Analysis of Coal Pillar Stability (ACPS): A New Generation of Pillar Design Software

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ABSTRACT

Thirty years ago, the Analysis of Longwall Pillar Stability (ALPS) inaugurated a new era in coal pillar design. ALPS was the first empirical pillar design technique to consider the abutment loads that arise from full extraction, and the first to be calibrated using an extensive database of mining case histories. ALPS was followed by the Analysis of Retreat Mining Stability (ARMPS) and the Analysis of Multiple Seam Stability (AMSS). These methods incorporated other innovations, including the Coal Mine Roof Rating (CMRR), the Mark-Bieniawski pillar strength formula, and the pressure arch loading model. They also built upon ever larger case history databases and employed more sophisticated statistical methods.

Today, these empirical methods are used in nearly every underground coal mine in the US. However, the piecemeal manner in which these methods have evolved resulted in some weaknesses. For example, in certain situations, it may not be obvious which program is the best to use. Other times the results from the different programs are not entirely consistent with each other. The programs have also not been updated for several years, and some changes were necessary to keep pace with new developments in mining practice.

The Analysis of Coal Pillar Stability (ACPS) now integrates all three of the older software packages into a single pillar design framework. ACPS also incorporates the latest research findings in the field of pillar design, including an expanded multiple seam case history data base and a new method to evaluate room and pillar panels containing multiple rows of pillars left in place during pillar recovery. ACPS also includes updated guidance and warnings for users and features upgraded help files and graphics.

INTRODUCTION

Pillar design is one of the fundamental elements of mining engineering. Pillars are necessary to control the great weight of the overburden during all phases of underground mining. Without stable pillars, ground control is impossible.

Pillars have been used since the earliest days of mining. The first scientific pillar design method for US coal mines was developed more than a century ago. Yet, as late as the 1980s, no design technique had achieved wide acceptance, and few pillars were truly engineered (Mark, 2006). Most mines sized their pillars using local rules of thumb that were based on past experience. Pillar failures (or "squeezes") occurred relatively frequently, particularly during pillar recovery, and were considered an inevitable part of mining.

The advent of modern longwall mining added to the difficulties. Longwall gate pillars were expected to maintain access to the longwall face, including the tailgate side of the panel. However, early pillar design methods did not consider the heavy abutment loads that are generated by longwall mining. The 1984 Wilberg Mine Disaster, in which 27 miners were trapped by a headgate fire and could not escape because roof falls blocked the tailgate entry, tragically illustrated the potential consequences of inadequate gate entry ground control.

The Analysis of Longwall Pillar Stability (ALPS) was developed in direct response to the Wilberg Mine Disaster. The two-dimensional "abutment angle" concept was developed to provide estimates of retreat mining abutment loads, based on an extensive stress measurement research program (Mark, 1990). ALPS used the Bieniawski formula to estimate pillar strengths, though that formula is only appropriate for square pillars. A Stability Factor (SF) was then calculated by comparing the load to the load-bearing capacity of the longwall pillar system.

When applied to the few available case histories, however, it was clear that the ALPS pillar SF could not predict tailgate stability on its own. Roof support, entry width, and most critically, roof geology, needed to be considered, as well. The Coal Mine Roof Rating (CMRR) rock mass classification was, therefore, developed so that geologic factors could be quantified and integrated into the longwall pillar design process. Ultimately, a large database of case histories was collected during visits to longwall mines throughout the US, and modern multi-variate statistical techniques were used for the first time to analyze the data (Mark, Chase, and Molinda, 1994). The study resulted in simple ALPS design guidelines that considered all the key elements of the tailgate stability problem.

