THE EVOLUTION OF INTELLIGENT COAL PILLAR DESIGN: 1981-2006

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ABSTRACT

The first International Conference on Ground Control in Mining opened with the topic of pillar design. Two classic papers were presented, one by Bieniwski and the other by Wilson. Unfortunately, the two methods were so radically different from each other that it was nearly impossible to reconcile them. Adding to the confusion were the many other pillar strength formulas (such as the Salamon-Munro, the Holland-Gaddy, and the Obert-Duvall, just to name a few) that were also available. Little wonder that discussions of pillar design in those days often ended with anguished cries of “but which formula is the right one?”

The past 25 years have seen substantial progress in the science of coal pillar design. Indeed, one testament to the improvement is the relative scarcity of papers on the topic at recent Conferences. Two factors have been largely responsible for the progress that has been made. The first has been the collection of large data bases of actual case histories of pillar performance in a variety of settings, from shallow room-and-pillar mines through deep cover longwalls. These have made possible the development of empirical design procedures that are closely linked to real world experience. The second important factor is the development of sophisticated computer models that can accurately simulate pillar behavior and roof/pillar/floor interactions. Together, these two lines of research have led to a new understanding of pillar mechanics that identifies three modes of pillar failure:

- ***Sudden, massive collapse***, accompanied by airblast, for slender pillars (width/height<4)
- ***Squeezing***, or slow, non-violent failure, for most room and pillar applications (4<w/h<10)
- ***Entry failure or bumps*** for deep cover and longwall applications (w/h>10)

It is particularly satisfying that the insights gained from numerical models broadly support those obtained from the empirical studies.

While far less controversial than in the past, pillar design problems continue to arise. One recent example is pillar design for highwall mining. NIOSH has just released a software package, called ARMPS-HWM, which employs a number of modern pillar design concepts. Since highwall mining web pillars are long and slender, the greatest danger is that of a sudden collapse. ARMPS-HWM suggests two possible prevention strategies, one which concentrates on the SF of the webs, and the other which creates a “pressure arch” using properly sized barrier pillars.

The paper will close with a discussion of some current needs in coal pillar design, including:

- Updating older empirical methods, such as ALPS, where changes in technology (new types of roof support, more demanding ventilation requirements, faster retreat rates) may have made some of the original case histories obsolete.
- Methods for determining site-specific coal strengths, focusing on bedding plane strength and other factors that may effect confinement, as input for both empirical and numerical design.
- Improved methods for evaluating coal pillar performance for environmental issues, such as surface subsidence and hydrologic impacts, which consider such factors as depth, w/h ratio, water immersion/drainage, and time dependent seam strength.

ACKNOWLEDGEMENT (AND APOLOGY)

The topic of pillar design is one of the most important in the field of coal mine ground control, and the substantial progress that has been made has been due to the collective effort of many researchers and practitioners. In a brief overview like this one, it was only possible to mention a few of those who have made important contributions. As an apology to the many whose valuable work I was unable to include, I can only say that you are in very good company.

INTRODUCTION

Babcock et al. (1981), writing in their survey paper for the First Conference on Ground Control in Mining, traced the science of pillar design all the way back to Coulomb in 1773. During the ensuing century, a variety of researchers tested rock specimens of a variety of sizes and shapes. However, it was not until 1911 that Bunting (1991) proposed the first true pillar design method for coal mines. Bunting described the necessity for pillar design this way: "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."

In developing his formula, Bunting and his collaborators tested the strength of coal specimens in the laboratory and conducted back-analysis of full-scale pillar failures ("squeezes") underground. Using essentially the same approach, a number of pillar design formulas were developed during the next 70 years around the world. These "classic" methods consisted of three steps:

1. Estimating the *pillar load* using tributary area theory;
2. Estimating the *pillar strength* using a pillar strength formula, and;
3. Calculating the pillar *"safety factor"* (SF).

Step 1, estimating the load, was fairly straight forward for an industry that relied almost exclusively on room-and-pillar mining at relatively shallow depth. The tributary area estimate was considered sufficient, though it was recognized that in narrow panels the pillars near the edges might not experience the full load.

More complex were the issues associated with pillar strength. The two big issues were the "size effect" and the "shape effect." The size effect was most prominent in the laboratory, where coal strength testing showed that larger specimens were much weaker than small ones. The shape effect referred to the observation that slender (low width-to-height ratio) pillars were weaker than ones that were more squat.

As the number of classic formulas proliferated, so did the arguments. Should the shape effect be represented as a straight line, or as an exponential equation? Was there such a thing as a "critical" specimen size? Could a "universal" formula even exist, or did each one have its own place? These issues were discussed at length in a number of survey papers that were a persistent theme in those days (Babcock et al., 1981; Logie and Matheson, 1983; Hustrulid, 1976).

In some respects, Bieniawski represented the culmination of the classic approach to pillar design. In his paper at the First Conference in Morgantown, Bieniawski clearly described the issues involved in pillar design, and the advantages and shortcomings of the available methods. He then outlined a logical, step-by-step approach to sizing coal pillars. Indeed, Bieniawski's work has provided a firm foundation upon which many of the developments of the past 25 years have been built.

However, the First Conference also contained a paper that described a radically new and different approach to pillar design. Arthur Wilson (1972, 1981) of the British National Coal Board had first proposed his "hypothesis concerning pillar stability" in 1972, but by 1981 he had expanded and refined it considerably. His frame of reference was deep longwall mining, where very large pillars were routinely employed. Here, the goal of pillar design was not to prevent a pillar collapse, but rather to ensure the serviceability of the gate entries.

