Recent Developments in Coal Pillar Design in The U.S.

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Abstract: As underground coal mining continues to evolve in the U.S., more reserves are being mined under deeper cover, with worse roof, or with interactions from previous workings. At the same time, the mining community is responding to higher safety standards, new subsidence regulations, and intense competitive pressures. The need for accurate pillar design has never been greater.

During the 1970's and 80's, a number of field studies were conducted in coal pillars underground. As research funding from both government and the private sector has diminished, the emphasis has shifted to empirical studies and numerical modeling. Empirical methods emphasize the collection and interpretation of case histories of pillar performance. Statistical methods are employed to determine those variables which are most important to the success of a pillar design. Large data bases of real-world pillar successes and failures have been compiled for the Analysis of Retreat Mining Pillar Stability (ARMPs) and Analysis of Longwall Pillar Stability (ALPS) formulas. Using these data, valuable insights into the importance of the width-to-height ratio (w/h), the role of coal strength testing, and the interaction between pillar performance and roof quality have been obtained.

Numerical models used for pillar design may be divided into two categories. Finite element (FEM) and finite difference (FDM) models are best suited for investigating the behavior of detailed cross-sections of pillars and surrounding strata. Boundary Element models (BEM) can analyze stress distributions in large three-dimensional areas of tabular deposits. FEM were used to investigate the effects of roof and floor frictional interfaces, the pillar width-to-height ratio, and clay partings on pillar strength. The results were compared to underground stress measurements and to empirical formulas. A new BEM program, called LAMODEL, incorporates laminated overburden which more accurately simulates overburden behavior than earlier versions. It is used to investigate the effects of multiple seams, mining steps, complex pillar layouts and variable topography on the pillar loading.

Despite the differences in technique, the empirical and numerical lines of inquiry have converged on several important conclusions. For example, three broad categories of pillar behavior have been identified:
- Slender pillars \((w/h<3.0)\), which are subject to sudden collapse;
- Intermediate \((3\leq w/h<8)\), in which pillar squeezes seem to be the most common failure mode, and;
- Squat pillars \((w/h\geq8)\), which are dominated by entry failure (rib, roof, or floor) and coal bumps.

There is also agreement that coal seam discontinuities and roof-pillar-floor interactions are critical to pillar strength. A key outstanding issue is the need for simple field techniques to evaluate the in situ strength of the floor and the coal seam.

**Introduction**

The science of pillar design in the U.S. goes back nearly a century. One early pioneer noted that "to mine without adequate pillar support will result, sooner or later, in a squeeze; the inherent effects of which are crushing of the pillars, caving of the roof, and heaving of the bottom" (Bunting, 1911). Various pillar design formulas were proposed in the early days, based upon laboratory testing, full-scale pillar testing, and back-analysis of in-mine case histories (see Mark and Barton, 1996). They were developed for an industry that relied almost exclusively on room-and-pillar mining at relatively shallow depth.

The energy crisis of the 1970's and 1980's saw a revival of interest in coal pillar design in the U.S. A number of ambitious field studies were undertaken, many of them funded or conducted by the U.S. Bureau of Mines. New concepts began to take hold, notably that of the in situ coal strength and theories of progressive pillar failure. The growth of longwall mining was a later catalyst, and so was the development of sophisticated numerical models.

Today, approximately 400 million tons are produced underground in the U.S., split almost 50-50 between large longwall mines and smaller, room-and-pillar mines. Most longwalls operate at depths of cover in excess of 300 m, and employ "squat" pillars with width-to-height \((w/h)\) ratios of 10, 20 or even greater. Room-and-pillar operations are still primarily at shallow depth, often working small, irregular deposits that were abandoned by earlier miners. Approximately 20\% of the room-and-pillar coal is won on retreat faces (Mark et al, 1997a).

Today's underground coal industry faces intense competitive pressures, from the $4/ton Powder River Basin strip mine coal, and from the pace-setting million-ton-per-month longwalls. Safety standards have improved dramatically, and there is little tolerance for a ground control failure that results in an injury to personnel. In many states, regulators now require subsidence plans that "guarantee" indefinite surface support.