Pillar design for room-and-pillar retreat mining was pursued next. Before 1994, pillar recovery operations had been associated with about 25% of all roof fall fatalities underground; in addition, at least 12 massive pillar collapses had occurred (Mark, McCall, and Pappas, 1997a; Mark, Chase, and Zipf, 1997b). The Analysis of Retreat Mining Pillar Stability (ARMPS) was developed as a first step towards addressing these retreat mining hazards. ARMPS employed the same "abutment angle" loading model as ALPS, but extended it to three dimensions (Mark and Chase, 1997). It also modeled a wide variety of mining geometries, including both production pillars and barrier pillars. The original ARMPS database included 140 room-and-pillar mining case histories, and the method explained the data very well up to depths of 650 feet or so. Two subsequent research projects added another 500 cases to the database, mainly from mines with depths of cover exceeding 750 feet. The latest version of ARMPS now incorporates a pressure arch loading model, which was derived from statistical analysis of the case history data (Mark, 2010).

After more than a century of underground coal mining, many of the remaining coal reserves in the US are affected by multiple seam interactions. These very complicated phenomena can result in subsidence or stress transfers that cause roof falls, rib failure, floor heave, and even coal bursts. The Analysis of Multiple Seam Stability (AMSS) was developed to help mine planners assess the likelihood and potential severity of such interactions. The AMSS database included 344 case histories representing the most difficult conditions encountered in the Western and Central Appalachian coalfields (Mark, Chase, and Pappas, 2007). Each of the case histories was defined by 22 variables, and a two-dimensional version of the numerical model LaModel was employed to estimate the multiple seam loads arising from an interaction. Logistic regression was used to winnow these down to six key parameters which were then combined into a design equation. AMSS has two components, one that predicts pillar failures and the other roof stability issues.

Today, the ALPS, ARMPS, and AMSS pillar design methods are used in nearly every underground coal mine in the US. Their success can be attributed to three main factors (Mark, 2015):

- They are reliable because they are based on case histories that represent the broad range of actual mining experience in the US.
- They are transparent because they employ concepts that can be easily understood even by non-specialists.
- They are user-friendly because the input parameters are readily available and because they have been available on high quality, easily understood computer platforms.

Although no statistics on pillar failure are collected on a regular basis, it is clear that improved pillar design has greatly reduced failure incidence in US coal mines. Longwall tailgate blockages are rare, typically only affecting short segments of the gateroad. Squeezes are very unusual today during pillar recovery, and massive collapses are almost unheard of. The near-universal use of barrier pillars, particularly under deep cover, has significantly reduced the risk of coal bursts.

Better pillar design has also contributed to the greatly improved overall ground control safety record of the US industry. The connection is clearest in the case of pillar recovery. Once miners realized that squeezes resulted from inadequate pillars, and not from "poor caving," they were free to install more roof support and leave large final stumps. With more effective ground control only one miner has been killed by a pillar recovery roof fall in the decade since 2007, compared with 19 in the decade prior (Mark and Gauna, 2016).

There has been one significant blemish on this record, however. In 2007, the catastrophic pillar failure at the Crandall Canyon Mine resulted in the deaths of six miners and three rescuers. The MSHA investigation found that a root cause of the disaster was that the "dimensions of pillars within the active workings, as well as dimensions of the adjoining barrier pillars, did not provide sufficient strength to withstand stresses" (MSHA, 2008). The investigation further found that process used to design the pillars was flawed because the "ARMPS analysis of the pillar dimensions was inappropriately applied" and the numerical model analysis was "faulty."

The Crandall Canyon Disaster confirmed the need for reliable, user-friendly pillar design techniques for coal mining. In the initial wake of the disaster, the ARMPS program was strengthened with new pop-up user warnings and an expanded help file. Significant technical improvements, notably the pressure arch loading model, were also made. AMSS and ALPS were also upgraded, but not to the same extent.

In the years since, it has become clear that the piecemeal manner in which the three programs developed and evolved resulted in some weaknesses. In certain situations, users may find it difficult to select the most appropriate program to use. Other times, the results from the different programs are not entirely consistent. To simplify and improve the pillar design process, the Analysis of Coal Pillar Stability (ACPS) now integrates all three of the older packages into a single pillar design framework.