Wilson's first problem was the need to go beyond tributary area and consider the abutment loads brought about by full-extraction mining. His concept of the "load balance," whereby the reduction of load in the gob equals the excess load carried by the chain pillars, allowed the first serious quantification of abutment loads.

More fundamental were Wilson's innovations in defining pillar strength. In contrast to the empirical formulas, where "strength" was simply the failure load divided by the pillar area, Wilson treated the pillar as a complex structure, with non-uniform stresses throughout. His key insight was that the "shape effect" is caused by the build-up of confining stress within the pillar, which creates a high-strength "core" in the pillar center. While Wilson's mathematics contained some serious flaws (Mark, 1987; Salamon, 1992), his basic concepts are unchallenged today and underlie virtually all numerical models (Gale, 1996).

For many First Conference participants, however, it was pretty difficult to see how Bieniawski's approach could ever be reconciled with Wilson's. While they both purported to address pillar design, the input parameters, mathematical formulas, and (most importantly) the predicted pillar sizes seemed to be radically different.

In 1992, the situation seemed, if anything, to have become more confused. In that year the U.S. Bureau of Mines sponsored the first Workshop on Coal Pillar Mechanics and Design (Iannacchione et al., 1992), which featured 22 different papers from leading practitioners from around the world. Nearly every paper described a different approach, and these were approximately evenly split between empirical, analytical, and numerical methods. Their predictions for pillar strength varied widely, however, even in their trend. Some predicted that pillar strength would increase exponentially as the w/h ratio increased, others predicted it would tend towards a maximum limiting value, and still others predicted an intermediate, linear increase (figure 1). Stress measurements from 34 coal pillars were also analyzed, but were no help in narrowing the field (Mark and Iannacchione, 1992).

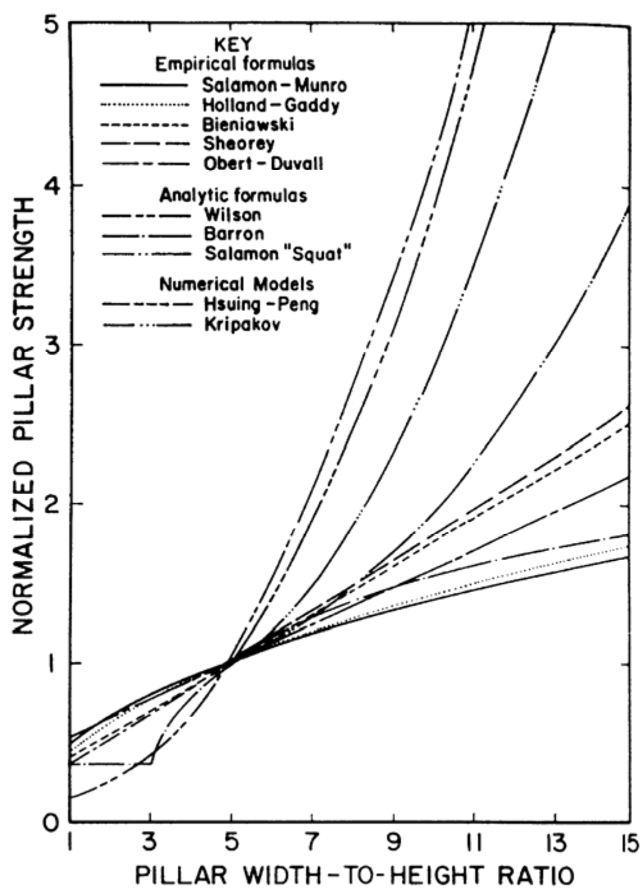

Figure 1. Comparison of pillar size predictions from selected pillar design formulas.

Moreover, the Workshop participants could not even seem to reach agreement on something as fundamental as what constituted pillar "failure." The classic approach contended that "pillars will fail when the applied load reaches the compressive strength of the pillars" and that "the load-bearing capacity of the pillar reduces to zero the moment the ultimate strength is exceeded" (Bieniawski, 1992). In this view, which was represented most strongly by the South African experience, the only true failures were those in which the panel width was very wide compared to the depth, and subsidence could actually be confirmed on the surface. Pillars with w/h ratios greater than about 10 were considered "indestructible" (Wagner, 1992).

At the other extreme were those whose experience was framed by longwall mining. These experts had seen plenty of examples where pillars with w/h ratios well in excess of 10 had proved too small and resulted in poor ground conditions. Obviously such squat pillars had not "failed" in the classic sense that their load-bearing capacity had disappeared. Yet they had failed to perform their ground control function. In many of these cases, conditions improved when the pillars were made larger. Clearly pillar design was still essential to maintaining gate road stability.

Observing the discussion, an outsider might have been forgiven for thinking that he had happened across a modern-day Tower of Babel. There were at least three groups, the empiricists, the modelers, and the theoreticians, each apparently speaking their own language. Even within each group there were bitter disputes.

Yet just seven years later, by the time of the second Workshop on Coal Pillar Mechanics and Design (Mark et al, 1999), a rough consensus had been reached on a unified theory of coal pillar mechanics. What had happened?

THE NEW PILLAR MECHANICS PARADIGM

The explanation can be summarized by another ancient parable, the one about the three blind scholars and the elephant. Each explored a different part of the elephant—one the trunk, another an ear, the third a leg. Based on his own observations, each one felt that he could describe the elephant, yet their descriptions were so different from one another that they could find no common ground. Only when they put all their observations together, however, could they get a true picture of the beast.

