the boundary effect; while an overly wide gob may eliminate the boundary effect but will require a much longer running time without improving the model's accuracy. The same buffer size situation exists for the active gob. Therefore, to balance the numerical calculation accuracy and program running time, an algorithm was determined to create an optimally sized buffer zone.

According to field observations, the abutment load has an average full extent of $9.3\sqrt{H}$ (Mark, 1992), and the LaModel calibration process give the overburden stiffness a similar influence zone. In order to be a bit conservative, the minimum buffer distance in ARMPS-LAM has been set at twice the single abutment extent of $18.6\sqrt{H}$. Since the center of a gob is potentially influenced from both abutments on either side, the threshold for a supercritical gob is set to be two times the $18.6\sqrt{H}$ (or $37.2\sqrt{H}$) to eliminate the abutment effect in the gob. Therefore, when a side gob width is smaller than $37.2\sqrt{H}$, a solid pillar with a width of $18.6\sqrt{H}$ will be created on the boundary side of the gob. The same approach is used for the length of an active gob. With these buffer distances, the AMZ has sufficient distance to the edge of model boundary to eliminate any edge effect. The flowchart of the subroutine which determines the buffer sizes of the gob and barrier pillar is shown in Figure 3.5.

Note: i is gob index where 2 is active gob, 3 is 1st side gob, 4 is 2nd side gob.

Figure 3.5 Flowchart of buffer zone algorithm.

First, this subroutine will access the ARMPS input and use the depth of cover (H) to calculate the values of $18.6\sqrt{H}$ and $37.2\sqrt{H}$. Then, it starts an iteration to check each gob

width to determine the buffer zone size (consistent with the ARMPS code, i is the gob index, 2 represents active gob, 3 represents 1st side gob, 4 represents 2nd side gob). If a gob width is less than $37.2\sqrt{H}$, the gob width will keep its value and a boundary buffer pillar will be created with a width of $18.6\sqrt{H}$ on the boundary side of the gob; otherwise, the gob width will be substituted by $37.2\sqrt{H}$ and no buffer pillar will be created. Finally, the results will be saved for generating the mine map.

3.2.3.2 Optimum Buffer Zone

In order to investigate the practical minimum buffer distance, five different values were selected ($5\sqrt{H}$, $9.3\sqrt{H}$, $12.4\sqrt{H}$, $15.5\sqrt{H}$ and $18.6\sqrt{H}$) and used to investigate the influence of the buffer distance on the accuracy of the AMZ SF. For this analysis, a subset of the most current ARMPS database consisting of fifty case histories was used. These fifty case histories all use the third loading condition in ARMPS, meaning the mine plans contain an active gob and one side gob. Additionally, the fifty case histories were selected in such a way that the range of input parameters matched the range of values observed in the ARMPS database (318 case histories). Table 3.2 lists the geometry ranges of the fifty case histories. The mining height ranges from 2.5 to 15 ft, the depth ranges from 240 to 2,200 ft, the active gob extent ranges from 200 to 3,000 ft, the 1st side gob ranges from 0 to 2,530 ft, the 1st side barrier pillar width ranges from 0 to 360 ft, the panel width ranges from 80 ft to 1,260 ft and the panel width-to-depth ratio ranges from 0.08 to 3.36.

Table 3.2 Mine geometry ranges of the selected fifty case histories.

	Mining Height	Depth	Front Gob Extent	1st Side Gob Extent	1st Side Barrier Pillar Width	Panel Width	Panel Width / Depth
Min	2.50	240	200	0	0	80	0.08
Max	15.00	2,200	3,000	2,530	360	1,260	3.36
Ave.	6.91	975	897	527	91	358	0.56

The above five buffer distances were applied to the boundary buffer zone and the effect on the AMZ SF was compared after running the fifty case histories (see Table 3.3 and Figure 3.6). For this comparison, the program was set to develop a mine grid with a maximum grid size of 2,000 by 2,000 for all of the buffer sizes. Also, the optimum element size determined for the $18.6\sqrt{H}$ buffer size was used for all of the models.

Table 3.3 Comparison of AMZ SF different with different boundary buffer zones.

Items			$5\sqrt{H}$	$9.3\sqrt{H}$	$12.4\sqrt{H}$	$15.5\sqrt{H}$	$18.6\sqrt{H}$
AMZ SF Error	Value	Ave.	0.0325	0.0090	0.0070	0.0062	0.0
		Stand. Dev.	0.0499	0.0131	0.0140	0.0116	0.0
	Percent	Ave.	1.72%	0.76%	0.66%	0.58%	0.0%
		Stand. Dev.	1.98%	1.69%	1.75%	1.60%	0.0%
Ave. Running Time (s)			9	22	32	43	61

Figure 3.6 Average AMZ SF error vs. boundary pillar sizes.

In order to compare the numerical calculation accuracy of using the different values for the buffer zone, the AMZ SF error (absolute difference in AMZ SF) was analyzed (see Table 3.3 and Figure 3.6), since the classification of a room-and-pillar mine design is based on the value of AMZ SF in an ARMPS analysis (Mark, 2010; Mark & Chase, 1997). To calculate the AMZ SF error for each case history, the calculated AMZ SF using the $18.6\sqrt{H}$ as the boundary buffer zone was selected as the most accurate or “Base” value. Then, the absolute differences of the AMZ SF values between the various buffer distances were used as the AMZ SF error. Finally, for all fifty case histories, the average value of the AMZ SF error were calculated and shown in Table 3.3 and Figure 3.6.

To determine a required SF limit, it is assumed that for an ARMPS analysis, the AMZ SF generally has an apparent accuracy of two decimal places. In that case, if the AMZ SF error is less than 0.005, the changes in the buffer zone size will not “significantly” affect the results of AMZ SF calculation. Therefore, an optimum value of the boundary buffer zone should meet the AMZ SF accuracy requirement, i.e., AMZ SF error < 0.005. The AMZ SF accuracy requirement is highlighted by a red line in Figure 3.6.

After running the fifty case histories using different values as the boundary buffer zone, the average values and standard deviations of the AMZ SF error were determined and shown in Table 3.3 and Figure 3.6. If the boundary buffer zone is $5\sqrt{H}$, $9.3\sqrt{H}$, $12.4\sqrt{H}$ and $15.5\sqrt{H}$, the average AMZ SF errors are 0.0325 (1.72%), 0.0090 (0.76%), 0.0070 (0.66%) and 0.0062 (0.58%), respectively. Note that the accuracy increases as the buffer zone size increases and that all of the errors are below 2%. However, none of the lower values can meet the SF desired accuracy requirement of 0.005 (although very close). Further, with the increase in buffer size from $5\sqrt{H}$ to $18.6\sqrt{H}$, the program running time increases from 9 second to 61 second.

Ultimately, based on this analysis above, the $18.6\sqrt{H}$ was selected as the optimum value of the boundary buffer zone, where the radius of stress influence has a practically negligible boundary effect on the AMZ SF, and the program running time is around one minute.

3.2.4 Mine Model Sizing

This subroutine mainly consists of geometric calculation and logic algorithms. This subroutine determines the model dimensions to be used in generating the AutoCAD mine map. In this subroutine, similar to the simplified mine layout used in ARMPS, the mine layout includes: the active gob, side gobs, AMZ, barrier pillars, slab cuts and bleeder pillars. However, in ARMPS-LAM, the model also may include the boundary buffer pillar to help eliminate the boundary effects. Figure 3.7 shows the flowchart of the mine model sizing subroutine. This subroutine uses the ARMPS input and previously calculated boundary buffer zone size to determine the mine model geometry. Based on the mine geometry

components, this subroutine calculates the overall model width and length separately. The components for calculating model width and length were shown in Figure 3.7 and discussed below.

Figure 3.7 General flowchart of mine model sizing.

To illustrate the generated mine model, a schematic mine map with the 4th loading condition (two side gobs) is shown in Figure 3.8. This figure shows the most complex geometric model in ARMPS including: two side gobs, two boundary pillars, three bleeder

pillars, and a slab cut. As shown in Figure 3.8, the coordinate origin is set at top-left corner of the AMZ. Because the side gob widths, WSG(3) and WSG(4) were smaller than the boundary buffer zone, two boundary pillar were created with widths of WSB(3) and WSB(4). Bleeder pillars of Row B extended to the top boundary pillar; bleeder pillars of Row C and Row D were on each side of the active panel. The barrier pillar widths were WBAR(3) and WBAR(4). The active gob extent, LAG, was smaller than two times the boundary buffer zone; therefore, a top buffer pillar was created with a length of LTB. Below the AMZ, the panel pillars extended to the bottom of the grid with a length of LBB. Details of each model component, and the calculation of model width and model length are discussed below.

Figure 3.8 Schematic of non-scale mine geometry in ARMPS-LAM.

3.2.4.1 Model Width

The model width includes: the width of the side buffer pillar, first side gob width, first side bleeder pillar width, first side barrier pillar width, the active panel width, the second side barrier pillar width, the second side bleeder pillar width, the second side gob width and the second side buffer pillar. Each component is described below and is illustrated in Figure 3.8.

- Side Buffer Pillar: The width of the buffer pillar is determined by the boundary buffer sizing subroutine. When the side gob width is smaller than two times the buffer zone, a boundary pillar with a width of buffer zone will be created on the boundary side of the gob, otherwise, there will not be a side buffer pillar on that side.
- Side Gob Width: If its value is greater than two times the buffer zone, it will be reset to two times the buffer zone; otherwise, it will not change.
- Bleeder Pillar Width: is same as the value used in ARMPS input.
- Barrier Pillar Width: is same as the value used in ARMPS input.
- Active Panel Width: is same as the panel width determined by the ARMPS input.

The total model width (TMW) is the sum of above components, which is shown in Equation 3.1 and is illustrated in Figure 3.8.

$$TMW = \sum_{i=3}^4 [WSB(i) + WSG(i) + WSBP(i) + WBAR(i)] + WAP \quad (3.1)$$

In this equation, consistent with the ARMPS code, the first side is designated by the index of 3 and the second side is designated by the index of 4. The “Side Buffer Pillar” listed above includes the widths of first and second boundary pillars, i.e., WSB(3) and WSB(4). The “Side Gob Width” includes the widths of first and second side gobs, i.e., WSG(3) and WSG(4). The “Bleeder Pillar Width” includes the widths of first and second

bleeder pillars (leave blocks), i.e., WSBP(3) and WSBP(4). The “Barrier Pillar Width” includes the widths of first and second side barrier pillars, WBAR(3) and WBAR(4). The “Active Panel Width” is represented by the WAP. Figure 3.8 shows a schematic mine map which illustrates the above components for calculating the model width.

3.2.4.2 Model Length

The model length includes: the length of the top buffer pillar, active gob length, AMZ breadth and the length of the bottom buffer pillar (see Figure 3.8). Each component is described below.

- Top Buffer Pillar: It is determined by the boundary buffer sizing subroutine. When the active gob width is smaller than two times the buffer zone, a boundary pillar with a width of buffer zone will be created on the boundary side of the gob otherwise, there will not be a top buffer pillar on the top boundary.
- Active Gob Length: is the length input by the user, or if the input length is greater than two times the buffer zone, its length will be substituted by two times the buffer zone.
- AMZ Breadth: is same as the value used in ARMPS input.
- Bottom Buffer Pillar: extend the pillars in the AMZ to the bottom of the grid. The pillars below the AMZ are called bottom buffer pillars. Their total length is set to the extent of the required buffer zone.

The total model length (TML) is the sum of the above components. Equation 3.2 shows its value in equation form. The “Top Buffer Pillar” is the length of the top boundary buffer pillar (LTB) above the active gob. The “Active Gob Length” is represented by the LAG. The “AMZ Breadth” is the breadth of the AMZ (AMZ). The “Bottom Buffer Pillar” is the length of extended buffer pillars (LBB) below the AMZ.

$$\text{TML} = \text{LTB} + \text{LAG} + \text{AMZ} + \text{LBB} \quad (3.2)$$

3.2.5 Mine Map Generation

Typically, for the LaModel analysis of an actual room-and-pillar mine design, an AutoCAD mine map of the pillar plan is used to develop the mine grid. In ARMPS-LAM, in order to stay consistent/compatible with the LaModel program, an AutoCAD mine map of the pillar plan (similar to that shown in Figure 3.8) is generated from the mine geometry information in the ARMPS input and the calculated mine model size.

In the generated AutoCAD mine map, all of the pillars and gobs are created as closed polylines with the origin of the coordinate system set at the top-left corner of the first pillar line (see Figure 3.8). The pillars and gobs are in the layers of “Pillar” and “Gob,” respectively.

This mine map is saved as the DXF file format. The DXF file extension is the abbreviation of “Drawing Exchange Format,” which is an AutoCAD file format developed by Autodesk for enabling data interoperability between AutoCAD and other programs (Lang & Klameja, 2011). In ARMPS-LAM, the generated AutoCAD file will have a fixed name of “*.DXF” where the “*” represents the base of the input file name. For example, if the input file is “Test.csv”; then, the output DXF is named “Test.DXF.”