STRUCTURE OF ACPS

ACPS users begin with the "Input Project Description" screen (Figure 1). Two basic project types can be defined. The "Room-and-Pillar / Development" analysis is used for the design of main headings and production panels. Project options are "multiple seam" and "pillar recovery." A "Longwall Gate" project also has the multiple seam option, though it is only applicable to the development phase of a gate entry service life.

ACPS has been designed so that different users may attack a design problem different ways, yet get consistent answers. For example, development of a three-entry longwall gate system may be analyzed using either of the project types. In the past, because ALPS and ARMPS used different loading models, users could get different SF values from the two programs.

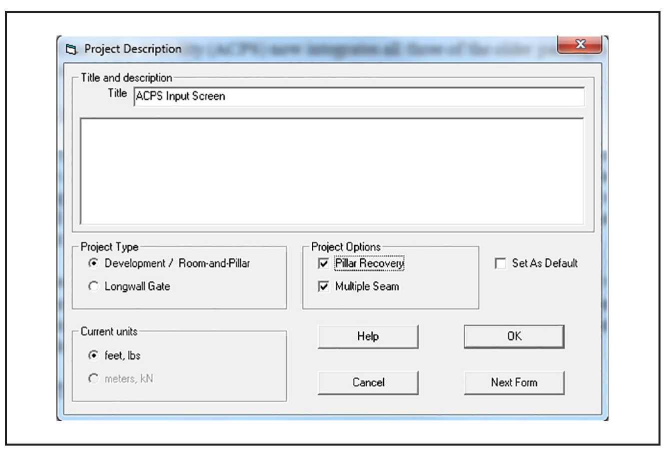

Figure 1. The ACPS Project Input Screen.

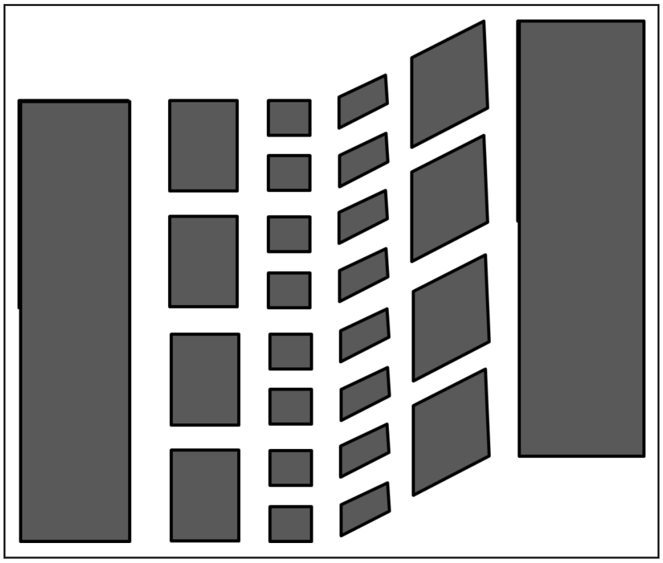

Figure 2. An "advanced geometry" panel that can be modeled in ACPS.

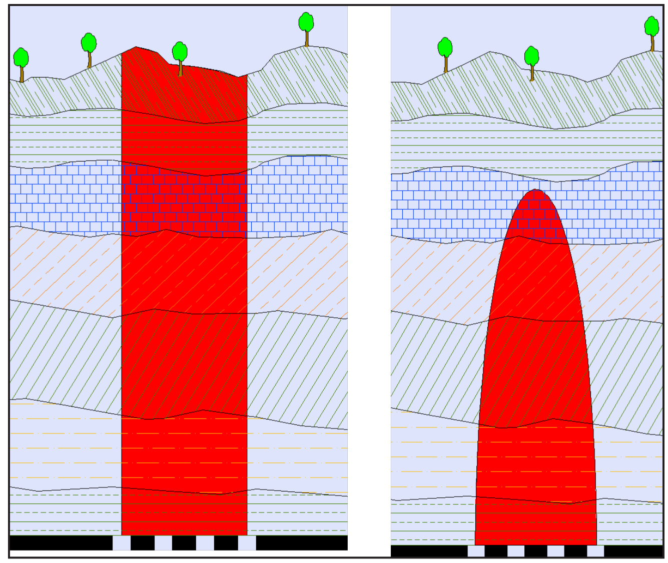

Figure 3. The tributary area (left) and pressure arch (right) loading models.