The answer in this case was that while all coal pillars are made of the same basic material, not just their strength but their ***behavior*** can vary dramatically depending on their shape. In fact, three broad categories of pillar behavior and failure mode can be identified, each defined by an approximate range of width-to-height ratios (Mark, 1999):

- **Slender pillars,** whose w/h ratios are less than about 3 or 4. When these pillars are loaded to their maximum capacity, they fail completely, shedding nearly their entire load. When large numbers of slender pillars are used over a large area, the failure of a single pillar can set off a chain reaction, resulting in a sudden, massive collapse accompanied by a powerful airblast.
- **Intermediate pillars** are those whose w/h ratios fall between about 4 and 8. These pillars do not shed their entire load when they fail, but neither can they accept any more load. Instead, they deform until flexure of the overburden transfers some weight away from them. The result is typically a non-violent pillar "squeeze," which may take place over hours, days, or even weeks. The large roof-to-floor closures that can accompany squeezes can cause hazardous ground conditions and entrap equipment.
- **Squat pillars** are those with w/h ratios that exceed 10. These pillars can carry very large loads, and may even be strain-hardening (meaning that they may never actually shed load, but just may become more deformable once they "fail."). None the less, the pillar *design* may fail because excessive stress is applied to the roof, rib, or floor, or because the coal bumps. Moreover, the strength of squat pillars can vary considerably depending upon the presence of soft partings, weak roof or floor interfaces, and other geologic factors.

Although derived from laboratory data, figure 2 illustrates how the post-failure behavior and the residual strength of coal pillars changes with their shape (Das, 1986).

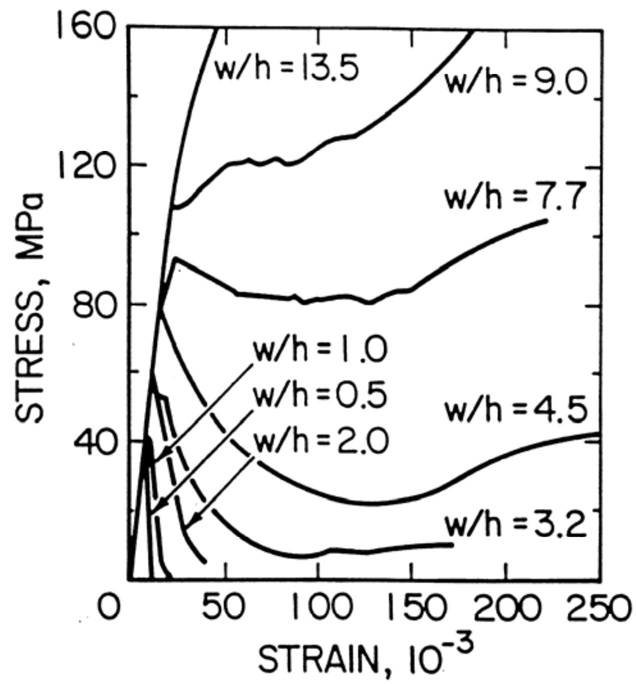

Figure 2. Effect of width-to-height ratio on the behavior of coal pillars.

What was the evidence for this new model of pillar mechanics? In essence, two largely separate lines of research had converged upon very similar conclusions. One source was a new generation of empirical studies, the other sophisticated numerical modeling.

EVIDENCE FROM MODERN EMPIRICAL METHODS

Prior to 1990, most classic pillar design methods had been derived from curve-fitting to coal strength data obtained from laboratory or in situ testing. The most notable exception was Salamon and Munro's formula, which was based entirely on statistical analysis of 98 unfailed and 27 collapsed pillar panels in South Africa. Salamon and Munro had developed their formula following the sudden, disastrous 1960 pillar collapse at the Coalbrook Colliery in which 437 lives were lost (Wagner, 1992).

Salamon's approach, that of using case histories involving full-scale pillars from actual mines, has a lot to recommend it. With such real-world data, it is not necessary to fully understand the mechanics, though a "reasonably clear understanding of the phenomenon in question" (Salamon, 1989) is needed to guide both the data collection and the statistical analysis. Moreover, the design equation that results from the analysis is generally simple, realistic, and thoroughly verifiable. In essence, it makes the past experience of a broad segment of the industry available to mine planners in a practical form.

The Analysis of Longwall Pillar Stability (ALPS) was the first modern pillar design method to employ a large case history data base like Salamon's (Mark, 1990; Mark, 1992). While the original ALPS research focused on defining longwall abutment loads using stress measurements, the real crux was identifying the proper SF to use for design. The case history data, obtained from a broad cross-section of mines across the U.S., showed that both successes and failures, defined in terms of tailgate serviceability, occurred over a wide range of pillar SFs. Clearly other factors—like the strength of the roof—were involved.

This observation fit well with studies conducted as early as the 1960's that had concluded that "whether or not the stress [from an extracted longwall panel] will influence a roadway depends more on the strength of the rocks which surround the roadway itself than on the width of the intervening pillar" (Carr and Wilson, 1982). Yet the variety and complexity of geologic environments had defied effective measurement, making it difficult to incorporate rock strength into design. The Coal Mine Roof Rating (CMRR) overcame this obstacle by providing a quantitative measure of the structural competence of coal mine roof (Molinda and Mark, 1994). When the CMRR was included in the analysis, ALPS could successfully predict the outcome in 85% of the case histories (figure 3). The analysis indicated that under very strong roof, the SF could be as low as 0.7, while under weak roof, an SF of 1.3 was required (Mark et al., 1994).