Pillar failures can hardly be afforded in this climate, yet they continue to occur. Some examples:

- **Massive Collapses:** In 1992, miners were splitting pillars at a southern West Virginia mine when the fenders in a 2.3 ha area suddenly collapsed. The miners were knocked to floor by the resulting air blast, and 103 ventilation stoppings were
destroyed. At least 12 similar events have occurred in recent years, miraculously without a fatality (Mark et al., 1997b).

- **Pillar Squeezes:** At a Kentucky coal mine, pillars were being extracted in the main entries under 270 m of cover. The pillars began to crush in response to the vertical load, resulting in a roof fall that killed two miners (MSHA, 1993). This incident is an extreme example of hazardous conditions that can be associated with slow pillar failure. Research has identified at least 45 recent instances of pillar squeezes in room-and-pillar mines (Mark and Chase, 1997).

- **Longwall Tailgate Blockages:** In 1984, 26 miners at the Wilberg Mine in Utah were trapped by a deadly fire, in part because the tailgate was blocked by a roof fall. Similar blockages were common in the 1980's, and 50 cases have been documented (Mark, 1992).

- **Pillar Bumps:** Extracting the initial lift from a standing pillar at a deep, eastern Kentucky operation resulted in a bump that killed two miners (MSHA, 1996). Bumps are not confined to pillars, however—another fatal bump occurred at a Utah longwall face just days later.

- **Multiple seam interactions:** Some studies indicate that most remaining underground coal reserves will experience multiple seam interactions. At a West Virginia mine where four seams had been previously extracted, one fatality occurred when the roof collapsed without warning beneath a remnant barrier pillar.

- **Abandoned mine subsidence:** As suburban development expands into historic coal mining areas, unplanned subsidence has become an important issue. In one case, water caused floor failure in a mined-out section of an active mine, causing $1 million in damage to an overlying chicken farm. In another, residents above 50 yr old workings were disturbed by seismicity emanating from collapsing pillars (Iannacchione and Mark, 1989).

**Approaches to Pillar Design**

The science of pillar design goes back more than 100 years. The oldest approach to estimating pillar strength is to use empirical formulas derived from laboratory compressive strength tests, large-scale in situ tests, or actual mining case histories. Empirical formulas have the advantage of being closely linked to reality and easy to use. Their greatest disadvantages are they cannot be easily extended beyond their original data base, and they provide little direct insight into coal pillar mechanics.

The analytic and numerical approaches begin with the concept that coal pillars are complex structures with non-uniform internal stress distributions. Their primary advantage is that they can test assumptions about pillar behavior as affected by a variety of geometric and geologic variables. Unfortunately, they require assumptions about material properties, failure criteria, and post-failure mechanics. As many of these issues are in dispute, it is difficult to use analytical methods in design.
Another issue is estimating the loading applied to pillars. The tributary area theory is adequate for development loads (unless the panel is narrow and the extraction ratio greatly exceeds than 50%). The caving that occurs during retreat mining applies abutment loads to the pillars that must also be considered in design. Again, both empirical and numerical methods are available.

**Rectangular Pillar Strength Formula**

A major drawback of most empirical pillar strength formulas is that they only apply to square pillars. They underestimate the strength of rectangular pillars that contain proportionately much more core area. The concept of the "stress gradient" provides the link which allows empirical formulas to be extended to rectangular pillars. The stress gradient defines the vertical stress within the pillar at maximum load as a function of the distance from the nearest rib.