ROOM-AND-PILLAR / DEVELOPMENT PROJECTS

The basic ACPS input screen for Room-and-Pillar / Development Projects is very similar to the current ARMPS screen. The most significant change is that the "advanced geometry" option, which was formerly available only in ALPS, is now available for any project. The "advanced geometry" option allows all entry spacings, crosscut spacings, and crosscut angles to be specified for each individual pillar in a pillar row (Figure 2).

The calculation of the SF follows the ARMPS methodology. First, the "active mining zone" (AMZ) is defined, with a width equal to the width of the mains or panel being evaluated, and a breadth equal to five times the square root of the depth of cover. For panels beneath 900 feet of cover, for example, the breadth of the AMZ is (5 * 30) = 150 feet.

Next, the strength of each pillar within the AMZ is determined, using the Mark-Bieniawski pillar strength formula. The individual pillar strengths are multiplied by the load-bearing areas of the pillars, and these are summed to determine the total load-bearing capacity of the pillars within the AMZ.

The load calculation begins with the tributary area approximation, which states that the pillars carry the entire weight of the overburden directly above them. When the panel is deeper than it is wide, a "pressure arch" is assumed to transfer some of the tributary area load to presumed solid coal on either side of the panel (Figure 3). A new pop-up warns users to check that the panel is bordered by solid coal or substantial barrier pillars that can carry the load.

The SF is determined by dividing the load-bearing capacity of the pillars within the AMZ by the applied load. The design criteria suggested by NIOSH are still considered to be appropriate (Tables 1a and 1b).

Table 1a. Standard ACPS suggested design guidelines.

Depth of Cover (ft)	ARMPS AMZ SF	Barrier Pillar SF
<650	1.5	—
>650	1.5	1.5

RETREAT OPTION

When the "retreat" option is selected, the data input screen again is very similar to the one used in ARMPS. The user can specify the following (Figure 4):

- Whether there is just the active retreat mining in the panel being evaluated, or if there are pre-existing worked-out panels (side gobs) on one or both sides of the panel
- The extent of the active gob, and the width of any side gobs
- The width(s) of the barrier pillar(s) separating the active panel from the side gobs

Table 1b. Alternative ACPS suggested design guidelines for narrow panels with stronger barrier pillars.

Depth of Cover (ft)	Panel Width (ft)	ARMPS AMZ SF	Barrier Pillar SF
650–1,000	< 425	1.5– (0.20*((Depth-650)/350))	> 2.0
>1,000	< 425	1.30	> 2.0

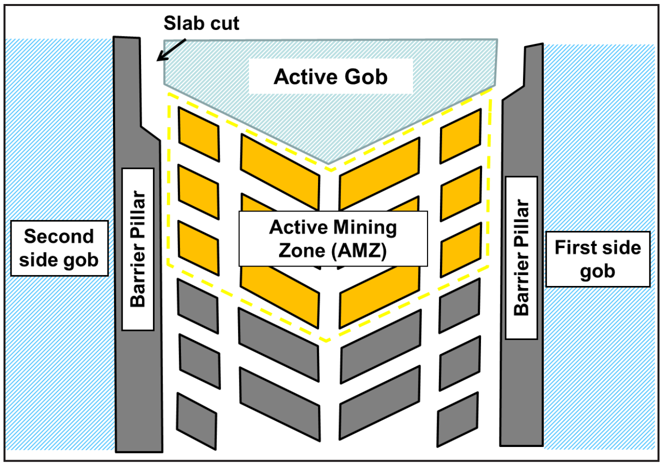

Figure 4. Room-and-pillar panel input parameters with the retreat mining option.