3.2.6 Element Sizing

3.2.6.1 Element Size Algorithm

Based on previous experience with LaModel, it is known that the element size has an effect on the model gridding accuracy and associated errors in the numerical calculation. The gridding accuracy in LaModel is essentially how well the element size fits the mine geometry. It is the difference in area between the simulated areas with discrete elements versus the true area of the mine geometry. For example, a pillar has an area of 10 ft by 10 ft and the generated pillar grid has an area of 9 ft by 9 ft with an element size of 9 ft. In that case, the gridding accuracy is 81%, e.g., the grid area of 81 ft^2 against true pillar area of 100 ft^2 . To minimize the gridding errors and improve the numerical calculation accuracy, a subroutine was developed to automatically determine the optimum element size within the constraints of the given model size and maximum grid dimensions.

The general flowchart of this subroutine is shown in Figure 3.9. First, the maximum grid size and element size are set based on the present defaults (1,000 elements and 10 ft, respectively). Then, based on the calculated model width, length, barrier pillar width, max grid size and material limit (maximum 52 materials can be defined in ARMPS-LAM), the minimum element size can be calculated using the largest value among A, B and C, which are shown in Figure 3.9. Specifically, the minimum element size is the largest of: the “Model width / Max grid size,” the “Model length / Max grid size” or the “Max barrier pillar width / Material limit.” Next, the subroutine starts to iterate and checks all of the possible element widths between the minimum and maximum with an increment of 0.01 ft. For each iteration, the AMZ area error and the AMZ grid size will be calculated. The AMZ error represents the difference in area between the simulated AMZ with discrete element sizes versus the true area of the AMZ.

In the algorithm, the entry width, pillar width, pillar length and the grid size are given different weights to calculate the AMZ area error and the AMZ grid size. It should be noted that the weights are given in such a way that: fitting the entry is more important than fitting the pillar; an integer value is more desirable than a decimal values; and a larger element size is better than smaller element size. For example, if the entry width, pillar width and length are 18 ft, 49 ft and 49 ft, respectively. Instead of using 7 ft to fit the pillar, 3 ft or 6 ft is better, because 3 ft or 6 ft can perfectly fit the entry and have an equal error on fitting the pillar. Here, 6 ft is better than 3ft, because 6 ft is greater than 3 ft and both of them can fit the entry exactly and have a similar error on pillar fitting.

In the iteration, the element size, which has the smallest values for the AMZ area error, and the AMZ grid size will be saved as the optimum element size. Using this algorithm the 645 case histories were analyzed, and 10% (or 65 case histories) have an optimum element size with two decimals, 20% (or 131 case histories) have an optimum element size with one decimal and 70% (or 449 case histories) have an integer element size.

Figure 3.9 General flowchart of optimum element size calculation.

3.2.6.2 Optimum Element Size

In order to investigate the effect of various element sizes on SF accuracy and run times, the optimum element size (from the sizing algorithm discussed above) was compared against three fixed element sizes, 10 ft, 5 ft and 2.5 ft (see Table 3.4). The optimizing algorithm, denoted as “Auto” in Table 3.4 and Figure 3.10, can automatically determine a best fit element size based on the gridding accuracy of the AMZ. In this comparison, a constant boundary buffer zone distance of $18.6\sqrt{H}$ was used, and the maximum grid size was set as 2,000 by 2,000. The same abbreviated but broad database (50 cases) used in evaluating the boundary buffer zone was used to analyze the influence of element size on the AMZ SF accuracy.

The true value of the AMZ SF is not known; therefore, in this analysis it is assumed that the automatic sizing algorithm (which produces an element size which best fits the section geometry) produces the most accurate SF. Then, the absolute differences of the AMZ SF between using other element sizes versus using the “element sizing algorithm” were calculated as the AMZ SF error. Table 3.4 and Figure 3.10 compare the AMZ SF error and the program running times.

Table 3.4 Comparison of AMZ SF with different element sizes.

Items			Element Size			
			10 ft	5 ft	2.5 ft	Auto
AMZ SF Error	Value	Average	0.0834	0.0299	0.0202	0.0000
		Standard deviation	0.0855	0.0579	0.0259	0.0000
	Percent	Average	5.84%	1.92%	1.11%	0.00%
		Standard deviation	6.03%	3.39%	1.23%	0.00%
Average Running Time (s)			10	73	1,012	61

Note: “Auto” represents the element sizing algorithm discussed above.

Figure 3.10 Average AMZ SF error vs. element size.

Table 3.4 and Figure 3.10 show that when a large element size of 10 ft was applied to each case history, it took 10 seconds, on average, to run; however, the AMZ SF error was very large, i.e., 0.0834 or 5.84%. The standard deviation is very large as well, i.e., 0.0855 or 6.03%. When the element size was fixed at 5 ft, the program run time increased, as expected, and the AMZ SF error decreased to 0.0299 or 1.92%. The standard deviation also decreased to 0.0579 or 3.39%. If the element size was fixed at 2.5 ft, the accuracy showed some enhancement with an average AMZ SF error of 0.0202 or 1.11%; however, the average program running time increased to 1,012 seconds, around 16 minutes. Ultimately, none of the fixed width element sizes can meet the desired AMZ SF accuracy requirement of ± 0.005 . When the element size was determined by the element sizing

algorithm to automatically calculate the best fit element size based on the gridding accuracy of AMZ, it took 61 seconds, on average, to run a case history.

The above analysis indicated that the element sizing algorithm produced a more accurate SF calculation in a reasonable time as compared to just minimizing the overall element size. Therefore, this algorithm was ultimately used to determine the optimum element size in ARMPS-LAM.

3.2.7 Grid Generation

3.2.7.1 Gridding Algorithm

In ARMPS-LAM, a graphics-based algorithm was developed in C++ to generate the mine grid from the internal mine map. This algorithm is very similar to the area-based method used in the advanced grid generator (see section 2.2.2) to grid the mine plan in AutoCAD (Wang, 2005). The main difference is that this subroutine can automatically build the mine grid using the area-based method without launching the AutoCAD program. In this subroutine, there is an iteration over each element to check and determine whether it belongs within a pillar, gob or entry. For example, if one element is in the center of the active gob polygon, then it is easy to determine that the material characteristic of the element is gob. However, if it is located at the edge of a polygon, or an even more complex situation, overlapped with both gob and pillar polygons or several polygons of various base materials, it is more difficult to determine its appropriate material (gob, pillar or entry). In the gridding algorithm, if the area of an element is more than 50% within a given polygon, then the element's material is set to the material of that polygon. In the code, the scan line filling algorithm (Foley et al., 1996) and the polygon clipping algorithm (Vatti, 1992) discussed in section 2.2.2 were used to perform the mechanics of the gridding algorithm.

3.2.7.2 Optimum Grid Size

Currently, the laminated overburden model (coded in ARMPS-LAM) has a capability of building a model grid of 2,000 by 2,000 elements. However, it may require several hours to run such a large model and that is too long for the ARMPS-LAM program. For the same mine map, a smaller grid size, say 500 by 500 elements, will use larger element size to

build the mine grid and take much less time to run; however, the larger grid size may be less accurate. It is obvious then that the grid size will affect both the program running time and the accuracy of the solution. In order to optimize the efficiency of gridding and program run times without losing accuracy, four grid sizes of 500, 1000, 1500 and 2000 were investigated (see Table 3.5 and Figure 3.11). In this comparison, the boundary buffer zone of $18.6\sqrt{H}$ was used, and the element size was determined using the element sizing algorithm. The same abbreviated 50 case database used in evaluating the boundary buffer zone was used to analyze the influence of grid size on the AMZ SF accuracy. Again, the AMZ SF accuracy is investigated based on the value of AMZ SF error as discussed in the buffer zone section 3.2.3. To calculate the AMZ SF error for each case history, the “Base” value of the AMZ SF was based on the numerical calculation result from the 2,000 by 2,000 grid size. Then, the absolute differences of the AMZ SF between using other grid sizes versus using 2,000 were calculated as the AMZ SF error.

Table 3.5 Comparison of using different grid sizes.

Items			Grid Size			
			500	1,000	1,500	2,000
AMZ SF Error	Value	Average	0.0137	0.0040	0.0036	0.0000
		Standard deviation	0.0200	0.0058	0.0052	0.0000
	Percent	Average	0.78%	0.19%	0.17%	0.00%
		Standard deviation	1.29%	0.21%	0.18%	0.00%
Average Running Time (s)			8	37	38	61

Figure 3.11 Average AMZ SF difference vs. grid size.

The four different element sizes, the associated AMZ SF error and the program running times are compared in Table 3.5 and Figure 3.11. The results show that increasing the grid size will improve the AMZ SF accuracy, while simultaneously increasing the program running time. The grid size of 500×500 runs the database very quickly, with an average program running time of 8 seconds per model. However, the average AMZ SF error is 0.0137 or 0.78%, which is greater than the desired 0.005 threshold of the AMZ SF accuracy. When the grid size is larger at 1,000 or 1,500, the average AMZ SF errors are at around 0.0040 or 0.2%. Since this is smaller than the desired 0.005, they both meet the accuracy needs of the program. And their standard deviations are very small as well, i.e., around 0.005 or 0.2%. The results of this analysis were also plotted in Figure 3.11. When the grid size was increased from 500 to 1,000, the program running time was increased by nearly 4.5 times (37 seconds). Then, the program running time kept almost constant when the grid

size increased from 1,000 to 1,500. When the grid size was increased from 1,500 to 2,000, the program running time increased from 38 seconds to 61 seconds.

In this analysis, it was found that the grid size of 1,000 meets the desired accuracy requirements with the minimum running times; therefore, in the ARMPS-LAM program, the maximum grid size has been set to 1,000 by 1,000 elements.

3.2.8 Yield Zone Application

In ARMPS-LAM, after all of the base coal and gob materials and remaining openings are defined, an appropriate set of material properties for a yield zone will be applied to the coal pillars. This yield zone provides a stress gradient on the pillar consistent with the Mark-Bieniawski pillar strength formula. The same algorithms used in the LamPre program for applying the yield zone are implemented into the ARMPS-LAM program. This algorithm will automatically assign the coal elements with associated in-seam coal properties based on its location in the pillar in relation to the nearest opening. In order for the pillars to yield and shed stress after failure, the yield zone has to extend across the entire width of all of the pillars. In particular, in ARMPS-LAM, it is desired for the barrier pillar to be able to yield, in order to allow realistic 3D load shedding and to allow calculation of a reasonable safety factor.

In order to make the yield zone extend across the barrier pillars (typically the largest), there has to be enough elements with elastic-plastic properties. Since the maximum grid size is pre-defined in ARMPS-LAM (1,000 × 1,000 elements), the most readily available option to insure enough yielding coal elements is to adjust the element size. Therefore, the element size algorithm discussed in section 3.2.6 considered the “Barrier pillar width/ Max material amount” in calculating the minimum element size.

3.2.9 Input File Generation

Finally, with all of the pre-processing steps completed and the final material properties and mine grid developed, ARMPS-LAM outputs the LaModel compatible input file of the case history. This input file is fully compatible with the LamPre 3.0 and LaModel 3.0. It

could be further modified or enhanced using the LamPre 3.0 program, or manually solved using the LaModel 3.0 program. This LaModel compatible input file is named “*.INP” where the “*” represents the input file base name. For example, if the input file is “Test.csv,” the generated LaModel input file is “Test.INP.”

Meanwhile, this subroutine will save the following pre-processing information to a debugging file (.OUT file, see section 3.4) for further analysis: the imported data of the ARMPS input, calibrated material properties, buffer zone calculation, mine map geometry information, element size and grid size.

3.3 Numerical Solution Module

To solve the model within ARMPS-LAM, a fully compatible internal version of LaModel is then run using the input file, and a classic LaModel output file (.fl file) is produced. This output file is fully compatible with the LamPlt 3.0 program and can be manually analyzed using LamPlt program if desired. The generated LaModel compatible output file is named as “*.fl” where the “*” represents the input file name.

For the convenience of debugging and further analysis, the numerical calculation information will be saved in a debugging file (.OUT file, see section 3.4).

3.4 Post-processing Module

Consistent with the results from ARMPS, the primary output from ARMPS-LAM is the stability factor of the AMZ. In ARMPS, the stability factor is calculated as the pillar strength divided by the applied load and often the load is greater than the strength. However, with the laminated overburden model the safety factor calculation is not so simple. Since the pillars in LaModel can yield, they will never show a load greater than their strength.

For the various pillars in the laminated overburden model, a “stress-based” safety factors is calculated based on the modeled pillar strength versus the pillar stress and/or strain. Each pillar consists of various elements with different elastic-plastic properties (which were decided by the Mark-Bieniawski pillar strength formula during calibrating the

coal strength as detailed section 2.2.1.3). Based on the number of various elements and their properties, the complete pillar stress-strain curve can be plotted for each pillar (an example is shown Figure 3.12). In this figure, the given pillar has a peak stress of 2,200 psi which is reached at a strain value of 0.0175, which is therefore defined as the “peak strain”. If the average pillar stress is 1,000 psi, then the pillar has a stress safety factor of 2.1 (2,200 psi / 1,000 psi = 2.2). However, if the pillar has gone past the point of peak stress/peak strain, and has a stress of 2,200 psi and associated the strain of 0.02, then the pillar is failed and the safety factor calculation switches to a strain-based calculation. In this case, with an average strain of 0.02, the associated strain-based safety factor would be 0.875 (0.0175 / 0.020 = 0.875). This method of using the pillars complete stress-strain curve to calculate the safety factor, is used for calculating the stability factors of the panel, barrier and remnant pillars in ARMPS-LAM. To determine the average stability factor of the AMZ, the area-weighted safety factors is used, which is calculated as detailed below.