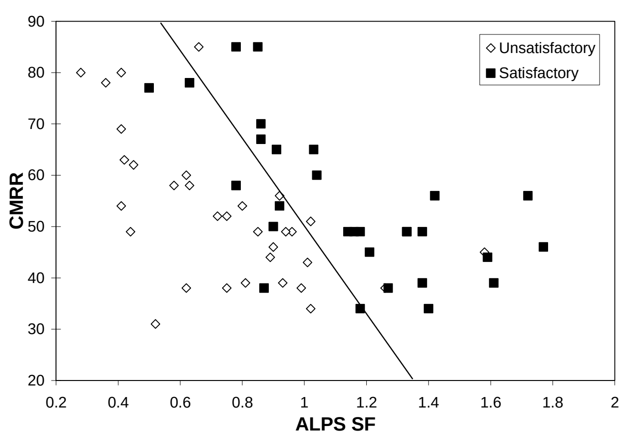

Figure 3. The ALPS case history data base and design formula, showing the effect of roof quality as measured by the CMRR.

Building on the success of the ALPS method, the research that culminated in the Analysis of Retreat Mining Pillar Stability (ARMPS) program employed an even larger case history data base. Here, most of the failures (unsatisfactory designs) involved pillar squeezes. For much of the data base, an SF of 1.5 seemed to separate the successful designs from the unsatisfactory ones (Mark and Chase, 1997). There were two interesting exceptions, however.

At one extreme, the ARMPS data base included case histories of 12 massive pillar collapses, each of which had occurred so suddenly that they generated powerful airblasts (Mark et al., 1997). Like the more common squeezes, the collapses all involved cases where the ARMPS SF was less than 1.5. 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 3 or less (figure 4). Subsequently, it was noted that all of Salamon's South African collapse cases also involved pillars with w/h less than 4. Apparently, these types of failures form a separate class, distinct from the squeezes that are more common in the U.S.

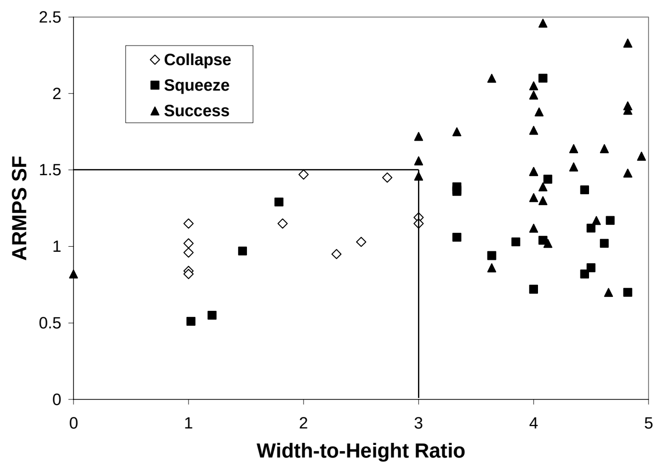

Figure 4. Pillar collapse case histories from the US: ARMPS SF and width-to-height ratio.

The other anomaly occurred with the cases where the depth of cover exceeded 750 ft. In this group, both successes and failures occurred with SF that were well under 1.5, and it was much more difficult to separate them. A later study (Chase et al., 2002) added nearly 100 more deep-cover cases to the data base. Most of the failures were still squeezes, but bumps became more common at greater depth and with stronger roof. The study concluded that the apparent pillar strength for these squat, deep cover pillars was more variable than it was for the typically more slender, shallower pillar cases (figure 5). Roof quality was found to be significant; as was the use of barrier pillars (which no doubt reduced the applied load).

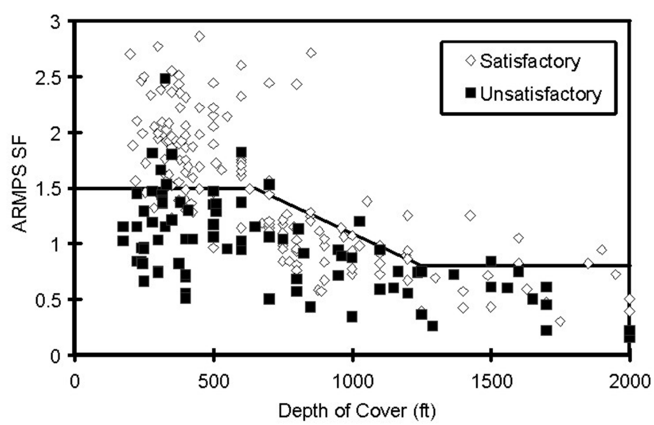

Figure 5. The ARMPS case history data base and design formula showing the effect of increasing depth of cover.

EVIDENCE FROM NUMERICAL MODELING

The ability of numerical models to contribute in a meaningful way to the understanding of coal pillar mechanics depended upon the development of computer codes that included (Gale, 2005):

- Post-failure simulation of the "strain softening" process.
- Simultaneous assessment of shear, tensile and bedding plane failure within the material, together with the effect of joints and structural weakness.
- Adequate simulation of the material properties and stress distribution within the ground.
- Ability to simulate failure of strata above and below the pillars, and to simulate the correct stress path within the pillar system.