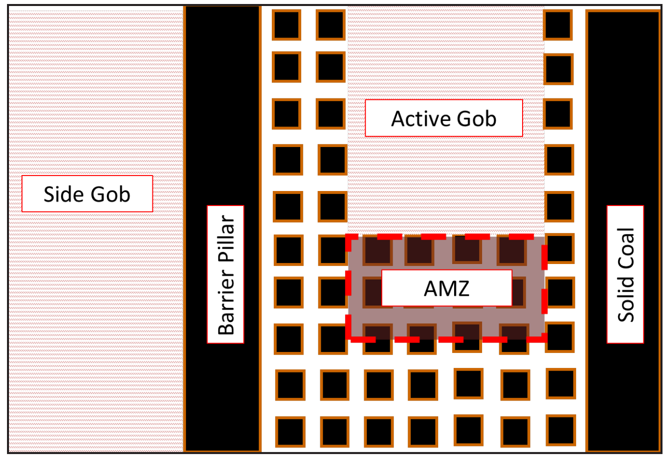

Figure 5. A room-and-pillar retreat panel with multiple rows of leave pillars that can modeled in ACPS.

- The depth of any slab cuts taken from the barrier pillars
- Whether a row of bleeder pillars has been left within a side gob, and the width of those bleeder pillars

The SF calculations are also essentially the same as in ARMPS. First, each barrier pillar SF is determined, considering the barrier tributary area loads, any pressure arch loads, and any loads due to the slab cuts. Then the load on the AMZ is determined, considering the development load, front and side abutment loads (possibly reduced by the pressure arch effect), and any loads transferred back to the AMZ from inadequate barrier pillars.

The most significant new feature is the manner in which ACPS treats leave pillars within the *active* panel. It is now common mining practice to leave one or more rows of unextracted pillars for ventilation and other reasons, and ACPS can now simulate a wide variety of pillar configurations. For example, figure 5 shows an eight-entry panel, with two leave pillars on one side, one leave pillar on the other side, and four pillars being extracted.

Leave pillars do not affect the calculation of the barrier pillar SF. Indeed, since the front abutment does not generally increase the load on the barrier pillar, and since slab cuts cannot be extracted when leave pillars are modeled, the barrier pillar SF is usually the same for both development and retreat.

Leave pillars do affect the calculation of the production pillar AMZ SF, however. ACPS defines a new AMZ for retreat mining that includes only those pillars on the active pillar line, excluding the leave pillars (Figure 5). Because the leave pillars are no stiffer than the production pillars, the pressure arch factor is the same as the one used in the development calculation.

MULTIPLE SEAM OPTION

AMSS provided two distinct evaluations of potential effects of a multiple seam interaction. The first is a pillar SF calculation that incorporates the multiple seam loads. Both the single seam tributary area loads and the multiple seam Lam2D loads are adjusted by the pressure arch factor described by Mark (2010). This calculation method is unchanged in ACPS.

The second evaluation is of the entry stability with a focus on the expected integrity of the roof and ribs. The ACPS calculations for this evaluation have been adjusted based on a new statistical analysis of an expanded database. The additional case histories helped to fill several gaps in the original database:

- While all original case histories were from the Central Appalachian and Western coalfields, the new ones are all from Northern Appalachia.
- The lowest CMRR in the original database was 45, while 16 of the new cases have a CMRR of 40.
- The new data includes a number of overmining cases where the depth of cover was less than 500 feet.

In all, a total of 53 new case histories were added from three mines. Two of the mines were described by Castner (2015), and the third was described by Stankus et al. (2012). On the other hand, 19 longwall tailgate cases were removed from the data base because they were considered too few to justify a separate class of multiple seam evaluations. In addition to the additional case histories, the new data base recalculated the total loads carried by the pillars using a pressure arch model matching the one used in the stability factor calculation.