Although empirical formulas do not explicitly consider the effect of internal pillar mechanics, it is apparent that they imply a non-uniform stress distribution because of the w/h effect. A derivation of the implied stress gradients was published by Mark and Iannacchione (1992). For example, the Bieniawski formula:

\[ S_p = S_i (0.64 + 0.36 \frac{w}{h}) \]

implies a stress gradient of: \[ S_v = S_i (0.64 + 2.16 \frac{x}{h}) \]

where: \( S_p \) = Pillar strength  
\( S_i \) = In situ coal strength  
\( S_v \) = Vertical pillar stress  
\( x \) = Distance from pillar rib

When this stress gradient is integrated over the load bearing area of a rectangular pillar, the Mark-Bieniawski pillar strength formula is obtained:

\[ S_p = S_i (0.64 + 0.54 \frac{w}{h} - 0.18 (\frac{w^2}{Lh})) \]

Where \( L \) = pillar length.

The approach is illustrated in figure 1, and described in more detail by Mark and Chase (1997).

**Design of Longwall Gate Entry Systems**

In the fifteen years after 1972 the number of U.S. longwall faces grew from 32 to 118 (Barczak, 1992). The new technology created a host of operational and safety problems, including the maintenance of stable travelways on the tailgate side. Researchers initially viewed gate entry ground control primarily as a pillar design issue. The clear correlation
between larger pillars and improved conditions that had been established by trial-and-error at many mines supported this approach.

Comparing longwall pillars to traditional coal pillars, the most obvious difference is the loading. Longwall pillars are subjected to complex and severe abutment loads arising from the retreat mining process. The loads are also changing throughout the pillar's service lives. The major contribution of the original ALPS method was a formula for estimating the longwall pillar load, based on numerous underground measurements (Mark, 1990).

It became clear, however, that tailgate stability required more than good pillar design. Other factors, such as roof quality and artificial support, must be important. Attacking this extremely complex problem with analytical or numerical models would have been extremely difficult. On the other hand, the problem was ideal for an empirical approach that could make full use of the wealth of full-scale case history data that was available.

Data were collected from approximately 55% of all U.S. longwall mines, selected to represent a geographic and geologic cross-section of the U.S. longwall experience. A total of 64 case histories were classified as "satisfactory" or "unsatisfactory." Unsatisfactory conditions almost always caused the mine to adjust their gate entry design in later panels. Satisfactory meant that no significant ground control delays were encountered on at least three successive panels.

Each case history was described by several descriptive variables, including the ALPS stability factor (SF), entry width, and primary support rating. The Coal Mine Roof Rating (CMRR) was developed to provide a quantitative measure of the variety and complexity of roof geology encountered at different longwall mines (Molina and Mark, 1994). The CMRR weighs the importance of the geotechnical factors that determine roof competence and combines them into a single rating on a scale from 0 to 100. The field data necessary for calculating the CMRR can be obtained from underground exposures of the roof strata or from logging and point-load testing exploratory drill core (Mark and Molinda, 1996). Figure 2 shows the geographic distribution of the CMRR in U.S. longwalls.

Multi-variate statistical analysis showed that when the roof is strong, smaller pillars can be used (Mark et al., 1994). For example, when the CMRR is 75, the an ALPS SF of

![Figure 2: Distribution of the Coal Mine Roof Rating (CMRR) observed in U.S. longwalls.](image-url)
0.7 is adequate. When the CMRR drops to 35, the ALPS SF must be increased to 1.3. Significant correlations were also found between the CMRR and both entry width and the density of primary support.

The ALPS data base was recently revisited, with several new variables added. These include:

- Rectangular pillar strength formula: All the SF were recalculated with the Mark-Bieniawski formula substituted for the original Bieniawski formula. The new result is designated as the ALPS (R) SF.

- Uniaxial compressive strength (UCS): Nearly 4,000 laboratory tests were compiled from the literature into the Database of Uniaxial Coal Strength, or DUCS (Mark and Barton, 1996). From these data, typical seam strength values were obtained for 60 U.S. coalbeds.

- Width-to-height ratio (w/h): The w/h of the largest pillar in the gate entry system was included as an independent variable, to check if the pillar strength formula could be improved.

- Depth of Cover (H): H was included as an independent variable primarily to check the loading formulation.

The entry width and the primary support were included as before.