Figure 3.12 Pillar stress vs. pillar strain.

According to the ARMPS method, the AMZ includes all of the pillars in the extraction front and extends outby a distance of $5\sqrt{H}$ (Mark & Chase, 1997). In an ARMPS-LAM analysis, the AMZ SF is the sum of the area-weighted pillar stress safety factors within the AMZ, as shown in Equation 3.3.

$$AMZSF = \frac{\sum_{\text{Within AMZ}} \left(\text{Pillar SF} \times \frac{A_{\text{Pillar within AMZ (C-to-C)}}}{A_{\text{Pillar area (C-to-C)}}} \right)}{\sum_{\text{Within AMZ}} \left(\frac{A_{\text{Pillar within AMZ (C-to-C)}}}{A_{\text{Pillar (C-to-C)}}} \right)} \quad (3.3)$$

where:

$A_{\text{Pillar within AMZ (C-to-C)}}$	= pillar center-to-center area within AMZ
$A_{\text{Pillar Area (C-to-C)}}$	= pillar center-to-center area
Pillar SF	= pillar stress safety factor

It should be noted that the AMZ SF in Equation 3.3 is weighted by each pillar's center-to-center area within the AMZ. To better understand the calculation, an example is given here, see Figure 3.13. In this figure, the red polygon represents the AMZ area, and the blue polygons are the center-to-center pillar areas, which are used to weight the pillar safety factor in the AMZ SF calculation. In this example, the AMZ is found to have a breadth of 140 ft and the pillars have 100 ft center-to-center crosscuts. (In the ARMPS-LAM analysis the AMZ breadth starts at the centerline of the crosscut that is essentially in the gob area.) In this case, the AMZ includes the entire first row of pillars and 40 ft from the crosscut centerline into the next row of pillars. The AMZ SF subroutine will take 40 ft out of 100 ft of second row pillar (center-to-center) and therefore use 40% of the average pillar safety factor from the second row and add it to 100% of the average safety factor from the first row, and then divide by 1.4 to get the area weighted safety factor of the AMZ. For example, assume that the first row of pillars has an average safety factor of 1.50 and the second row of pillars has an average safety factor of 1.8. Therefore, the area-weighted AMZ SF has a value of $(1.5 \times 100\% + 1.8 \times 40\%) / (100\% + 40\%) = 1.59$.

Figure 3.13 Schematic of AMZ SF calculation.

It should be noted that for consistency with the AMZ SF calculation in ARMPS, the bleeder pillars within the panel will not be counted into the AMZ in ARMPS-LAM, as illustrated in Figure 3.13.

In order to compare the results from ARMPS-LAM with those of ARMPS, additional output data designed to duplicate some of the output from ARMPS is calculated by ARMPS-LAM. In particular, the barrier pillar safety factors, remnant pillar safety factors, together with various pillar strength, the AMZ safety factor and other data are calculated and saved in an output text file. All told, this text file contains 47 items, which are listed in Appendix B, and include the units, model information (e.g., grid size, grid amounts), stability factor (e.g., stability factors of AMZ, barrier pillars and remnant pillars), pillar information (e.g., pillar strength, area and load) and program running time. The file name is in the format of “*_ARL.csv,” where the “*” represents the prefix name of the input file. For instance, if an input file “Test.csv” is imported into the ARMPS-LAM program, the

program will generate a file named “Test_ARL.csv.” Because the results are saved in a text format, it is easy to access the data and read the data with other programs. Therefore, it will be easy to read this data into the present ARMPS program.

In addition to the (f1 and _ARL) output files, another text file will be generated as well. The file name is in the format of “*.OUT,” where the “*” represents the prefix name of the input file. This file, used for program debugging, contains data on the pre-processing, numerical calculation and post-processing. The “OUT” file includes: the data read from the ARMPS input, calibrated material properties, buffer zone calculation, mine map geometry information, element size and grid size, numerical calculation information, the calculated stability factors and other outputs.

3.5 Predefined Parameters

Since ARMPS and the laminated overburden model are based on totally different methods, some mechanical parameters necessary for ARMPS-LAM are not available in the ARMPS input data. Therefore, some predefined values are needed in ARMPS-LAM. In general, these default values of parameters are based on previous research and experience with LaModel (Akinkugbe & Heasley, 2004; Heasley, 2008, 2012; Heasley et al., 2010; Sears & Heasley, 2013; Tulu & Heasley, 2011) and the default values used in LamPre3.0. All of these predefined parameters and their values are listed in Table 3.6.

Table 3.6 Addition default parameters used in ARMPS-LAM.

Parameter	Default Value	Parameter	Default Value
Rock mass Poisson's ratio	0.25	Over-relaxation factor	1.65
Rock mass modulus	3,000,000 psi	Displacement convergence level	0.00001 in
Coal Poisson's ratio	0.33	Max iteration	20,000
Coal modulus	300,000 psi	Initial step number	1
Gob Poisson's ratio	0.33	Boundary condition	Symmetric
Initial gob modulus	100 psi	Gob height factor	1.0
Upper limit gob stress	4,000 psi	Max element size	10 ft
Max grid size	1,000	Max material amount	52

3.6 Summary

A computer code, ARMPS-LAM, has been developed to effectively implement the laminated overburden model into the ARMPS program. It consists of three primary modules: the pre-processing, numerical solution and post-processing. This program takes the basic ARMPS geometric input for defining the mining plan and loading condition and then automatically develops, runs and analyzes a full LaModel analysis of the mining geometry to output the stability factor of the AMZ and other important data, all without further user input. In particular, the program automatically calibrates the material properties, sizes the boundary buffer zones, sizes the mine model, generates the pillar and gob geometries, sizes the elements, fills the mine grid with material codes, creates a LaModel input file, runs the LaModel file and determines the stability factor of the AMZ, barrier pillars and other parameters for pillar design analysis. From the user's perspective, only the traditional ARMPS input is required and the output is the traditional stability factor of the AMZ. Further, the ARMPS-LAM program can be run in batch mode as well; therefore, the large ARMPS database can be analyzed very quickly.

Chapter 4. Program Validation and Case Study

In order to validate and illustrate the automated model building and analysis process of ARMPS-LAM, one case history from the ARMPS database was selected to be checked by hand. This example case history is presented in detail here. It is located in Kentucky, and has: a cover depth (H) of 860 ft, an entry height (h) of 7.7 ft, a crosscut angle of 60 °, an entry width of 20 ft, and a crosscut spacing of 60 ft. It uses the default abutment angle of 21 ° and has an active and one side gob (loading condition three). There are five entries with the same center-to-center spacing of 55 ft. The front active gob has an extent of 1,000 ft and the first side gob has a width of 320 ft with a 75 ft wide barrier pillar separating the two retreat sections. The slab cut is 50 ft. The original ARMPS analysis used the recommended default in-situ coal strength of 900 psi (this default empirical value is used when no other more accurate value is available), the recommended default overburden density of 162 lbs/ft³ and the recommended default AMZ breadth of 147 ft ($5\sqrt{H}$). Table 4.1 presents the basic mine geometry information.

Table 4.1 Mine geometry information of case history.

Item	Value	Item	Value
Location	KY	Entry Width	20 ft
Entry Height	7.7 ft	Crosscut Spacing	60 ft
Depth of Cover	860 ft	Number of Entries	5
Crosscut Angle	60 °	Entry Spacing (center-to-center)	55 ft (all same)
Loading Condition	3	1st Side Gob: Extent	320 ft
Bleeder Pillars	N/A	1st Side Gob: Abutment Angle	21 °
Active Gob: Extent	1,000 ft	1st Side Gob: Barrier Pillar Width	75 ft
Active Gob: Abutment Angle	21 °	1st Side Gob: Slab Cut Depth	50 ft
In-situ coal strength	900 psi	AMZ breadth ($5\sqrt{H}$)	147 ft

4.1 Preprocessing Module Validation

4.1.1 Data Import

The proceeding ARMPS parameters were stored in a one-line input file in the format shown in Appendix A. This file was then read into ARMPS-LAM in the data import step. The input variables were then automatically saved to the “.OUT” text file where they were checked for debugging or further analysis.

4.1.2 Property Calibration

Next, the ARMPS-ALM program uses the formal LaModel calibration processes (Heasley, 2008; Heasley et al., 2010) to automatically calibrate the overburden, coal and gob material properties. For this sample case history, a lamination thickness of 320 ft, 31 coal materials with an in-situ coal strength of 900 psi (as implemented using the Mark-Bieniawski formula), and two strain-hardening gob materials with a final gob modulus of 2.20×10^6 psi (active gob) and 1.71×10^6 psi (1st side gob) were developed. In order to validate the calibration results, the LamPre 3.0 program was used to manually calculate their values as shown below.

To validate the lamination thickness, the inputs parameters of the rock mass and seam were manually entered into the “Lamination Thickness Wizard” (see Figure 4.1). In the group of “Rock Mass Parameters,” the elastic modulus, Poisson’s ratio and vertical stress gradient were set as 3,000,000 psi, 0.25 and 1.125 psi/ft, respectively. For this case history, considering an entry width of 20 ft and five entries with the same center-to-center spacing of 55 ft, the panel width (“width of gob” in Figure 4.1) was set as 240 ft ($4 \times 55 \text{ ft} + 20 \text{ ft} = 240 \text{ ft}$). Further, in the group of “Seam Parameters,” the elastic modulus, seam thickness, seam depth, and in-situ coal strength were set as 300,000 psi, 7.7 ft, 860 ft, and 900 psi, respectively. Then, the suggested values of abutment extent and percentage of overburden load were calculated based on a default abutment angle of 21° and 90% abutment load extent of $5\sqrt{H} = 5\sqrt{860} = 147 \text{ ft}$. Finally, in an interactive solution, the yield zone was determined to be 7 ft. Finally, the lamination thickness was determined to be 320 ft, the same as that calculated by ARMPS-LAM.

Lamination Thickness Wizard

Rock Mass Parameters

Elastic Modulus (psi)	3000000
Poisson's Ratio	0.25
Vertical Stress Gradient (psi/ft)	1.125

Seam Parameters

Elastic Modulus (psi)	300000
Seam Thickness (ft)	7.7
Seam Depth (ft)	860
Width of Gob (ft)	240
In-Situ Coal Strength (psi)	900

Abutment Extent Parameters

Empirically Suggested Abutment Extent (ft)	146.628782986	☒ Use the Suggested Value
Extent of Abutment Load (ft)	146.628782986152	
Portion of Load Within Given Extent	0.9	

Yield Zone Parameters

Suggested Percentage of the Overburden Load	0.818249600131951	☒ Use the Suggested Value
Percentage of the Overburden Load	0.818249600131951	
Trial Lamination Thickness (ft)	319.644088902753	
<input type="button" value="Calculate"/>	Calculated Yield Zone (ft)	7.1554235764331
	Width of Yield Zone (ft)	7.1554235764331
<input type="button" value="Calculate"/>	Lamination Thickness (ft)	319.644088902753

Figure 4.1 Lamination thickness calculated by LamPre 3.0.

For the calibration of the coal strength, 15 yield zones were set and 31 materials were defined. Because the final mine grid used an element size of 2.5 ft (see section 4.1.6) and the yield zone needs to extend through the first side barrier pillar (75 ft), the yield zone was 15 ($75 \text{ ft} / 2 / 2.5 \text{ ft} = 15$) zones and the total coal materials are 31 ($15 \times 2 + 1 = 31$). (2 per yield zone plus a core elastic material, as is the system in LamPre.) The coal strength

calibration was based on the Mark-Bieniawski pillar strength formula with an in-situ coal strength of 900 psi in ARMPS. The calibrated 31 coal materials are completely the same as those defined by ARMPS-LAM. The peak stress of the elastic-plastic coal materials range from 786 psi to 9,728 psi consistent with the pillar stress gradient Equation 2.17.

The gob modulus is calibrated to obtain the desired average gob stress based on the abutment angle concept. For this case history, two strain-hardening gob materials were defined, one for the active gob and one for the 1st side gob. In the tab of “Strain-Hardening for GOB” in Figure 4.2, the inputs of overburden parameters, coal properties, gob width (the active gob is 240 ft and the 1st side gob is 320 ft) and initial and upper limit stress were set based on the default values for initial modulus and ultimate stress parameters in ARMPS-LAM (see Figure 4.2). Then, the final gob modulus of the active gob and 1st side gob were calculated as 2.20×10^6 psi and 1.71×10^6 psi, respectively. These are the same as those calculated by the ARMPS-LAM program. Figure 4.2 shows the manual calculation in LamPre 3.0 program.