Also, it was essential to validate the model results with extensive field monitoring programs.

Su and Hasenfus (1999) employed finite element models (FEM) to explore the effect of various geologic conditions on pillar strength. They found that a rock parting may increase the pillar strength, while a clay parting could reduce it. A weak floor could reduce the pillar strength by as much as 50%. All of these effects were minimal for slender pillars, but became much more pronounced once the w/h exceeded 5 (figure 6). The models also indicated that varying the uniaxial coal strength had almost no effect on pillar strength. Field measurements of pillar strength, though limited in extent, supported the modeling results.

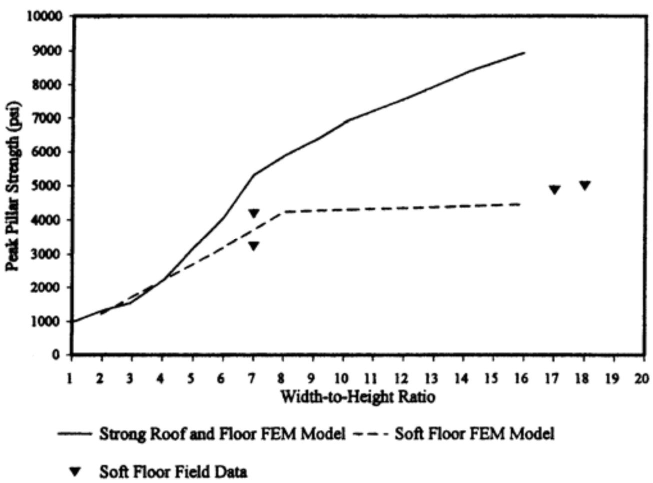

Figure 6. Results of numerical simulation of coal pillar mechanics (Su and Hasenfus, 1999).

Gale (1996, 1998) reported on stress measurements and FLAC models conducted during coal pillar design investigations in numerous mines. Gale concluded that a key advantage of numerical modeling is that it is possible to look beyond the pillar itself, and explore the interactions between the coal and the surrounding rock. He observed that pillar strengths seemed to fall into two groups:

- *Strong roof and floor rock* where confinement was easily generated within the pillar, and;
- *Weak rock or bedding planes*, which could fail either in compression or shear, and which limited the confinement that could be developed within the pillar, and thus limited the strength of the pillar system.

As a first pass, Gale suggested that the strength of the first group could be approximated by the Bieniwski formula using a coal strength of about 900 psi, while the second group would require a coal strength of about 600 psi (see figure 7). These pillar strength estimates are not very different from those obtained from ALPS if a range of SFs from 1.0 to 1.5 is employed.

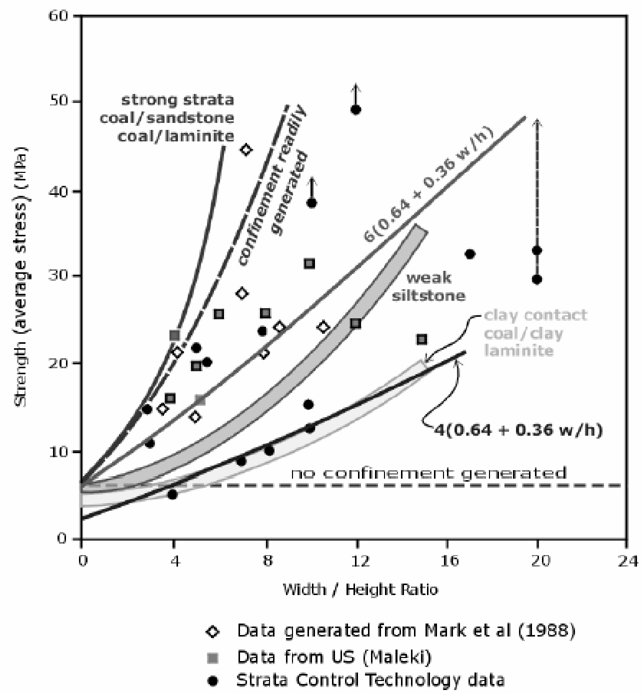

Figure 7. Results of numerical simulation of coal pillar mechanics (Gale, 1996).

Gale (2005) emphasized that the strength of a typical squat pillar system can be impacted by three main factors:

- The presence of weak materials or bedding planes within the pillar, at the roof and floor interfaces, or in the immediate roof or floor;
- A change in the stress field, particularly a reduction in the horizontal (confining) stress, such as that which can occur adjacent to a longwall gob, and;
- The ability of the pillar to minimize roadway deformation.

Gale (2005) also observed that "in small pillars (w/h <4 or 5) the ability to develop confinement in the pillars is less, and as such the post-failure load capacity of the system is low. The effect occurs irrespective of the strength of surrounding strata, and is also increasingly dependent upon actual coal properties."

One other development helped break down the walls between the empirical and the analytic and numerical methods. Mark and Iannacchione (1992) showed that each empirical formula actually implies a non-uniform stress distribution that can be calculated explicitly, so long as some reasonable assumptions are made. These implied stress distributions can be compared directly to a stress distribution obtained in a numerical model or a Wilson-type formula. The stress distribution implied by the Bieniawski formula was used to develop the Mark-Bieniawski formula for rectangular pillars (Mark and Chase, 1997). It has also been used to derive strength parameters for use in boundary element models (Heasley and Chekan, 1999; Karabin and Evanto, 1994). Thus the modeler can have confidence that the modeled pillar strengths are closely linked to real-world behavior, while the model's analytical mechanics allow it to accurately analyze complex mining situations including multiple seams, random pillar layouts and/or variable topography. The result is a powerful synthesis of empirical and numerical approaches to pillar design.