![Figure 3. - ALPS(R) SF and CMRR for longwall tailgate performance case histories.](image-url)
The statistical analysis showed that the ALPS (R) SF and the CMRR could correctly predict 85% of the outcome, including 94% of the failures (figure 3). All three of the new variables (DUCS, w/h, and H) were found to be statistically insignificant. Figure 3 shows the distribution of the case histories, and the revised design equation:

\[ \text{ALPS (R) SF} = 2.0 - 0.016 \times \text{CMRR} \]

Since 1987, ALPS has become the most widely-used pillar design method in the U.S. The ALPS-CMRR method directly addresses gate entry performance, and makes U.S. longwall experience available to mine planners in a practical form. Tailgate blockages are far less common today than they were 10 years ago, and ALPS can surely claim some of the credit.

**Pillar Design For Retreat Mining**

The classical empirical pillar strength formulas were all developed for room and pillar mining. However, none considered the abutment loads that occur during pillar recovery operations.

The Analysis of Retreat Mining Pillar Stability (ARMPS) adapted the abutment load formulations from ALPS to three dimensions for the more complex and varied mining geometries used in pillar recovery (Mark and Chase, 1997). The Mark-Bieniawski pillar strength formula is used to estimate pillar strength. Features such as varied entry spacings, angled crosscuts, barrier pillars, and slab cuts in the barrier can all be modeled (figure 4).

![Diagram of pillar design parameters](image)

**Figure 4. - Section layout parameters used in ARMPS.**

To evaluate the validity of ARMPS, more than 200 retreat mining case histories have been obtained from field visits throughout the U.S. Covariates considered in the statistical analysis included the w/h, CMRR, UCS, and H. When the entire data set was evaluated, it was found that 77% of the outcomes could be correctly predicted simply by setting the
ARMPS SF to 1.46. Including either the depth or the w/h increased the r² slightly, without improving the accuracy (figure 5). The depth and the w/h ratio were strongly correlated with each other within the data set.

![Figure 5. - ARMPS SF and depth of over for 200 retreat mining case histories.](image)

When the data set was limited to cases where the w/h was less than 8 and H was less than 200 m, the accuracy improved to 83%. For cases where H exceeded 200 m, only 58% of the cases were correctly predicted at ARMPS SF=0.93. No other covariates would be included at the 90% confidence level. The conclusion seems to be that ARMPS works quite well at shallow depth and moderate w/h ratios. It is of much less value for squat pillars at greater depth.

![Figure 6. - ARMPS SF compared with coal specimen strength.](image)

None of the analyses indicated that UCS was of any value in predicting the strength of coal pillars, thus confirming the results of an earlier study (Mark and Barton, 1996). That study found that the best results are achieved with ARMPS when the in situ coal strength is assumed to be 6.2 Mpa (figure 6). It concluded that while the in situ strength of U.S. coal seams is probably not uniform, laboratory tests do not measure the geologic features (like bedding planes and rock partings) which are most likely responsible for variations in seam strength.
Massive Pillar Collapses

Most of the pillar failures included in the ARMPS data base are "squeezes" in which the section converged over hours, days or even weeks. Another important subset are 13 massive pillar collapses (Mark et al., 1997b). These occurred when undersized pillars failed and rapidly shed their load to adjacent pillars, which in turn failed. The consequences of such chain reaction-like failures typically include a powerful, destructive, and hazardous airblast.

Data collected at 12 massive collapse sites revealed that the ARMPS SF was less than 1.5 in every case, and was less than 1.2 in 81% of the cases (figure 7). What really distinguished the sudden collapses from the slow squeezes, however, was the pillar's w/h ratio. Every massive pillar collapse involved slender pillars whose w/h was less than 3. Laboratory tests have shown that pillars of w/h<3 typically have little residual strength, which means that they shed almost their entire load when they fail (figure 8). As the specimens become more squat, their residual strength increases, reducing the potential for a rapid domino failure. The mechanism of massive collapses has been replicated in a numerical model (Zipf, 1996).