Wizard for Defining In-Seam Material Models

Elastic-Plastic for COAL | Strain-Softening for COAL | Strain-Hardening for GOB

Geometry and Overburden Parameters

Elastic Modulus of Rock Mass (psi) 3000000

Poisson's Ratio of Rock Mass 0.25

Lamination (Layer) Thickness (ft) 319.644089

Vertical Stress Gradient (psi/ft) 1.125

Current Seam Number: 1

Seam Thickness (ft) 7.7

Overburden Depth (ft) 860

Coal Properties

Coal Modulus (psi) 3e+005

Plastic Modulus (psi) 0

Coal Strength (psi) 900

Gob Input Parameters

Number of Gob Materials to be Defined: 3

Current Gob Number: 1

Width of Gob Area (ft) 240

Suggested % Overburden Load on Gob 0.18175

% Overburden Load on Gob 0.18175

Gob Default Parameters

Initial Gob Modulus (psi) 100

Upper Limit Stress for Gob (psi) 4000

Gob Height Factor 1

Final Modulus for Gob (psi) 2202858.827905

Calculate

Define Set

Total Number of Materials Defined 34

Material Summary

Next Form

OK

Cancel

Help

a. Final gob modulus of active gob

b. Final gob modulus of 1st side gob

Figure 4.2 Gob modulus calculated by LamPre 3.0.

4.1.3 Boundary Buffer Sizing

To determine the appropriate width of boundary buffer zone to use around the LaModel grid, the previously discussed radius of stress influence in the laminated overburden model is $18.6\sqrt{H}$. Given a depth (H) of 860 ft, the boundary buffer zone was determined as 545 ft, which was shown in Equation 4.1. The 545 ft matches the boundary buffer zone calculated in the ARMPS-LAM program.

$$\text{Boundary Buffer Zone} = 18.6\sqrt{H} = 18.6\sqrt{860} = 545 \text{ ft} \quad (4.1)$$

4.1.4 Mine Model Sizing

The overall size of the LaModel mine grid is determined by the input mine geometry and the calculated boundary pillar width. Figure 4.3 is the scaled AutoCAD mine map generated by ARMPS-LAM. Some annotations were added to illustrate the dimensions of the model and its components. The calculation of entire model size and its component sizes have been discussed before (see Equation 3.1 & 3.2). To validate the mine model size, the model width (TMW) and length (TML) were calculated manually and presented in Equation 4.2 and 4.3 below.

Equation 4.2 shows the manual calculation of total model width (TMW). For this case history, the extents of first side gob is 320 ft, which is smaller than two times buffer zone size ($37.2\sqrt{H} = 37.2\sqrt{860} = 1091$ ft). There is no second side gob. Therefore, the “Side Buffer Pillars,” WSB(3) & WSB(4) were created with same extent of 545 ft (see Figure 4.3). The first “Side Gob Width,” WSG(3), has a width of 320 ft. There is no bleeder pillars and the “Bleeder Pillar Width,” WSBP(3) and WSBP(4) equal to 0. There is only a first side barrier pillar with a “Barrier Pillar Width,” WBAR(3), of 75 ft. The “Active Panel Width,” WAP, has a value of 240 ft. The total model width, TMW, shown in Equation 4.2 has a value of 1,725 ft.

$$\begin{aligned}
 \text{TMW} &= \sum_{i=3}^4 [\text{WSB}(i) + \text{WSG}(i) + \text{WSBP}(i) + \text{WBAR}(i)] + \text{WAP} \\
 &= \text{WSB}(3) + \text{WSG}(3) + \text{WSBP}(3) + \text{WBAR}(3) + \\
 &\quad \text{WSB}(4) + \text{WSG}(4) + \text{WSBP}(4) + \text{WBAR}(4) + \text{WAP} \\
 &= 545 \text{ ft} + 320 \text{ ft} + 0 + 75 \text{ ft} + 545 \text{ ft} + 0 + 0 + 0 + 240 \text{ ft} \\
 &= 1,725 \text{ ft}
 \end{aligned} \tag{4.2}$$

Equation 4.3 shows the manual calculation of total model length (TML). The length of “Top Buffer Pillar,” LTB, has a value of 545 ft, because the “Active Gob Length,” (LAG) is 1,000 ft, which is smaller than two times buffer zone size ($37.2\sqrt{H} = 37.2\sqrt{860} = 1,091$ ft). The “AMZ Breadth,” (AMZ), has an extent of 147 ft ($5\sqrt{H} = 5\sqrt{860} = 147$ ft). The “Bottom Buffer Pillar,” LBB, has a value of 545 ft. The total model length, TML, shown in Equation 4.3 then has a value of 2,237 ft.

$$\begin{aligned}
 \text{TML} &= \text{LTB} + \text{LAG} + \text{AMZ} + \text{LBB} \\
 &= 545 \text{ ft} + 1,000 \text{ ft} + 147 \text{ ft} + 545 \text{ ft} \\
 &= 2,237 \text{ ft}
 \end{aligned} \tag{4.3}$$

The mine model size calculated by hand is the same as that calculated by the ARMPS-LAM program. The detail mine geometry dimensions are shown in Figure 4.3.

4.1.5 Mine Map Generation

In ARMPS-LAM, the mine model sizes determined in the previous subroutine along with the geometry input and boundary buffer zone size were then used to generate the precise polygon geometries and coordinates for the mine pillars and gob areas. This graphical mine geometry was also saved as an AutoCAD DXF file. The scaled mine map from the output DXF file is shown in Figure 4.3, where the magenta polygons (in the “Gob” layer) are the gobs and the black polygons (in pillar “Pillar” layer) are the pillars. Their dimensions have been validated manually by checking the coordinates in the AutoCAD map (see Figure 4.3). The geometric dimensions of the generated mine map were validated as same as the values calculated by the “Mine Model Sizing” subroutine in the ARMPS-LAM program.

Figure 4.3 Scaled AutoCAD mine map generated by ARMPS-LAM.

4.1.6 Element Sizing

A fairly complex algorithm examines the critical dimensions in the model (including the entry width, the production pillar dimensions and the barrier pillar widths) and determines the optimum element size that will best fit all the required dimensions. In this example case history, the algorithm determined that an element size of 2.50 ft was optimum. Table 4.2 shows the area error of the modeled pillars within the AMZ with this element size. Since all of the pillars are the same in the AMZ, only the first pillar line is listed. Table 4.2 indicates that the area error is around 1.61% for all of the pillars within the AMZ.

Table 4.2 Area error of modeled pillars in AMZ.

Pillars (from left to right)	Original Area (ft²)	New Area (ft²)	Area Error (ft²)	Area Error (%)
No.1 Pillar	1291.71	1312.5	20.79	1.61
No.2 Pillar	1291.71	1312.5	20.79	1.61
No.3 Pillar	1291.71	1312.5	20.79	1.61
No.4 Pillar	1291.71	1312.5	20.79	1.61

The calculation results listed in Table 4.2 is based on the subroutine shown in Figure 3.9. First, the subroutine reads the ARMPS input and set the max element size to be 10 ft. For this particular case history, the max grid size is 1,000, the maximum material number is 52, the entire model width is 1,725 ft, the entire model length is 2,237 ft and the max barrier pillar width is 75 ft. Then, the “Model width / Max grid size,” “Model length / Max grid size” and “Max barrier pillar width / Material limit” (A, B & C in Figure 3.9) equals: 1.73 ft (1,725 ft / 1,000 = 1.73 ft), 2.24 ft (2,237 ft / 1,000 = 2.24 ft) and 1.44 ft (75 ft / 52 = 1.44 ft), respectively. In this case, the minimum element size is set as 2.24 ft. So, the potential element sizes ranges from 2.24 ft to 10.00 ft. Next, the subroutine starts the iteration checking various element sizes. It checks the 2.24 ft first and then 2.25 ft, 2.26 ft, etc., up to 10.00 ft (an increment of 0.01 ft). For each number, the subroutine will calculate the gridding error of the AMZ (area difference) and the AMZ grid size. As we know, the

AMZ consists of a number of pillars on the extraction front. And the pillar geometry of the first pillar line is used represent all of pillars in the AMZ. For the first pillar line, all of the pillars have the same pillar geometry of 35 ft by 36.91 ft (width by length, rib-to-rib) with a rib-to-rib area of 1,292 ft². For an element size of 2.50 ft, 14 elements ($35 / 2.5 = 14$) and 15 elements ($36.91 / 2.5 = 15$) are needed to grid the pillar (rib-to-rib) in the width and length directions, respectively. For the entry (20 ft), 8 elements are needed. The simulated pillar with a discrete element size (rib-to-rib) is going to be 35 ft ($14 \times 2.5 \text{ ft} = 35 \text{ ft}$) by 37.5 ft ($15 \times 2.5 \text{ ft} = 37.5 \text{ ft}$) with a rib-to-rib area of 1,312.5 ft². The generated entry is going to be 20 ft ($8 \times 2.5 \text{ ft} = 20 \text{ ft}$). The single pillar area difference is 1.61% ($(1,312.5 \text{ ft}^2 - 1,292 \text{ ft}^2) / 1,292 \text{ ft}^2 = 1.61\%$) with no area errors for the entry. Since all of the pillar lines are the same as the first pillar line and all pillars have same shape, the AMZ area difference is 1.61% as well. After several iterations, another element size, say 5.0 ft, is going to be analyzed. Using 5.0 ft for the element size, the element amount for a single pillar is going to be less (7×7 elements); however, the AMZ area difference is larger (5.19%), which cannot meet the requirements to make the 5.0 ft as the optimum element size. During the iteration, all of the values between 2.24 ft and 10.00 ft were checked. Finally, 2.50 ft was determined to be the optimum element size, because it had the least area difference from the original AMZ geometry with the largest elements (within the constraints).

4.1.7 Grid Generation

Using the element size of 2.50 ft as calculated above, the mine grid generated by ARMPS-LAM has 690 elements in the X direction and 890 elements in the Y direction. To validate the model grid, the advanced grid generator in AutoCAD was used to check the grid. Figure 4.4a shows the model (AMZ area) gridded by the advanced grid generator in AutoCAD, where each grid element has been checked based on the area method discussed before. In Figure 4.4a, the red areas are coal pillars, the yellow areas are the gobs and the green areas between them are the entries. Figure 4.4b is the mine grid developed by the ARMPS-LAM program. Comparing with the model gridded by the advanced grid generator, it is determined that they are identical to each other.

a. Modelgrided by advanced grid generator in AutoCAD.

b. Mine grid generated by ARMPS-LAM.

Figure 4.4 Mine grid validation by advanced grid generator.

4.1.8 Yield Zone Application

Since all of the base coal, gob materials and remaining openings were applied to the mine grid, an appropriate set of material properties for a yield zone can be applied to the coal pillars. In the previous subroutine, ARMPS-LAM has generated and calibrated all of the in-seam materials, i.e., 31 coal materials (1 elastic model, material code ‘A’; 30 elastic-plastic model with 15 yield zones, material code ‘B’–‘e’) and 2 gob materials (strain-hardening model, material code ‘f’ & ‘g’). Based on the developed coal materials, the yield zone application provides a stress gradient on the pillar consistent with the Mark-Bieniawski pillar strength formula. Initially, when the coal materials were generated, the material properties for each yield material were designed to coincide with a specific distance/location within a coal pillar. Now, once the location of the coal elements are known, these yield materials are applied to the coal elements based on the location of the given element within the coal pillar.

The yield zone generated by ARMPS-LAM was validated by using the advanced grid generator in AutoCAD and then the yield zone generator in LamPre 3.0. The 31 coal materials generated by the ARMPS-LAM were identical to that calibrated by the LamPre 3.0. (The coal materials used in this case study are listed in Appendix D.) Figure 4.5a is the model (local view) after gridding in AutoCAD. Figure 4.5b is the materials applied with the yield zone generator in LamPre 3.0. After manually building the grid and applying the yield zone, the mine grid was checked with the one generated by ARMPS-LAM. The comparison indicated that the yield zone was correctly applied to the mine grid generated by ARMPS-LAM.

a. Local view of mine model gridded by advanced grid generator in AtuoCAD.

b. Local view of mine grid with yield zone applied by LamPre 3.0.

Figure 4.5 Applying the yield zone to the mine grid.

4.1.9 Input File Generation

Finally, with all of the pre-processing steps completed and the final material properties and mine grid developed, ARMPS-LAM outputs the LaModel compatible input file of the example case history (.INP file). The file was successfully imported into the LamPre 3.0 program and the LaModel input parameters were checked to be identical to the values discussed above.

In addition, the results calculated through each subroutine was saved in a debugging file (.OUT file). And the data in the debugging file was manually checked to assuring the calculations performed by associated subroutines were correct.

4.2 Numerical Solution Validation

To validate the process module, the LaModel program was used to run the generated LaModel input file. The file ran correctly and the classic LaModel compatible output file (.f1 file) was produced. This output file could be analyzed using the LamPlt program, as shown in Figure 4.6, which presents the colored square plot of the pillar stress safety factor of the example case history.

Figure 4.6 Colored square of plot of stress safety factor.

4.3 Post-processing Module Validation

With the LaModel output file, ARMPS-LAM then calculated and reported the AMZ SF, barrier pillar SF, pillar strength and other parameters (comparable to an ARMPS analysis). To validate the AMZ SF, the area-weighted (pillar center-to-center area) stress safety factor of the pillars and partial pillars within the AMZ were used to calculate the

AMZ SF by hand. For the case history, the first two pillar lines and about 45% of the third pillar line are included in the AMZ, which is illustrated in Figure 4.7.

Figure 4.7 Schematic of pillar area (center-to-center) in AMZ.