PILLAR DESIGN FOR HIGHWALL MINING

The new pillar mechanics paradigm is not in itself a method for pillar design. Rather, it provides a framework within which solutions to specific pillar design problems can be developed. One recent example is the new NIOSH program for highwall mining, called ARMPS-HWM.

Highwall mining now accounts for perhaps 4% of U.S. coal production, and that percentage seems to be growing rapidly (Zipf and Mark, 2005). During highwall mining, overburden support is provided by web and barrier pillars (figure 8). Unfortunately, there have been a number of major pillar failures, both in the U.S. and in Australia (Zipf, 1999; Shen and Duncan-Fama, 2001). These have resulted in large rockfalls from the highwall, and in many cases have trapped the continuous mining machines underground (figure 9).

Figure 8. Typical highwall mining web and barrier pillars.

Figure 9. Consequences of the collapse of highwall mining pillars.

Development of the ARMPS-HWM methodology involved a series of steps, each of which was informed by the lessons that have been learned about pillar design. The first step was to define the likely failure mode. Because highwall mining usually takes place under relatively light cover, the web pillars are typically slender (w/h<3). The pillar mechanics model suggests that the failure of such pillars could take the form of a sudden, massive collapse, and indeed most highwall mining pillar failures have been of this nature.

Based on the experience of underground room-and-pillar mining, two alternative strategies have been developed to prevent massive pillar collapses (Mark et al., 1997):

- **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 key to the success of the containment approach is to limit the compartment to a width that is too narrow to collapse, or is at least narrow enough that the consequences of a collapse are manageable. The containment approach has been likened to the use of compartments on a submarine.

The next step was therefore to select the appropriate panel width (distance between barriers) for the two design strategies. The potential for a collapse involving slender pillars depends upon the load-bearing capacity of the pillars and the local mine stiffness (LMS). The LMS in turn depends upon the width of the panel (Zipf, 1999). Based on case histories of pillar collapses underground (Mark et al., 1997), a maximum panel width of 200 ft was determined for the containment approach. In many cases, 200 ft between barriers translates into about 10 holes. ARMPS-HWM also suggests that the maximum number of holes between barriers be limited to 20 even when the prevention approach is being used, to minimize the consequences of any potential failure.

Next, it was necessary to define the load applied to, and the strength of, the web pillars. Tributary area provided a simple estimate of the load. The strength prediction would have been more complicated 25 years ago, because the webs are long strip pillars rather than the square pillars assumed by the traditional pillar strength formulas. Fortunately, the Mark-Bieniawski formula now provides a convenient way to estimate the strength of strip pillars (or indeed any rectangular or parallelogram shaped pillars).

A critical part of the analysis was to select the minimum suggested SF for the web pillars. ARMPS-HWM again called upon the experience with slender pillars in underground room-and-pillar mining, where an SF=2.0 has been suggested when using the prevention approach (Mark et al., 1997). However, since the potential consequences of a highwall mining collapse are not as severe as those that could be associated with an underground collapse, a minimum suggested SF of 1.6 was recommended.

For the containment approach, the barriers are assumed to be close enough together that they will shield the webs from the full overburden load. Rather than attempting to adjust the estimated load, however, the same effect was achieved by reducing the required SF. Therefore, a minimum suggested web SF of 1.3 was selected.

With either the containment or the prevention approaches, it was recommended that the web w/h ratio be maintained at 1.0 or higher, to help maintain web pillar integrity. In addition, there is very little data available on coal pillars with w/h ratios that are less than 1.0, so it is unclear whether the pillar strength formulas are still valid. Recent studies in underground stone mines have found that the strength of very slender pillars can be highly variable because they are subject to different failure processes than traditional pillars (Esterhuizen, 2006).

The barrier pillars are integral part of the highwall mining pillar system. The Mark-Bieniawski formula can again be used for the pillar strength, but the loading estimate was a little more complicated. ARMPS-HWM assumed a “worst case” where the webs on either side of the barrier might have failed. The residual strength of the failed webs would probably be very low, but would not be less than the gob that is modeled in ALPS and ARMPS. Therefore the same default abutment angle of 21 degrees is used to define the barrier pillar load in ARMPS-HWM (figure 10).

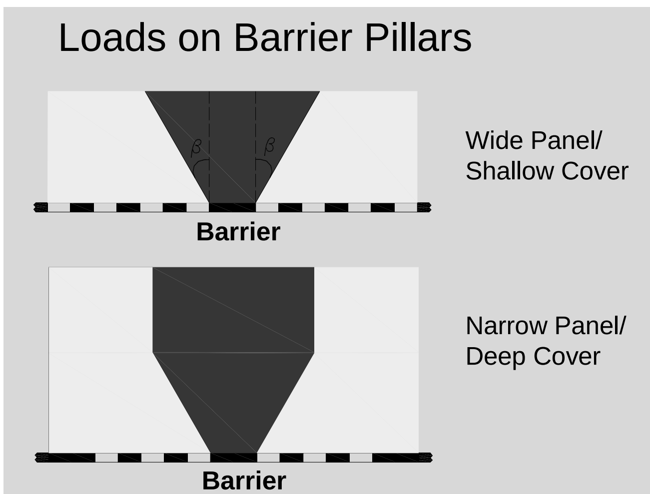

Figure 10. Barrier pillar loadings used in ARMPS-HWM.