Two alternative strategies were proposed to prevent massive pillar collapses:

- **Prevention**: With the prevention approach, the panel pillars are designed so that collapse is highly unlikely. This can be accomplished by increasing either the SF of the pillars, or their w/h ratio.

- **Containment**: In this approach, high-extraction is practiced within individual compartments that are separated by barriers. The small pillars may collapse within a compartment, but because the compartment size is limited, the consequences are not great. The barriers may be true barrier pillars, or they may...
be rows of development pillars that are not split on retreat. The containment approach has been likened to the use of compartments on a submarine.

Design charts have been developed for each approach, considering the width of the panel, the seam thickness, and the depth of cover (Mark et al., 1997b).

Use of Finite Element Modeling (FEM) in Pillar Design

In recent years, FEM has been used to predict in situ coal pillar strength, especially under non-ideal conditions where interface friction and roof and floor deformation are the primary controlling factors. A practical coal pillar design consideration was presented by Su and Hasenfus (1996) which incorporated the results of finite element modeling and field measurements. Nonlinear pillar strength curves were first presented to relate pillar strength to width-to-height ratio under simulated strong mine roof and floor conditions (Figure 9). Confinement generated by the frictional effect at coal/rock interfaces is demonstrated to accelerate pillar strength increase at a width-to-height ratio of about 3. Frictional constraint limitations and coal plasticity decelerate pillar strength increase at w/h of about 6. The simulated pillar strength curve under strong roof and floor compares favorably with measured peak strengths of five failed pillars in two southwestern Virginia coal mines (Figure 10), and is in general agreement with many existing coal pillar design formulas at w/h<5.

![Figure 9. - Comparison between FEM model pillar strength and existing formulas.](image)

FEM has also been used to evaluate the effect of in-seam and near seam conditions, such as rock partings, seam strength, and weak floor rock on pillar strength (Su and Hasenfus, 1997). Rock partings within the coal seam was found to have a variable effect on pillar strengths, depending on the parting strength. A competent shale parting within the coal seam reduces the effective pillar height, thus, increasing the ultimate pillar strength (Figure 11). Conversely, a weak claystone parting slightly decreases pillar strength. Seam strength was found to have a negligible effect on the peak strength for pillars at high width-to-height ratios (Figure 12). For practical coal pillar design, determination of intact coal strength thus becomes unnecessary and for wide pillars, and an average seam strength
of 6.2 to 6.6 Mpa may suffice for most U.S. bituminous coal seams. In addition, weak floor rocks may decrease the ultimate pillar strength by as much as 50% compared to strong floor rock conditions (Figure 13). Field observations confirm pillar strength reduction in the presence of weak floor rocks.

An earlier numerical study, employing the FDM technique, concluded that pillar strength was highly dependent upon the frictional characteristics of the coal/roof and coal/floor interfaces (Iannacchione, 1990).

![Graph showing comparison between peak strength of model pillars and field measurements.](image)

**Figure 10.** - Comparison between peak strength of model pillars and field measurements.

![Graph showing effect of clay and shale partings on model pillar strength.](image)

**Figure 11.** - Effect of clay and shale partings on model pillar strength.
The Boundary-element Method for Coal Pillar Design

The displacement-discontinuity (DD) variety of BEM is often the method of choice for analyzing the loadings imposed upon pillars in complex mining geometries in tabular deposits. The practical strength of the DD method is in calculating the gross stress and displacement changes associated with single or multiple-seam mining areas several hundred, to thousands, of feet on a side, as opposed to calculating the exact failure or residual behavior of roof, rib or floor.
Traditionally, DD programs have assumed a homogeneous isotropic elastic overburden (Zipf, 1992). Recently, a laminated overburden model was implemented into a full-featured DD program (Heasley and Salamon, 1996a, 1996b). This program, LAMODEL, simulates the overburden as a stack of homogeneous isotropic layers with frictionless interfaces and with each layer having the identical elastic modulus, Poisson’s ratio, and thickness. This “homogeneous stratification” formulation does not require specific material properties for each individual layer, and yet it still provides a realistic suppleness to the overburden that is not possible with the homogeneous overburden (Salamon, 1989; Heasley and Salamon, 1986b).