The percentage of each pillar's center-to-center area in the AMZ were calculated by hand and listed in Table 4.3. Table 4.3 shows that the value of the AMZ stability factor is based on each pillar's stress safety factor and the area within AMZ. For this case history, the final manual AMZ SF was determined to be 0.97, which was same as the value automatically calculated using the ARMPS-LAM. Meanwhile, the barrier pillar SF was determined to be 1.58 and the remnant pillar SF was determined to be 0.70 (see Figure 4.6).

Table 4.3 AMZ stability factor determination.

Pillar	Row	Col.	Stress Safety Factor	Area Percentage within AMZ	Weighted SF
1	1	1	0.87	10.38%	0.09
2		2	0.90	10.38%	0.09
3		3	0.97	10.38%	0.10
4		4	1.01	10.38%	0.11
5	2	1	0.95	10.38%	0.10
6		2	0.97	10.38%	0.10
7		3	1.00	10.38%	0.10
8		4	1.02	10.38%	0.11
9	3	1	1.00	4.24%	0.04
10		2	1.00	4.24%	0.04
11		3	1.01	4.24%	0.04
12		4	1.04	4.24%	0.04
Sum				100.00%	0.97

For this example case study, each module and its component algorithms of the ARMPS-LAM program were validated manually. Further, the case study and validation illustrated the methods and algorithms used in ARMPS-LAM and allowed checking the program accuracy. For this particular case history, the complete ARMPS-LAM analysis took about two minutes of computer time, with most of that being taken to solve the LaModel grid. To develop the laminated overburden model, run the analysis and calculate the AMZ SF by hand would have taken several hours. Thus, it is clear that the automation functions of ARMPS-LAM can save the user considerable time and effort. From the user perspective, only the traditional ARMPS input was required and the output is comparable to the traditional ARMPS stability factor of the AMZ.

Chapter 5. Database Analysis and Comparison

To evaluate the performance of the ARMPS-LAM program in determining the success or failure of a given case history, the complete ARMPS 2010 case history database was analyzed and the results were compared with those from ARMPS 2010. Primarily, the stability factors (SF) from two programs are compared and analyzed. Based on the results, five significant variables were investigated. Moreover, the statistical analysis technique used in developing the ARMPS design criteria was used to compare the classification accuracy of the laminated overburden model (as implemented in ARMPS-LAM) and ARMPS 2010.

5.1 ARMPS Database Overview

The ARMPS 2010 database is supplied in the installation directory of ARMPS 2010. This 2010 database includes 645 case histories, which are extracted from the original 692 case histories NIOSH collected by excluding the “borderline” and “floor heave” cases (Mark, 2010). NIOSH personnel made the determination of success or failure during their visit to the mine and with 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 (Mark & Chase, 1997):

- **Squeezes**, which are non-violent pillar failures that may take hours, days or even weeks to develop;
- **Collapses**, which occur when large areas supported by slender pillars ($w/h < 4$) fail almost simultaneously, resulting in an air blast and;
- **Bumps**, which are sudden, violent failures of one or more highly stressed pillars.

The database analysis does not specifically consider: the geology, the cut sequence, the specific coal strength or the type and amount of roof support. For the 645 case histories studied, 125 case histories (19%) were considered failures and 520 case histories (81%)

were considered successful. Categorized by the loading conditions, the case histories are listed as following.

- **Loading condition 1:** 170 case histories (26% of total), 35 failures and 135 successes;
- **Loading condition 2:** 138 case histories (21% of total), 21 failures and 117 successes;
- **Loading condition 3:** 318 case histories (49% of total), 57 failures and 261 successes;
- **Loading condition 4:** 19 case histories (3% of total), 12 failures and 7 successes.

In this database, 206 case histories (32%) have a cover depth equal or less than 650 ft and 439 case histories (68%) are more than 650 ft deep. Figure 5.1 presents the database categorized by the ARMPS loading conditions, success or failure, and depth.

Figure 5.1 Database categorized by ARMPS loading conditions.

Within the database, the mining height ranges from 3 ft to 18 ft with an average of 6 ft; the depth of cover ranges from 145 ft to 2,200 ft with an average of 892 ft; the entry width ranges from 9 ft to 37 ft with an average of 20 ft; the crosscut spacing ranges from 30 ft to 150 ft with an average of 78 ft; the center-to-center entry spacing ranges from 25 ft to 140 ft with an average of 70 ft; the crosscut angle ranges from 60 ° to 90 ° with an average of 85 °; and the number of entries ranges from 2 to 10 with an average of 7. Also, all of the case histories use the same default abutment angle of 21 °. Table 5.1 presents the ranges of above ARMPS input parameters within the database.

Table 5.1 ARMPS input parameters ranges within the database.

Item	Min	Max	Average	Standard Deviation
Mining Height (ft)	3	18	6	2
Depth of Cover (ft)	145	2,200	892	436
Entry Width (ft)	9	37	20	1
Crosscut Spacing (ft)	30	150	78	18
Crosscut Angle (°)	60	90	85	11
Number of Entries	2	10	7	2

5.2 Stability Factor Comparison

The ARMPS 2010 and ARMPS-LAM programs were used to calculate the stability factor for the entire 645 case history database. The stability factor criterion of 1.50 was applied to both programs. The results of the ARMPS analysis is based on the Excel version of ARMPS 2010 provided by the NIOSH for this research. It took only couple of minutes to run the entire database with the Excel version of ARMPS 2010. For ARMPS-LAM, the entire database took around 10 hours to run. The average running time for the case histories is 52 seconds and the maximum running time was 7 minutes. It shows that the ARMPS-LAM program greatly improves the efficiency of performing a manual LaModel analysis.

5.2.1 ARMPS 2010 Results

Figure 5.2 shows the ARMPS 2010 SF versus the depth, with the suggested design criterion of 1.50 marked (Mark, 2010). The AMZ SF calculated by ARMPS 2010 ranges from 0.40 to 7.54 with an average of 1.79 and a standard deviation of 1.06. The entire database has 645 case histories. Using a SF of 1.50 as the guideline, ARMPS 2010 can successfully classify 59% of the successes and 82% of the failures, with an overall classification accuracy of 63%.

Figure 5.2 Database analysis results using ARMPS 2010 (Mark, 2010).

5.2.2 ARMPS-LAM Results

The AMZ SF calculated by ARMPS-LAM ranges from 0.26 to 9.40 with an average value of 1.95 and a standard deviation of 1.20. Figure 5.3 shows the ARMPS-LAM SF

versus the depth with same SF equal 1.5 as used by ARMPS 2010 marked. ARMPS-LAM has good performance on the results as well. It can successfully classify 59% of successes and 70% of failures with an overall classification accuracy of 61%. Its overall classification accuracy (61%) is slightly lower than that of ARMPS 2010 (63%). They have same rate in classifying the successes (59%); however, ARMPS 2010 is more accurate in classifying the failures (82%) than ARMPS-LAM (70%); ARMPS-LAM has to increase the stability factor criterion from 1.50 to 1.66 to get same accuracy in classifying the failures (55% for total classification accuracy using 1.66, see Figure 5.3).

Figure 5.3 Database analysis results using ARMP-LAM.

5.2.3 Stability Factor Correlations

To investigate the correlations between the two programs, the value of the calculated ARMPS-LAM SF is plotted versus the ARMPS 2010 SF in Figure 5.4. As might be expected, there is a fairly good correlation between their stability factors with an R^2 value of 0.8797 for the best fit line (green dash line) and an R^2 value of 0.8794 for the line forced to go through the origin (blue solid line). This means that 88% of the difference in the ARMPS-LAM SF can be explained by the ARMPS 2010 SF for the database study. When the slope of the line is forced to go through the origin, the trend line indicates that the ARMPS-LAM SF averages about 8% higher than the ARMPS 2010 SF (blue line, see Figure 5.4).

Figure 5.4 Relationship between ARMPS-LAM SF and ARMPS 2010 SF.

Although the ARMPS-LAM SF and the ARMPS SF show a strong correlation (trend line in Figure 5.4), some significant outliers do occur. Figure 5.4 indicates that some case histories have quite a different stability factor when comparing both programs. In order to further explore any significant statistical difference between the ARMPS-LAM SF and the ARMPS 2010 SF, a stability factor (SF) ratio was created by dividing the ARMPS-LAM SF by the ARMPS 2010 SF for each case study (see Equation 5.1).

$$\text{SF Ratio} = \frac{\text{ARMPS-LAM SF}}{\text{ARMPS2010 SF}} \quad (5.1)$$

Based on previous research and experience with the laminated overburden model (Esterhuizen et al., 2011; Heasley, 2012; Heasley et al., 2010; Sears & Heasley, 2013; Tulu et al., 2010), the SF ratio was compared with five potentially significant variables: depth, mining height, panel width, panel width-to-depth ratio and pillar width-to-height ratio to analyze for any significant trends. For the pillar width-to height ratio (w/h), the average value of the pillars is used. Because the strength of a rectangular pillar is different from that of a square pillar (Darling, 2011; Dolinar & Esterhuizen, 2007), the shape effect is considered by using the value of four times the area divided by perimeter, i.e., $w = 4A/C$, as a substitute for the pillar w/h ratio (Wagner, 1980).

After reviewing the results from the potential significant variables, there only appear to be a noteworthy trend with the depth ($R^2 = 0.21$). In particular, it appears that the SF ratio decrease as the depth increases, which is shown in Figure 5.5. This means that the ARMPS-LAM SF is generally greater than the ARMPS 2010 SF in a shallow cover condition ($< 1,200$ ft); but when the depth is greater than 1,200 ft; the ARMPS-LAM SF is generally smaller than ARMPS 2010 SF. In this investigation, there did not appear to be any significant correlation between the SF ratio and the mining height ($R^2 = 0.0049$), panel width ($R^2 = 0.0082$), panel width-to-depth ratio ($R^2 = 0.050$) or pillar width-to-height ratio ($R^2 = 0.060$).

Figure 5.5 Influence of the depth on the stability factor ratio.

5.2.4 Stability Factor Differences

In further analyzing the results between ARMPS-LAM and ARMPS 2010, it was found that both programs correctly identified 349 case histories (270 successes and 79 failures), and both programs failed to classify 187 case histories (172 successes and 15 failures). For the remaining 109 case histories, the programs gave opposite answers. This means that in these 109 case histories, when ARMPS-LAM predicts it to be a success, ARMPS predicts it to be a failure, or vice-versa. In these cases, it should be note that only one of the programs gives the right answer. Since ARMPS-LAM and ARMPS 2010 gave opposite predictions for this small subset of the database with 109 case histories, this subset was used to further explore the differences between two programs. Further, it is hoped that

the results of this deviation analysis can be used to identify potential improvements for the ARMPS-LAM program.

Table 5.2 shows that in this small database of 109 case histories, ARMPS-LAM correctly classifies 47 of them (43% of total) comparing with ARMPS 2010 correctly classifying the remaining 62 case histories (57% of total). Specifically, there are 78 successful case histories (72% of total) where ARMPS-LAM correctly predicted 38 (49%) of them (ARMPS 2010 fails) and ARMPS 2010 correctly predicted the remaining 40 (51%) successes (ARMPS-LAM fails). There are 31 failed case histories (28% of total) where ARMPS-LAM correctly predicts 9 (29%) of them (ARMPS 2010 fails) and ARMPS 2010 correctly predicts the remaining 22 (71%) failures (ARMPS-LAM fails).

Table 5.2 Case histories where the two programs disagree in classification.

Program	Prediction Result	Case Histories with Opposite Results from Programs		
		Total	Success	Failure
		109	78	31
ARMPS-LAM	Correct	47	38 (<1,000 ft)	9 (>1,000 ft)
ARMPS 2010	Correct	62	40 (>1,000 ft)	22 (<1,000 ft)

Further, Table 5.2 also indicates that the difference in prediction accuracy between the programs is correlated to the depth (H). In order to investigate this correlation, the ARMPS-LAM SF versus depth from the 109 case histories was plotted in Figure 5.6. This figure indicates that in this particular database, when the depth is less than around 1,000 ft (only two successes occurred at 1,069 ft and one success occurred at 1,025 ft), the ARMPS-LAM SF is greater than 1.50 for both successes and failures; when the depth is greater than 1,000 ft (only three failures and one success is below 1,000 ft), the ARMPS-LAM SF is less than 1.50 for both successes and failures (and often incorrect). This trend (see Figure 5.6) indicates partially explains why ARMPS-LAM can correctly classified the 49% of the successes (because their depth is less than 1,000 ft and ARMPS-LAM gets SFs larger than

1.50) and why ARMPS-LAM can only correctly classify 29% of the failures (because their depth is greater than 1,000 ft and ARMPS-LAM gets SFs smaller than 1.50). It is believed that this trend is caused by the loading mechanisms of the laminated overburden model (LaModel, implemented in ARMPS-LAM) which distributes less load on the AMZ for shallow cover where the depth is less than 1,000 ft (results in a higher stability factor) and more load on the AMZ for deep cover where the depth is more than 1,000 ft (results in a lower stability factor). Therefore, it can be seen that one of the potential future improvement to LaModel is to distribute more load for shallower cover ($H < 1,000$ ft) and less load for deep cover ($H > 1,000$ ft). This change will help LaModel to more accurately identify the failures with shallow cover and the successes with deep cover. However, it should be noted that this change may cause LaModel to fail to predict some successes with shallow cover and some failures with deep cover (see Figure 5.6).