The w/h ratio of the barrier was another concern. If the potential failure is to be limited to a single compartment, it is essential that the barrier pillar itself not collapse. The likelihood of collapse is minimized when the barrier is not a slender pillar itself. Therefore the suggested minimum SF for the barrier is 2.0 when the barrier’s w/h is less than 4.0, and 1.5 when the w/h is greater than 4.0.

Table 1 summarizes the design criteria used in ARMPS-HWM. In addition to the SFs for the webs and the barriers, ARMPS-HWM also calculates an overall SF for the pillar system consisting of one barrier and one panel of webs. The suggested minimum SF for the system is 2.0.

The final step was to verify ARMPS-HWM using real-world case history data. The analysis could not be based on collapse experience, because the available collapse data was considered insufficient. However, NIOSH was able to collect data from more than 3000 successful highwall mining holes mined in southern West Virginia during a recent three-year period (Zipf and Mark, 2005). Each case was analyzed to determine the maximum depth of cover, the web thickness, the number of holes between barrier pillars, and the barrier width. Some of the results are shown in figure 11. Based on these analyses, it appears that ARMPS-HWM does provide a reasonable first approximation of minimum suggested pillar widths.

Table 1. ARMPS-HWM design guidelines.

ARMPS-HWM SUGGESTED MINIMUM SF	
Web pillar SF	
1.6	When the panel width (excluding the barrier) exceeds approximately 200 ft (60 m)
1.3	When the panel width (excluding the barrier) is less than approximately 200 ft (60 m)
Barrier SF	
2.0	When the barrier’s width-to-height ratio < 4.0
1.5	When the barrier’s width-to-height ratio >= 4.0
Overall SF	
2.0	Applicable to all conditions

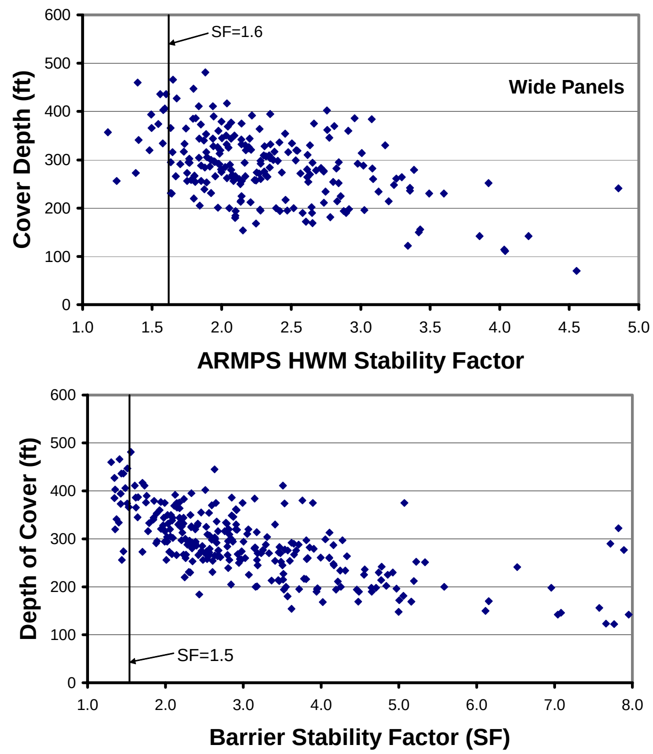

Figure 11. Comparison of ARMPS HWM design equations to the data base of successful HWM case histories in central Appalachia. (a) Web pillars. (b) Barrier pillars.

NEW FRONTIERS IN PILLAR DESIGN

Underground coal mining continues to evolve, and pillar design must keep up. Three areas of current interest are discussed below.

Updating Older Empirical Formulas

Empirical design methods draw their strength from being closely connected to actual mining experience. But what happens when that experience changes over time? The ALPS method, for example, is based on longwall mining case histories from the 1980’s and early 1990’s. A lot has changed since those early days that have affected gate road stability and design requirements, including:

- *Improved tailgate support:* Nearly every ALPS case history employed wood cribs for secondary support in the tailgate. Today, wood cribs have been almost entirely replaced by concrete, engineered wood, or cable supports. The greater strength and stiffness of these new roof supports may have reduced the amount of pillar support necessary for stability.
- *Ventilation requirements:* The simple U-ventilation system was used in most of the ALPS case histories. This meant that the only ventilation requirement was to keep the tailgate open outby the longwall face for return air. Currently, most U.S. longwalls bring some fresh air up the tailgate, and there are usually some expectations that the center entry will remain available for airflow. These new requirements may place an extra burden on the pillar system.
- *Increased extraction rates and panel dimensions:* Tailgate stability problems are much more likely to develop when the full tailgate abutment load sits in one place for a long period of time. Since longwalls now mine coal much more rapidly than they did 15 years ago, and they are subject to far fewer mechanical delays, it should be easier to "run away" from stability problems before they get out of control. On the other hand, wider faces mean that each pass takes longer to complete, and longer panels subject future tailgates to the side abutment load for longer periods of time.

For these reasons, it probably makes sense to revisit ALPS with an updated case history data base, one that reflects the longwall experience of the past 15 years. A new study would also benefit from the powerful analytical tools that have been developed during that time, including Support Technology Optimization Program (STOP) for evaluating tailgate support, Analysis of Roof Bolt Systems (ARBS) for rating primary support, and Analysis of Horizontal Stress in Mines (AHSM) for measuring the impact of horizontal stress on tailgate stability.