For practical pillar design using a DD model, the input coal strength is generally derived from empirical pillar strength formulas which are solidly based on observed pillar behavior, as opposed to laboratory tests (Mark and Barton, 1996). The recent derivation (Mark and Iannacchione, 1992) of the specific stress gradient implied by the various empirical formulas allows the strength of a DD model coal element to be direct determined based on its distance from the edge of the pillar (see Heasley, 1998). Similarly, the gob and overburden properties in the DD model are calibrated so that the resultant gob and abutment stresses closely match field measurements/observations such as the abutment load formulas in ALPS or ARMPS.

Then, once realistic pillar strengths and load distributions have been established, the mechanics-based overburden behavior in the DD model can be effectively used to accurately analyze the complicated stresses and displacements associated with complex mining scenarios. This technique of combining empirical pillar strength and abutment load formulas with the analytical mechanics of a DD model capitalizes on the strengths of both the empirical and analytical approaches to pillar design. The empirical formulas base the model on realistic behavior while the analytical mechanics allow the model to accurately determine the effect of numerous geometric and geologic variables. Using this technique, a DD model can be the most practical approach for stress analysis and pillar design in complex mining situations such as: multiple seams, random pillar layouts and/or variable topography (as demonstrated in figure 14).

Figure 14.- LAMODEL stress analysis of a multiple-seam coal mine.
Conclusions

Despite their differences in approach, the empirical and numerical methods seem to have converged on a fundamentally similar conceptual model of coal pillar mechanics. The important features of this model include:

- The stress distribution within a coal pillar is highly non-uniform, and dependent upon the confinement that is generated within the pillar;

- The degree of confinement is largely determined by the lithologic contacts at the roof and floor, bedding planes or partings within the pillar, and the floor characteristics;

- The strength becomes more difficult to predict as the pillar becomes more squat;

- Laboratory testing of small coal samples, particularly uniaxial compressive strength tests, are not useful for predicting pillar strength;

- The post-failure stiffness and residual strength are very important for predicting the behavior of pillar systems, and;

- Many ground control problems must be considered from the standpoint of entry stability, where pillar behavior is just one component.

From a practical standpoint, it seems useful to identify three broad categories of pillar behavior:

- **Slender pillars** (w/h<3), which have little residual strength and are prone to massive collapse when used over a large area;

- **Intermediate pillars** (3<w/h<8), where "squeezes" are the dominant failure mode in room-and-pillar mining, and where empirical pillar strength formulas seem to be reasonably accurate, and;

- **Squat pillars** (w/h>8), which can carry very large loads and exhibit strain-hardening upon yield, and which are dominated by entry failure (roof, rib, and floor) and by coal bumps.

Certainly, more work remains before the age-old questions of pillar design are finally solved. In particular, there is much more to learn about the mechanics of squat pillars and roof-pillar-floor interactions. Currently, there is no accepted way to determine the frictional characteristics of the contacts, bedding planes, and partings that are so crucial to pillar strength. It is similarly difficult to characterize the bearing capacity of the floor. Simple, meaningful field techniques for estimating these properties will be necessary for further progress with either numerical or empirical techniques. Indeed, the cross-pollination between the numerical and empirical methods that has characterized the recent past can be expected to bear further fruit in the future.
References


Mine Safety and Health Administration (1993), Fatality at Kentucky Coal Mine.

Mine Safety and Health Administration (1996), Fatality at Harlan-Cumberland Mine.


Salamon, M. D. G. 1963. Elastic Analysis of Displacements and Stresses Induced by the Mining of Seam or Reef Deposits, Parts I. Journal of the South African Institute of Mining and Metallurgy. v. 64, no. 4, pp. 128-149.