Figure 5.6 ARMPS-LAM SF vs. depth for case histories where the programs disagree in classification.

Based on the analysis above, it can be seen that compared with ARMPS 2010, LaModel distributes less load and then gets a higher SF for shallow cover mines; and distributes more load and then gets a lower SF for deep cover mines. To further explore this phenomenon, the results from the entire ARMPS database were used. Figure 5.7 is the plot of the ARMPS-LAM SF versus the depth with categories marked (success and failure). The success category was further split into two sub-categories: ARMPS-LAM is correct and ARMPS-LAM is wrong. In this graph, it can be seen that most of the incorrectly classified successes occur with low ARMPS-LAM SF at deep cover ($H > 1,000$ ft) and that most of the incorrectly classified failures occur with high ARMPS-LAM SF at shallow cover ($H < 1,000$ ft).

Figure 5.7 ARMPS-LAM SF vs. depth using ARMPS database.

The details of the classification accuracy related to depth shown in Figure 5.7 are tabulated in Table 5.3. The results show that the laminated overburden model can correctly identify 34% of the deep successes (50 out of 148) and 56% of the shallow failures (41 out of 73). The trends observed above are duplicated in the table where LaModel is seen to be good at classifying the shallow (<1,000 ft) successes (258 out of 372, 69%) and the deep (>1,000 ft) failures (47 out of 52, 90%). Of course, the corollary is also true (see Table 5.3). LaModel only correctly classifies: 44% of shallow failures (32 out of 73) and 66% of deep successes (98 out of 148). It should be note that it is not absolute that LaModel has a greater SF for shallow mines and smaller SF for deeper mines.

Table 5.3 Classification accuracy of ARMPS-LAM using the SF guideline of 1.5.

Case History Category	ARMPS-LAM SF	ARMPS-LAM Prediction	Total		H < 1,000		H > 1,000	
			Val.	Per.	Val.	Per.	Val.	Per.
Successes	> 1.5	Correct	308	59%	258	69%	50	34%
	<= 1.5	Wrong	212	41%	114	31%	98	66%
	Total		520	100%	372	100%	148	100%
Failures	<= 1.5	Correct	88	70%	41	56%	47	90%
	> 1.5	Wrong	37	30%	32	44%	5	10%
	Total		125	100%	73	100%	52	100%

Based on the analyses above, it can be concluded that generally the ARMPS-LAM SF has a strong correlation to the ARMPS 2010 SF, but averages about 8% higher. Further, the depth of mining (H) is the most correlated variable when comparing the SF between ARMPS-LAM and ARMPS. The investigation of the case histories where the two programs give different results indicates that ARMPS-LAM distributes less load on the AMZ for shallow cover cases (H < 1,000 ft) and distributes more load on the AMZ for deep-cover cases (H > 1,000 ft). This results in a relatively higher SF for LaModel analysis of shallow cover mine and a relatively lower SF for LaModel analysis of deep-cover mine. The investigation of the stability factor above identified that a potential area for future

improvement of LaModel is to improve its load distribution mechanisms to distribute more load for shallow cover and less load for deeper covers.

5.2.5 Classification Accuracy

Simply using the stability factor criterion of 1.50, the classification accuracies of ARMPS-LAM and ARMPS 2010 were compared based on the 645 case histories. Table 5.4 shows that ARMPS 2010 can correctly classify 59% of successes (307 out of the 520) and 82% of failures (102 out of 125), for an overall classification accuracy of 63% (409 out of 645); ARMPS-LAM can correctly classify 59% of successes (308 out of 520) and 70% of failures (88 out of 125), for an overall classification accuracy of 61% (396 out of 645). According to the detail results in Table 5.4, one can see that both programs have almost the same accuracy in classifying the successes (59% of successes); however, ARMPS 2010 has better performance in classifying the failures (82% of failures) using a stability factor of 1.50 as the room-and-pillar mine design guideline. It should be note that both programs use the Mark-Bieniawski pillar strength, the 21 ° abutment loading and an empirical value of 90% abutment load ($5\sqrt{H}$).

Table 5.4 Comparison of classification accuracy with SF guideline of 1.50.

Program	Program Prediction	All Case Histories		Successes		Failures	
		Num.	Per.	Num.	Per.	Num.	Per.
		645	100%	520	81%	125	19%
ARMPS 2010	Correct	409	63%	307	59%	102	82%
	Wrong	236	37%	213	41%	23	18%
ARMPS-LAM	Correct	396	61%	308	59%	88	70%
	Wrong	249	39%	212	41%	37	30%

5.3 Statistical Analysis

To further evaluate the overall classification accuracy of the ARMPS-LAM program, a statistical analysis was performed to compare the results from ARMPS-LAM and ARMPS 2010. This comparison was based on the current ARMPS 2010 database with 645 case histories. To be consistent with the previous accuracy evaluation of ARMPS 2010 (Mark, 2010; Mark et al., 2007), a similar technique of logistic regression was used on ARMPS-LAM to quantify the classification accuracy.

5.3.1 Logistic Regression

Logistic regression is the most commonly used multivariate statistical technique when the outcome, or dependent, variable is binary (in this case “success” or “failure”). In order to obtain the coefficients of the independent variable, the outcome has to be in “binary” form (i.e., “1” or “0”); therefore, a successful panel was chosen to be equal to “1,” while panel failure was chosen to be “0.” The goal of logistic regression analysis is to develop a model that can best fit the “outcome” using a combination of the independent input variables. The logistic regression analysis method was employed to develop the ARMPS design criteria (Mark, 2010; Mark & Chase, 1997) and to calibrate the LaModel program for shallow cover (Sears & Heasley, 2013).

Since the previous analysis was based on the single ARMPS stability factor criteria, a single variable of the ARMPS-LAM stability factor was analyzed first. This initial regression also helps illustrate the regression analysis procedure that will be used for the following multiple variable analysis. Ultimately these different regression models of ARMPS-LAM were compared with ARMPS 2010 to highlight the best performance model of ARMPS-LAM.

5.3.1.1 Single Variable

First, the single variable regression model using the AMZ SF calculated by ARMPS-LAM was created and the results are presented in Table 5.5. In the table, the coefficients represent the multiplicative factor of the variable; the standard error is the standard deviation; the z-value (z) is calculated by dividing the coefficient by the standard error, which provides an assessment of the portion of the standard error in the answer caused by each variable; and the P-value (P) denotes the significance of the individual variable, where a variable is more significant as its P-value decreases. It can be seen that the AMZ SF is a significant variable with a small P-value and a standard error around 0.22.

Table 5.5 Logistic regression of AMZ SF.

Variable	Coefficient	Standard Error	z	P
AMZ SF	1.4064	0.2181	6.448	1.14E-10
(Intercept)	-0.7912	0.3188	-2.482	0.0131

Based on the coefficients in Table 5.5, the regression model can be written as shown in Equation 5.2. The function $g(x)$ represents the analogous function that they formed. The function $g(x)$ is also called the maximum likelihood, which represents the goodness-of-fit at certain probability value (p). It presents the probability that ARMPS-LAM predicts the case histories correctly and ranges from 0 to 1.0 (Hosmer & Lemeshow, 2000).

$$g(x) = 1.406 * AMZSF - 0.7912 = \ln\left(\frac{p}{1-p}\right) \quad (5.2)$$

In a regression analysis, to analyze the goodness-of-fit of the logistic regression models, the Receiver Operating Characteristic (ROC) curve needs to be used (Brown & Davis, 2006), this curve functions as an alternate to the R^2 parameter in linear regression analysis, of which most people are familiar. The ROC curve is a graphical plot which illustrates the performance of a binary classifier system as its discrimination threshold is varied. For the dichotomous outcome of “success/failure,” it is created by plotting the correctly predicting successes out of real successes (Sensitivity) versus the false predicted failures out of real failures (1-Specificity). The ROC analysis provides a tool to evaluate and select potentially optimal models from the class distribution of success/failure (Hosmer & Lemeshow, 2000).

Specifically, the area under the ROC curve (AUC) is proportional to the ability of a given model to achieve a correct discrimination between the two outcomes (success or failure) within the database. The AUC of the ROC curve ranges from 0.5 (no discrimination or same as chance) to 1.0 (perfect discrimination). The AUC for Equation 5.2 is 0.72, which is shown in Figure 5.8. It implies that the ARMPS-LAM provides good discrimination of the ARMPS database using a single variable (ARMPS-LAM SF).

Figure 5.8 ROC curve for Equation 5.2.

Further, the logistic regression model's optimum cut-point can be determined from plotting of both the sensitivity and specificity versus the probability cutoff point (see Figure 5.9). The intersection of these two curves maximizes the overall classification accuracy of the regression Equation 5.2, resulting in an optimum cutoff point of $p = 0.77$. During development of the stability factor criteria of ARMPS, the specificity of 0.82 was chosen to improve ARMPS-LAM's ability of classifying failures to a same level as ARMPS (Mark, 2010; Mark & Chase, 1997). Figure 5.9 shows that ARMPS-LAM can correctly classify 82% of the failures, as ARMPS 2010 does, when the regression Equation 5.2 has a probability cutoff (p) of 0.83.

Figure 5.9 Optimum cutoff point for Equation 5.2.

Substituting the p value of 0.83 into Equation 5.2, It can be determined that the critical AMZ SF, which matches ARMPs 2010's 82% correct classification accuracy of the failures, equals to 1.66. At this point, ARMPs 2010 has an overall classification rate of 63%; however, ARMPs-LAM can only correctly classify 55% of the overall cases. To improve the overall classification accuracy, other significant variables and logistic regression models with multiple variables were investigated and discussed as following.

5.3.1.2 Multiple Variables

According to previous research (Heasley, 2012; Heasley et al., 2010; Sears & Heasley, 2013; Tulu et al., 2010), some variables have obvious effect on LaModel analysis results, such as the depth (H). Based on previous investigations of the significant variables

resulting in the difference between the ARMPS-LAM SF and ARMPS 2010, several logistic regression models with multiple variables were developed.

Ultimately eight variables were investigated, the AMZ SF, depth (H), BP SF, mining height (h), panel width (P_w), panel width-to-depth ratio (P_w/H), extraction ratio and pillar width-to-height ratio (w/h). Based on the logistic regression analysis, the classification accuracy of ARMPS-LAM does not appear to be related to the panel width (P_w), panel width-to-depth ratio (P_w/H) or extraction ratio. The five most significant variables, in order of significance, were found to be:

1. Stability factor of the AMZ (AMZ SF)
2. Depth of cover (H)
3. Stability factor of the barrier pillar (BP SF)
4. Mining height (h)
5. Pillar width-to-height ratio (w/h)

Table 5.6 presents the logistic regression results with the above five variables. It was very assuring to see that the AMZ SF was the most significant variable. However, the fact that the depth (H) appeared as a significant variable leads to a number of questions that will should be addressed in future research.

Table 5.6 Logistic regression results for the model containing five variables.

Variable	Coefficient	Standard Error	z	P
AMZ SF	2.18683	0.35457	6.168	6.94E-10
H	1.81858	0.43107	4.219	2.46E-05
BP SF	0.96764	0.2766	3.498	0.000468
h	-0.21925	0.06321	-3.469	0.000523
w/h	-0.10372	0.06651	-1.559	0.118894
Intercept	-1.17565	0.84594	-1.39	0.164603

In the database, there were many ARMPS case histories (loading condition 1 and 2) where there was no barrier pillar, but rather a solid block of coal. In this situation, it was not clear how to accurately determine a “barrier pillar” stability factor to use in the logistic regression of the ARMPS-LAM results. Obviously this solid block of coal would have a very high stability factor, but the exact value was unknown. To handle this conundrum, it was decided to input the barrier pillar safety factor in a “binary” form around the safety factor of 1.5, where the BP SF is equal to 0, if the BP SF is smaller than 1.5 (unstable) and the BP SF is equals to 1 if the BP SF is larger than 1.5 (stable). The BP SF was input in this binary manner for the ARMPS-LAM results shown in Table 5.6. Similarly, there appeared to be a binary effect in the database with the depth (H), so the H was also input in binary form around 650 ft, with H equal to 0 if the depth was less than 650 ft and H equals to 1 if the depth was greater than 650 ft. Pillar width-to-height ratio (w/h) is the average value of the pillars within the AMZ. The other three variables — AMZ SF, h and w/h — were input consistent with their real values.

Based on the relative significance of the above variables, five different logistic regression models with an increasing number of independent variables were developed and analyzed in order to determine the practical accuracy of the different models. Model No.1 only has the most significant independent variable, AMZ SF and Model No. 2 has both the

AMZ SF and H. Model No.3 has three variables, i.e., AMZ SF, H and BP SF. Model No. 4 has the four most significant variables, while Model No.5 contains all five significant variables. Table 5.7 shows the equations with the regression coefficients for each of the trial models.

Table 5.7 Logistic regression models with different variables.