Seam Specific Coal Strengths

The issue of coal strength has bedeviled pillar design from the beginning. The "classic" approach was to test the uniaxial compressive strength (UCS) of small specimens in the laboratory, and then apply a "size effect" reduction factor to obtain an estimate of the in situ strength. This approach was thoroughly discredited by a comprehensive study, involving 4000 individual UCS test results from over 60 coal seams, which found that there was no correlation between the laboratory UCS and actual pillar strength (Mark and Barton, 1996). It seems that laboratory tests actually measure the degree of cleating in the specimen, but that cleat density has little relationship to pillar strength.

Mark and Barton's study also confirmed that the design formulas were far more successful in predicting performance when a uniform strength of 900 psi was employed. Studies conducted in South Africa and Australia have also found that a uniform coal strength worked reasonably well in pillar design formulas (Galvin et al., 1999).

While it is fortuitous that a uniform coal strength is sufficient for many pillar design problems, it is hardly satisfactory. Mark and Barton's study did not prove that all coal seams actually *are* the same strength, it only showed that laboratory testing was no help in identifying the differences that surely exist. Recent South African studies have indeed focused on determining seam-specific strengths through back calculation (Salamon et al., 2006), and they have concluded that there are significant variations between the coalfields.

In obtaining a solution, it will probably be necessary to divide the problem into two parts. For pillars whose w/h ratio is less than about 4 or 5, the in situ UCS may be an important contributing factor to overall pillar strength (Gale, 2005). But since laboratory UCS tests don't correlate with in situ strength, and in situ testing is too expensive, could rock mass classification help? Some tentative efforts in this direction were too early to be informed by more recent understanding of pillar mechanics (Kalamaras and Bieniawski, 1993; Trueman et al., 1992). A new attempt would have to focus on the presence of softer and harder layers of coal that can be found within a pillar, as well as partings consisting of rock, bone coal, and clay. For U.S. applications, it would also be necessary to consider the effect of the rock "cap" that is created when extra height is mined above thin seams.

The strength of squat pillars, in contrast, is determined almost exclusively by the confinement that can be generated within them. The confinement in turn is determined by the strength of the bedding planes within the pillar, roof and floor contacts, and even weak bedding planes in the immediate roof and floor. Developing simpler techniques for evaluating the strength of these contacts, and implementing them in pillar design, presents a significant challenge.

Protecting Infrastructure and the Environment

Pillar design is becoming increasingly important to protect surface structures, crop land, gas wells, surface streams, and groundwater supplies. "Guaranteeing" long-term stability is a tricky proposition, however.

One issue is the long-term strength of the pillars themselves. A South African study showed that the rate of pillar scaling (or sloughing) increased with the height of the pillars, but decreased over time (van der Merwe, 1998). It is not clear whether these results were applicable outside the Vaal Basin, however. In the U.S., one study found that as clay partings in the ribs weathered over time, their strength decreased substantially (Biswas et al., 1999). On the other hand, the rate of deterioration of the partings (towards the center of the pillar) decreased as the pillars aged, and the coal itself was hardly affected by weathering. Long term pillar failure has also been associated with floor failure (Chugh and Trent, 1996) and with inundation of sealed workings (Grgic et al., 2006).

The long-term strength of coal pillars is only one aspect of the problem, however. A more significant issue may be related to the potential *consequences* of pillar "failure." Many subsidence regulations were developed when most coal mining involved room and pillar extraction of "thick" seams (>6 ft) at shallow cover (Unrug et al., 2001). Under such conditions, a pillar squeeze or collapse would be expected to result in severe damage to the surface. Any "failure" of the squat pillars employed today surely causes much less deformation at the seam level, and the resulting ground strains are further mitigated by the greater depths of cover. It seems that there may be plenty of room to update subsidence rules of thumb by eliminating antiquated concepts based on extraction ratios and laboratory UCS testing, and replacing them with more scientific ones that employ w/h ratios, stability factors, and calculated surface strains.

One reason that long term pillar strength remains so poorly understood, at least in the U.S., is that there has never been a thorough, scientific, empirical study of pillar failures in abandoned mines. There should be plenty of raw material, in the form of case histories in the files of state subsidence regulatory agencies. The few studies that have been published have used only a small fraction of the case histories that should be available (Marino, 1989). Since subsidence does not pose a hazard to today's working miners, however, government safety research funds are not available for such a study.

CONCLUSIONS

Recent years have seen significant advances in the state-of-the-art in coal pillar design. From a practical standpoint, the development of reliable empirical methods like ALPS and ARMPS has been particularly valuable. They have been widely accepted throughout the mining community because they have been verified by extensive data bases of real-world case histories, and because they have been readily available in user-friendly computerized formats. The tremendous advances in numerical modeling have been another important success story.

The research has led to some other important conclusions, including:

- Laboratory testing of small coal samples, particularly uniaxial compressive strength tests, are not useful for predicting pillar strength;
- The strength becomes more difficult to predict as the pillar becomes more squat;
- The w/h ratio is important for predicting not just the pillar strength, but the mode of failure, and;
- Many ground control problems must be considered from the standpoint of entry stability, where pillar behavior is just one component.

Certainly, more work remains before the age-old questions of pillar design is 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.

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