The logistic regression analysis resulted in slightly different weightings for the factors included in the predictive model. For example, as shown in Table 2, *extra roof support* was equivalent to adding the protective value of 87 feet of interburden in the original AMSS model, while it adds just 54 feet in the ACPS model. Table 2 also shows that the *multiple seam configuration* (undermining or overmining) is also less influential in the ACPS model, while the *total vertical load* and the *CMRR* have greater influence on the predicted entry stability outcome. The new ACPS multiple seam predictive equation has approximately the same goodness-of-fit

Table 2. Comparison between the logistic regression multiple seam entry stability equations employed by AMSS and ACPS.

Parameter	AMSS Values	ACPS Values
	(equivalent feet of interburden)	
Vertical Stress (per 1000 psi)	–35	–74
Undermining vs Overmining	77	47
Extra Roof Support	87	54
Gob-Solid Boundary vs. Remnant Pillar	–77	–76
CMRR (* ln(CMRR –20))	83	111
Constant	–359	–372
ROC	0.88	0.88
Number of Cases	309	362

to the data as the original AMSS equation (see the ROC values in Table 2).

A new feature of ACPS is a "CMRR estimator" that helps users select appropriate values of this critical entry stability parameter. The tool can be used when reliable geologic data is available from core logs or underground observations, but no strength testing has been conducted. The ACPS CMRR estimates are conservative and coalfield-specific and based on experience with the most common roof geologies throughout the US. For example, the CMRR of Central Appalachian shale is estimated to be about 45, while the estimates for weaker Illinois Basin shales are 38–40.

LONGWALL GATE ENTRY PROJECT

The longwall gate entry module closely resembles the former ALPS program on which it is based. The most significant changes are that the SF results for the longwall "development," "bleeder," and "isolated" loading conditions are now consistent with the equivalent calculations in the "room-and-pillar" module. This was accomplished by incorporating the pressure arch into the longwall gate loading model and by using the Mark-Bieniawski pillar strength formula throughout. The ALPS "classic" option, which used the Bieniawski formula, was eliminated, as was the ALPS "sizing" option. Other new features of longwall gate entry module are that panel widths and abutment angles can be specified for individual panels, and the CMRR estimator can be used to help obtain input CMRR values where they help determine the appropriate tailgate pillar SF. The simplified longwall tailgate input screen is shown in Figure 6.

The multiple seam option is only available for the development phase of an ACPS longwall gate entry project. In retrospect, the AMSS multiple seam loading model for longwall extraction made unrealistically conservative assumptions for the longwall extraction phases, so these calculations were not carried over into ACPS.

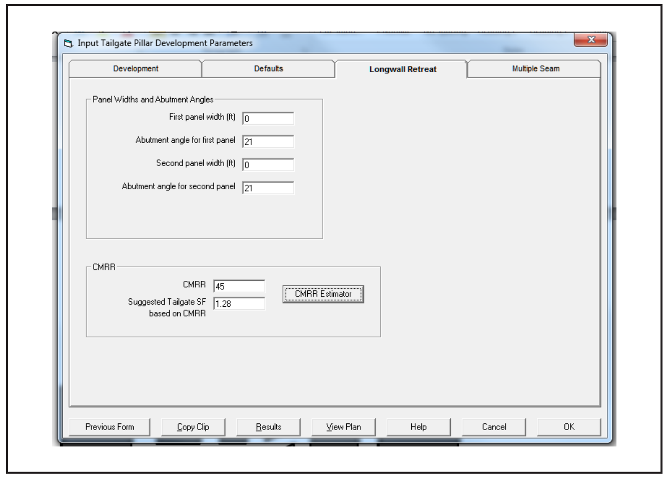

Figure 6. The ACPS longwall tailgate parameters screen.

CONCLUSIONS

Significant advances have been achieved in the science of pillar design during the past 30 years. User-friendly empirical design methods have made valuable contributions to coal mine safety. By integrating ALPS, ARMPS, and AMSS into a single pillar design framework, ACPS represents the logical next step for pillar design. ACPS also incorporates the latest research findings in the field of pillar design, including an expanded multiple seam case history database and a new method to evaluate room and pillar panels containing multiple rows of bleeder pillars.

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