Model	Model Equation
No. 1	$g(x) = 1.406 * AMZSF - 0.7912$
No. 2	$g(x) = 2.202 * AMZSF + 1.928 * H - 3.3163$
No. 3	$g(x) = 2.177 * AMZSF + 1.789 * H + 1.021 * BP SF - 3.4843$
No. 4	$g(x) = 1.887 * AMZSF + 1.367 * H + 0.899 * BP SF - 0.178 * h - 1.4859$
No. 5	$g(x) = 2.189 * AMZSF + 1.819 * H + 0.968 * BP SF - 0.219 * h - 0.104 * (w/h) - 1.1757$

5.3.2 Classification Accuracy Comparison

According to the logistic regression performed by Mark (2010), ARMPS 2010 with only the one variable (SF) achieved an AUC of 0.7569, which implies good discrimination between the two outcomes (success or failure) within the database (see Table 5.8). In this initial logistic regression analysis of ARMPS-LAM, the single variable model (with SF) obtained an AUC of 0.7163. However, Model No. 2, which contained both the ARMPS-LAM SF and depth (H) has an AUC value of 0.7837, a significant improvement and slightly better than ARMPS 2010. The next models, Nos. 3 and 4, only show a slight increase in the AUC with the additional variables (see Table 5.8). However, Model No. 5 with all five of the most significant variables, shows the best AUC of 0.8315.

Table 5.8 Logistic regression results of different models.

Model	Variables of equation	Area under ROC curve (AUC)
ARMPS 2010	AMZ SF	0.7569
No. 1	AMZ SF	0.7163
No. 2	AMZ SF, H	0.7837
No. 3	AMZ SF, H, BP SF	0.8180
No. 4	AMZ SF, H, BP SF, h	0.8274
No. 5	AMZ SF, H, BP SF, h, w/h	0.8315

For ARMPS 2010, the design criteria was ultimately determined to be an ARMPS SF of 1.5 where 82% of the failed case histories and 59% of the successful case histories were correctly classified, for an overall classification accuracy of 63% (see Table 5.9). The 1.5 value of stability factor for ARMPS 2010 was not the optimum overall classification point, but rather, the recommended stability factor was increased to more accurately classify the critical unsuccessful case histories. For the regression models of ARMPS-LAM, the same criteria of 82% accuracy in classifying the failure cases was applied and the results are shown in Table 5.9. For Model No. 1 using only the ARMPS-LAM SF, the overall accuracy is only 55% (compared to 63% for ARMPS 2010). However, for Model Nos. 3 and 4, the overall accuracy is 72% and for Model No. 5, the overall accuracy drops to 70%. It is even lower than previous models, although it has a higher AUC value. Because the regression model is not a continuous model, its accuracy may stay at some range and then jump with a small number of additional case histories. Model No.3 has essentially the same classification accuracy as Model No. 4 but with fewer variables; therefore, based on this analysis, Model No. 3 is determined to be the preferred option.

Table 5.9 Different models with same classification accuracy for failures.

Model	Successful case histories		Failed case histories		Total case histories	
	Correctly classified	Incorrect classified	Correctly classified	Incorrect classified	Correctly classified	Incorrect classified
ARMPS 2010	59%	41%	82%	18%	63%	37%
No. 1	49%	51%	82%	18%	55%	45%
No. 2	52%	48%	82%	18%	58%	42%
No. 3	69%	31%	82%	18%	72%	28%
No. 4	70%	30%	82%	18%	72%	28%
No. 5	68%	32%	82%	18%	70%	30%

Based on the statistical analysis results, the regression Model No.3 shown in Table 5.9 has a cutoff probability (p) of 0.82, when its failure classification is 82% (and the success classification is 69% and overall classification accuracies is 72%. Similar to logistic regression with a single variable as described in Section 5.3.1.1, for multiple regression the descriptive function, $g(x)$, is equal to the logistic function, $f(p)$, at a certain cutoff probability value, p. In particular, for regression Model No.3 at the cutoff probability (p) of 0.82, the following Equation can be obtained.

$$f(p) = g(x)$$

$$f(p) = \ln\left(\frac{p}{1-p}\right) = \ln\left(\frac{0.82}{1-0.82}\right) = 1.516 \quad (5.3)$$

$$g(x) = 1.516 = 2.177 * AMZSF + 1.789 * H + 1.021 * BPSF - 3.4843$$

Since $f(p)$ equals to $g(x)$ in value, the final design criterion for Model No.3 which determines the required AMZ SF is shown as Equation 5.4. It should be noted as mentioned previously, that the independent variables of depth (H) and barrier pillar stability factor are “binary” variable (0 and 1, see previous significant variable description).

$$AMZSF = 2.297 - 0.822 * H - 0.469 * BP\ SF \quad (5.4)$$

Equation 5.5 specifies that if the depth (H) exceeds 650 ft ($H = 1.0$), the required AMZ SF criterion would decrease by 0.822. Similarly, if the barrier pillar stability factor (BP SF) exceeds 1.50 ($BP\ SF = 1.0$), the AMZ SF criterion would decrease by 0.469. So, for a particular case history greater than 650 ft deep and with a BP SF greater than 1.5, the regression equation for Model No.3 predicts that the case history will be successful when its AMZ SF value exceeds 1.01:

$$AMZSF = 2.297 - 0.822 * 1.0 - 0.469 * 1.0 = 1.01 \quad (5.5)$$

Although, this is only a preliminary analysis of the ARMPS-LAM results and a number of potentially improved ARMPS-LAM algorithms will be implemented in the future by other researchers, these initial results are very encouraging. In a direct comparison with ARMPS 2010, which correctly classified 82% of the failed case histories and 59% of the successful case histories, for an overall classification accuracy of 63%, the ARMPS-LAM analysis was able to accurately classify 82% of the failed case histories and 69% of the successful case histories for an overall classification accuracy of 72%. In the future, this classification accuracy may yet increase with additional research.

Chapter 6. Summary and Conclusions

6.1 Summary

Pillar stability is critical to safe and economic operations of room-and-pillar retreat mines. For many years, both the ARMPS and the LaModel programs have been successfully used in the U.S. coal industry for room-and-pillar design. The ARMPS program has been very successful since it is easy and quick to use, and its design guidelines are based on analysis of a large database (Mark, 2010). On the other hand, the LaModel program is more applicable for detailed stress analysis and more flexible for analyzing various mining conditions; however, it consumes considerable of time to develop, run and analyze the model. It is the objective of this dissertation to enhance coal mine safety by improving the current technology of room-and-pillar coal mine design through integrating the ARMPS and LaModel programs.

In this research, a computer code, ARMPS-LAM, has been developed to effectively implement the laminated overburden model (LaModel) into the ARMPS program. It consists of three modules: pre-processing, numerical solution and post-processing. It takes the basic ARMPS geometric input for defining the mine plan and loading condition and then automatically develops, runs and analyzes a full LaModel analysis to output the stability factor and other data for mine design analysis. Further, the algorithms in the program have been improved to optimize the numerical calculation accuracy and the program efficiency. The ARMPS-LAM program also can run in batch mode.

The ARMPS-LAM program and its subroutines have all been manually validated and demonstrated in this dissertation. Finally, an analysis of the ARMPS database has been conducted and several key points are highlighted.

- 1) The ARMPS-LAM program greatly improves the efficiency of the LaModel analysis. The entire database was analyzed in 10 hours. The average run time for a single case history was 52 seconds, with a maximum run time of 7 minutes.
- 2) The ARMPS-LAM SF averages about 8% higher than the ARMPS 2010 SF.

- 3) Compared with ARMPS 2010, the laminated overburden model (implemented in ARMPS-LAM) distribute less load on the AMZ for shallow cover ($< 1,000$ ft) and more load for deep cover ($> 1,000$ ft), where the “1,000 ft” separation between “shallow” and “deep” used here is solely based on the database analysis conducted in this dissertation.
- 4) Simply using a stability factor of 1.50 as the criterion, ARMPS-LAM can correctly classify 61% of the case histories. When the SF criterion is increased to 1.66, ARMPS-LAM can match the same accuracy in classifying the failures of ARMPS (82%); however, its overall classification accuracy drops to 55%.
- 5) The five most significant variables for classification accuracy with ARMPS-LAM are (in order of significance): the stability factor of AMZ, the depth of cover, the stability factor of barrier pillar, the mining height, and the pillar width-to-height ratio.
- 6) When only the stability factor is used, ARMPS-LAM can only classify 55% of the ARMPS database, which is lower than the classification accuracy of ARMPS 2010 (63%). However, with additional significant variables included, ARMPS-LAM’s classification accuracy can reach 72%.

6.2 Conclusions

In this dissertation, the ARMPS-LAM program, which effectively integrate the LaModel and ARMPS programs, was successfully developed and validated. The ARMPS-LAM can automatically runs and analyzes a full LaModel analysis of ARMPS-type mine design without further user’s input. Further, the algorithms in the program have been optimized to improve the numerical calculation accuracy and the program efficiency. And, the ARMPS-LAM program is also able to run in batch mode.

Based on an analysis of the ARMPS database, it was found that the laminated overburden model as implemented in ARMPS-LAM has a classification accuracy of 55%, versus ARMPS 2010, which has a classification accuracy of 63%. However, with additional significant variables, ARMPS-LAM can correctly classify 72% of the database.

Ultimately, the research work presented in this dissertation has improved room-and-pillar mine design technology through developing a new methodology to accurately, efficiently and automatically conduct a LaModel analysis of ARMPS-type mine design. Moreover, this methodology can serve as a future platform to quickly evaluate other models or methods to continuously improve pillar design technology.

In the future, this program is going to be implemented into a new version of the ARMPS program and will be readily used in coal mines in the U.S. and around the world.

6.3 Areas for Future Research

Based on the ARMPS database analysis in this research work, it was seen that the laminated overburden model (as implemented in LaModel/ARMPS-LAM) distributes less load for shallow cover (where the depth of cover is less than 1,000 ft) and too much load for deep cover (where the depth is more than 1,000 ft). This load distribution mechanism in LaModel/ARMPS-LAM could be revised to improve its classification accuracy. For instance, the utility of a new abutment loading algorithm proposed by Tulu and Heasley (2012), or the utility of using strain-softening coal properties (Karabin & Evanto, 1999) or looking at different lamination thicknesses could be potential solutions to improve the accuracy of estimating pillar load.

In the future, due to its batch capability, the ARMPS-LAM program can be used to quickly evaluate the utility of any number of new ground control approaches against the large ARMPS database. Based on the performance of the new algorithms or models, the classification accuracy of ARMPS-LAM can be enhanced to improve the safety of retreat room-and-pillar mining operations in the United States and around the world.

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Appendix A. Input File Data Structure

File name: “*.CSV,” where ‘*’ represents the input file name

File format: ASCII in the form of comma-separated values (CSV)

Contents: 52 items of ARMPS input

No.	Item Name	Description
1	State	State name
2	Mine	Mine name
3	Mining Height	Mining height
4	Depth of Cover	Depth of cover
5	Entry Width	Entry width
6	Crosscut Spacing	Crosscut spacing
7	Crosscut Angle (degrees)	Crosscut angle in degree
8	Number of Entries	Number of entries, from 1 to 10
9	No.1 entry spacing (c-to-c), default is 0	1 st entry spacing, center-to-center, default is 0
10	No.2 entry spacing (c-to-c), default is 0	2 nd entry spacing, center-to-center, default is 0
11	No.3 entry spacing (c-to-c), default is 0	3 rd entry spacing, center-to-center, default is 0
12	No.4 entry spacing (c-to-c), default is 0	4 th entry spacing, center-to-center, default is 0
13	No.5 entry spacing (c-to-c), default is 0	5 th entry spacing, center-to-center, default is 0
14	No.6 entry spacing (c-to-c), default is 0	6 th entry spacing, center-to-center, default is 0
15	No.7 entry spacing (c-to-c), default is 0	7 th entry spacing, center-to-center, default is 0
16	No.8 entry spacing (c-to-c), default is 0	8 th entry spacing, center-to-center, default is 0
17	No.9 entry spacing (c-to-c), default is 0	9 th entry spacing, center-to-center, default is 0
18	Loading Condition	Loading condition, value ranges from 1 to 4
19	Front Gob Extent	Front Gob extent
20	1st Side Gob Extent	1 st side Gob extent
21	2nd Side Gob Extent	2 nd side gob extent
22	1st Barrier Pillar Width	1 st side barrier pillar width, rib-to-rib, default is 0
23	2nd Barrier Pillar Width	2 nd side barrier pillar width, rib-to-rib, default is 0
24	1st Slab Cut Depth	Slab cut depth in 1st side barrier pillar, default is 0
25	2nd Slab Cut Depth	Slab cut depth in 2nd side barrier pillar, default is 0

26	CMRR	CMRR rating, default is 0
27	Roof Strength Rating	Roof strength rating, default is 0
28	Thickness of Caprock	Thickness of caprock, default is 0
29	Region	Region name, default is blank
30	Number of cases	Cases of the same region in ARMPS database, default is blank
31	Weight	Weight of current case in ARMPS database, default is blank
32	w2	w2 value, default is blank
33	Seam Strength	Seam strength, default is blank
34	Hard Grove Index (HGI)	HGI, default is blank
35	Success	0' represents fail; '1' represents success
36	Fail Type	Fail type, value ranges from 1 to 4.5
37	Sort	Sort number in ARMPS database, default is blank
38	Unit	'0' represents "ft, lbs"; '1' represents "m, kN"
39	Coal strength	In-situ coal strength, psi or MPa, based on unit
40	Overburden weight	Overburden weight, pcf or kN/m ³ , based on unit
41	Breadth of AMZ	Breadth of AMZ, default value is $5\sqrt{H}$
42	Abutment angle: Active gob	Abutment angle of active gob, default is 21 °
43	Abutment angle: 1st side gob	Abutment angle of 1 st side gob, default is 21 °
44	Abutment angle: 2nd side gob	Abutment angle of 2 nd side gob, default is 21 °
45	Bleeder pillar: Row A	Left bleeder pillar in AMZ, '0' – No, '1' - Yes
46	Bleeder pillar: Row B	Right bleeder pillar in AMZ, '0' – No, '1' - Yes
47	Bleeder pillar: Row C	Bleeder pillar in 1 st side gob, '0' – No, '1' - Yes
48	Bleeder pillar: Row D	Bleeder pillar in 2 nd side gob, '0' – No, '1' - Yes
49	Bleeder pillar: Width of Row C	Width of bleeder pillar in 1 st side gob, rib-to-rib
50	Bleeder pillar: Width of Row D	Width of bleeder pillar in 2 nd side gob, rib-to-rib
51	Element size value	'0' represents using ARMPS-LAM to determine element size; '1' means using user defined value
52	User defined element size	Users defined element size, default is 0

Appendix B. Output File Data Structure

File name: “*_LAM.ARL” where the ‘*’ represents the prefix name of the input file.

File format: plain text (ASCII) in the format of comma-separated values (CSV)

Contents: 47 items of ARMPS-LAM outputs

No.	Item Name	Description
1	Serial	Serial number in the input file, it will be one if there is only one case in the input file
2	Sort	Sort number in the ARMPS database
3	Unit	0 is “ft,” 1 is “m”
4	Load Cond	Loading condition in ARMPS from ‘1’ to ‘4’
5	Total Step	‘1’ for development condition; ‘2’ for other condition
6	Grid Size Option	‘0’ using program to determine element size.; ‘1’ using customized element size
7	Grid Size	Element size in “ft” or “m”
8	X Grid	Grid number in X direction
9	Y Grid	Grid number in Y direction
10	AMZ SF Dev	AMZ SF for development condition
11	AMZ SF Ret	AMZ SF for retreat condition
12	BP3SFDev	1 st side Barrier Pillar SF for development condition
13	BP3SFRet	1 st side Barrier Pillar SF for retreat condition
14	BP4SFDev	2 nd side Barrier Pillar SF for development condition
15	BP4SFRet	2 nd side Barrier Pillar SF for retreat condition
16	RP3SFDev	1 st side Remnant Pillar SF for development condition
17	RP3SFRet	1 st side Remnant Pillar SF for retreat condition
18	RP4 SF Rev	2 nd side Remnant Pillar SF for development condition
19	RP4 SF Ret	2 nd side Remnant Pillar SF for retreat condition
20	Pillar1Strength	1 st pillar on the first pillar line in psi or Pa. (from left)
21	Pillar2 Strength	2 nd pillar on the first pillar line in psi or Pa. (from left)
22	Pillar3Strength	3 rd pillar on the first pillar line in psi or Pa. (from left)
23	Pillar4 Strength	4 th pillar on the first pillar line in psi or Pa. (from left)
24	Pillar5 Strength	5 th pillar on the first pillar line in psi or Pa. (from left)
25	Pillar6 Strength	6 th pillar on the first pillar line in psi or Pa. (from left)
26	Pillar7 Strength	7 th pillar on the first pillar line in psi or Pa. (from left)
27	Pillar8 Strength	8 th pillar on the first pillar line in psi or Pa. (from left)
28	Pillar9 Strength	9 th pillar on the first pillar line in psi or Pa. (from left)
29	BP3 Strength	1 st side Barrier Pillar’s pillar strength in psi or Pa
30	BP3 Area	1 st side Barrier Pillar’s pillar area in in ² or m ²
31	BP3 Load Dev	1 st side Barrier Pillar’s development load in lb or N
32	BP3 Load Ret	1 st side Barrier Pillar’s retreating load in lb or N
33	BP4 Strength	2 nd side Barrier Pillar’s pillar strength in psi or Pa
34	BP4 Area	2 nd side Barrier Pillar’s pillar area in in ² or m ²

35	BP4 Load Dev	2 nd side Barrier Pillar's development load in lb or N
36	BP4 Load Ret	2 nd side Barrier Pillar's retreating load in lb or N
37	RP3 Strength	1 st side Remnant Pillar's pillar strength in psi or Pa
38	RP3 Area	1 st side Remnant Pillar's pillar area in in ² or m ²
39	RP3 Load Dev	1 st side Remnant Pillar's development load in lb or N
40	RP3 Load Ret	1 st side Remnant Pillar's retreating load in lb or N
41	RP4 Strength	2 nd side Remnant Pillar's pillar strength in psi or Pa
42	RP4 Area	2 nd side Remnant Pillar's pillar area in in ² or m ²
43	RP4 Load Dev	2 nd side Remnant Pillar's development load in lb or N
44	RP4 Load Ret	2 nd side Remnant Pillar's retreating load in lb or N
45	BleP3Strength	1 st side Bleeder pillar's pillar strength psi or N
46	BleP4 Strength	2 nd side Bleeder pillar's pillar strength psi or N
47	Time	Entire running time in second

Appendix C. Flowchart Symbols

Process / Operation Symbols

Symbol	Name	Description
Process	Show a Process or action step. This is the most common symbol in both process flowcharts and process maps.
Predefined Process (Subroutine)	A Predefined Process symbol is a marker for another process step or series of process flow steps that are formally defined elsewhere. This shape commonly depicts sub-processes (or subroutines in programming flowcharts). If the sub-process is considered "known" but not actually defined in a process procedure, work instruction, or some other process flowchart or documentation, then it is best not to use this symbol since it implies a formally defined process.
Alternate Process	As the shape name suggests, this flowchart symbol is used when the process flow step is an alternate to the normal process step. Flow lines into an alternate process flow step are typically dashed.
Delay	The Delay flowchart symbol depicts any waiting period that is part of a process. Delay shapes are common in process mapping.
Manual Operation	Manual Operations flowchart shapes show which process steps are not automated. In data processing flowcharts, this data flow shape indicates a looping operation along with a loop limit symbol.

Input and Output Symbols

Symbol	Name	Description
Data (I/O)	The Data flowchart shape indicates inputs to and outputs from a process. As such, the shape is more often referred to as an I/O shape than a Data shape.
Document	Pretty self explanatory - the Document flowchart symbol is for a process step that produces a document.
Multi-Document	Same as Document, except, well, multiple documents. This shape is not as commonly used as the Document flowchart shape, even when multiple documents are implied.
Display	Indicates a process step where information is displayed to a person (e.g., PC user, machine operator).
Manual Input	Manual Input flowchart shapes show process steps that must be manually input into a system.

File and Information Storage Symbols

Symbol	Name	Description
Stored Data	A general Data Storage flowchart shape used for any process step that stores data.
Magnetic Disk (Database)	The most universally recognizable symbol for a data storage location, this flowchart shape depicts a database.
Direct Access Storage	Direct Access Storage is a fancy way of saying Hard Drive.
Internal Storage	Used in programming flowcharts to mean information stored in memory, as opposed to on a file.
Sequential Access Storage	Although it looks like a 'Q', the symbol is supposed to look like a reel of tape.

Appendix D. Case Study Input Validation

One case study has been used to validate the ARMPS-LAM program in Chapter 4. This case was verified using LamPre 3.0. All of the inputs were entered by hand and they are shown below.

General Model Information

General Model Information

Project Title: 32

General Parameters

Number of Seams: 1

Number of In-Seam Materials: 34

Number of Steps: 2

☐ Define Off-Seam Plane

☐ Define Fault Plane

Current Units

☐ Inches and pounds per sq.inch [in, psi]

☒ Feet and pounds per sq.inch [ft, psi]

☐ Meters and pascal [m, Pa]

☐ Meters and megapascals [m, MPa]

Help Cancel OK Next Form

Seam Geometry Boundary Conditions

The dialog box is titled "Seam Geometry Boundary Conditions". It is divided into three main sections: "Seam Geometry", "Seam Location", and "Seam Boundary Conditions".

Seam Geometry:

- Element Width (ft): 2.5
- Number of Elements in X axis: 690
- Number of Elements in Y axis: 890
- Total number of Grid Points: 614100

Seam Location:

- Current Seam Number: 1
- X coordinate of Grid Origin: 0
- Y coordinate of Grid Origin: 0
- Overburden Depth (ft): 860
- Seam Thickness (ft): 7.4

Seam Boundary Conditions:

A central diagram shows a red grid labeled "SEAM GRID". Surrounding it are four directional boxes, each with "Rigid" and "Symmetric" radio buttons:

- North:** ☐ Rigid, ☒ Symmetric
- West:** ☐ Rigid, ☒ Symmetric
- East:** ☐ Rigid, ☒ Symmetric
- South:** ☐ Rigid, ☒ Symmetric

Buttons on the right: Help, Cancel, OK, Next Form.

Overburden / Rock Mass Parameters

The dialog box is titled "OverBurden / Rock Mass Parameters". It contains a section for "Overburden / RockMass Parameters" with the following fields:

- Poisson's Ratio: 0.25
- Elastic Modulus (psi): 3000000
- Lamination (Layer) Thickness (ft): 319.644166666667
- Vertical Stress Gradient (psi/ft): 1.125

On the right side, there is a button labeled "Lamination Thickness Wizard".

Buttons at the bottom: Help, Cancel, OK, Next Form.

Summary of Defined Material Models

No.	Char.	Material	Material Type	Para. 1	Para. 2	Para. 3	Para. 4	Para. 5
1	A	Coal	Linear elastic	300000	112782	0	0	0
2	B	Coal	Elastic plastic	9727.95	0.032427	0	0.33	0
3	C	Coal	Elastic plastic	9622.75	0.032076	0	0.33	0
4	D	Coal	Elastic plastic	9096.78	0.030323	0	0.33	0
5	E	Coal	Elastic plastic	8991.58	0.029972	0	0.33	0
6	F	Coal	Elastic plastic	8465.61	0.028219	0	0.33	0
7	G	Coal	Elastic plastic	8360.42	0.027868	0	0.33	0
8	H	Coal	Elastic plastic	7834.44	0.026115	0	0.33	0
9	I	Coal	Elastic plastic	7729.25	0.025764	0	0.33	0
10	J	Coal	Elastic plastic	7203.27	0.024011	0	0.33	0
11	K	Coal	Elastic plastic	7098.08	0.02366	0	0.33	0
12	L	Coal	Elastic plastic	6572.1	0.021907	0	0.33	0
13	M	Coal	Elastic plastic	6466.91	0.021556	0	0.33	0
14	N	Coal	Elastic plastic	5940.94	0.019803	0	0.33	0
15	O	Coal	Elastic plastic	5835.74	0.019453	0	0.33	0
16	P	Coal	Elastic plastic	5309.77	0.017699	0	0.33	0
17	Q	Coal	Elastic plastic	5204.57	0.017349	0	0.33	0
18	R	Coal	Elastic plastic	4678.6	0.015595	0	0.33	0
19	S	Coal	Elastic plastic	4573.4	0.015245	0	0.33	0
20	T	Coal	Elastic plastic	4047.43	0.013491	0	0.33	0
21	U	Coal	Elastic plastic	3942.23	0.013141	0	0.33	0
22	V	Coal	Elastic plastic	3416.26	0.011388	0	0.33	0
23	W	Coal	Elastic plastic	3311.06	0.011037	0	0.33	0
24	X	Coal	Elastic plastic	2785.09	0.009284	0	0.33	0
25	Y	Coal	Elastic plastic	2679.9	0.008933	0	0.33	0
26	Z	Coal	Elastic plastic	2153.92	0.00718	0	0.33	0
27	a	Coal	Elastic plastic	2048.73	0.006829	0	0.33	0
28	b	Coal	Elastic plastic	1522.75	0.005076	0	0.33	0
29	c	Coal	Elastic plastic	1417.56	0.004725	0	0.33	0
30	d	Coal	Elastic plastic	891.584	0.002972	0	0.33	0
31	e	Coal	Elastic plastic	786.39	0.002621	0	0.33	0
32	f	Gob	Strain hardening	100	2.20E+06	4000	1	0.33
33	g	Gob	Strain hardening	100	1.71E+06	4000	1	0.33
34	h	Gob	Strain hardening	100	2.20E+06	4000	1	0.33

Program Control Parameters

Program Control Parameters

Control Options

Over - Relaxation Factor	<input type="text" value="1.65"/>
Displacement Convergence Level (ft)	<input type="text" value="0.00001"/>
Maximum Number of Iteration	<input type="text" value="2000000"/>
Initial Step Number	<input type="text" value="1"/>

Solution Options

- ☐ Include Free Surface Effects
- ☐ Input Topography from Topographic File
- ☒ Calculate Safety Factors
- ☐ Calculate Multiple Seam Subsidence
- ☐ Include Energy Calculations
- ☐ Include Roof Beam Bending Stresses

Help Cancel OK Finish