Overview of Ground Control Research for Underground Coal Mines in The United States

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ABSTRACT: Underground coal mining continues to evolve in the U.S., and 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 and intense competitive pressures. The need for effective ground control design has never been greater. Ground control safety issues that have been addressed by recent the National Institute for Occupational Safety and Health (NIOSH) research include: Improving roof support performance; Maintaining safe tailgate escapeways from longwalls; Optimizing pillar design for retreat mining; Controlling multiple seam interactions; Predicting roof conditions during extended cuts, and; Preventing massive pillar collapses. As funding from both government and the private sector has diminished, the emphasis in research has focused on providing the mining community with practical techniques for improved ground control design. Many projects have successfully employed empirical methods that emphasize the statistical analysis of case histories from underground mines. Other projects have employed numerical models and large-scale laboratory testing of roof support elements. Using these data, NIOSH has developed an entire toolbox of computer programs that have been effectively transferred to the mining community.

1 INTRODUCTION

Roof falls have been the single greatest hazard that underground coal miners face in the U.S. Throughout the 20th century, roof falls accounted for approximately half of all deaths underground. While overall safety in U.S. coal mines has improved dramatically in the last 50 years, fatality rates continue to exceed other major industrial sectors (fig. 1). Fatalities due to ground falls still make up a significant portion of this rate.

Currently, underground coal production in the U.S. is 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. 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. Ground failures can hardly be afforded in this climate, yet they continue to occur. Some examples:

Roof falls: In 1998, more than 1,800 unplanned roof falls occurred where the roof had already been supported. While few of these resulted in injuries, each one represented direct threat to life and limb, and an indirect threat to ventilation, escape, and equipment. In each of these roof falls, the majority of which occurred in intersections, the roof bolt system failed to perform successfully.

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 the floor by the resulting air blast, and 103 ventilation stoppings were destroyed. At least 12 similar events have occurred in recent years,

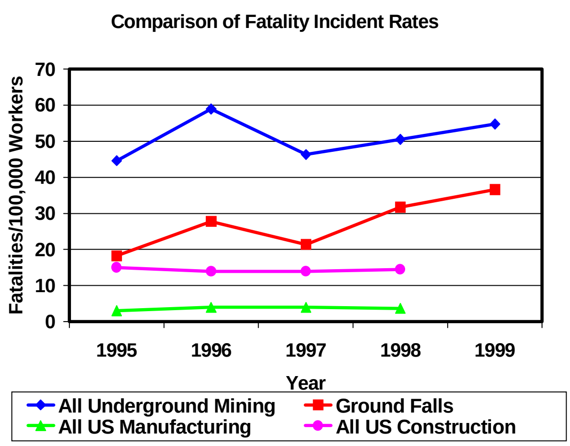

Figure 1. Fatality rates in mining and other U.S. industrial sectors.

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. 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 could not escape a deadly fire because of a tailgate roof fall. Similar blockages were common in the 1980's, and 50 cases have been documented (Mark, 1992).

Multiple Seam Interactions: Studies indicate that the majority of remaining room-and-pillar reserves, and 33% of longwalls, will be subject to multiple seam interactions. At one West Virginia mine where four seams had previously been extracted, a fatality occurred when the roof collapsed without warning beneath a barrier pillar.

The National Institute for Occupational Safety and Health (NIOSH) has the primary responsibility for conducting research to reduce mining hazards in the U.S. NIOSH continues the tradition of the U.S. Bureau of Mines, which was closed in 1995. Mining research is conducted at two Research Laboratories, one in Spokane and the other in Pittsburgh.

The past 20 years has seen a steady decline in the resources devoted to ground control research. The labor- and instrumentation-intensive field studies of past years are rarely feasible today. As a result, NIOSH scientists have had to develop new approaches to conducting ground control research.

2 THE COAL MINE ROOF RATING (CMRR)

One approach that has proven exceptionally successful for solving complex problems is the empirical, or statistical, approach. It relies on the scientific interpretation of actual mining experience represented as case histories. For example, hundreds of longwall and room-and-pillar panels are mined each year, and each one is a full-scale test of a pillar design. Once data has been collected on enough of these case histories, statistical techniques can be used to determine those combinations of factors most likely to result in pillar failure. A key advantage is that critical variables may be included even if they are difficult to measure directly, through the use of rating scales. A significant breakthrough was the development of a rock mass classification system specifically applicable to coal mine roof.

Coal Mine Roof Rating (CMRR) was proposed because neither traditional geologic reports nor laboratory strength tests on small rock samples adequately described the structural competence of mine roof. The CMRR combined 20 years of research on geologic hazards in mining with worldwide experience with rock mass classification systems (Molinda and Mark, 1994). Field data was collected from nearly 100 mines in every major U.S. coalfield (figure 2).

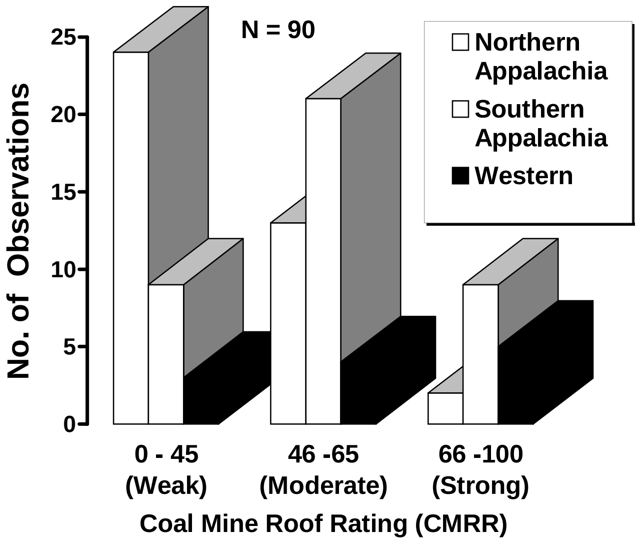

Figure 2. The Coal Mine Roof Rating observed in various U.S. coalfields

The CMRR weighs the geotechnical factors that determine roof competence, and combines them into a single rating on a scale from 0 to 100. The underlying philosophy of the CMRR is that it is not the strength of the intact rock that determines the stability of a mine roof, but rather the defects or discontinuities which weaken or destroy the roof beam.

The CMRR makes four significant contributions:

- Focuses on the characteristics of bedding planes, slickensides, and other discontinuities that weaken the fabric of coal measure rock;
- Applies to all U.S. coalfields, and allows meaningful comparison even where lithologies are quite different;
- Concentrates on the ability of the immediate roof to form a stable structure, focusing on the characteristics of the strongest bed within the bolted interval, and;
- Provides a methodology for geotechnical data collection.

Originally, the data for the CMRR was collected at underground exposures like roof falls and overcasts. To make it more generally useful, procedures were developed for determining the CMRR from drill core (Mark and Molinda, 1996). The drill core procedures employ the Point Load Test to estimate the uniaxial compressive rock strength and the rock strength parallel to bedding. A new conversion factor from point load index of strength ($I_{s(50)}$) to uniaxial compressive strength (UCS) has been determined from a large data base provided by a large U.S. coal company (Rusnak and Mark, 2000).

The CMRR has found many applications in ground control research and mining practice, as described in many of the examples below. It has also been successfully applied in Australia and South Africa (Colwell et al., 1999; Mark, 1998; Mark, 1999). A computer software package has recently been developed that makes the CMRR easier to use and to integrate into exploratory drilling programs.

3 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 (figure 3). 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.

In 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 Analysis of Longwall Pillar Stability (ALPS) was a formula for estimating the longwall pillar load, based on numerous underground measurements (Mark, 1990).

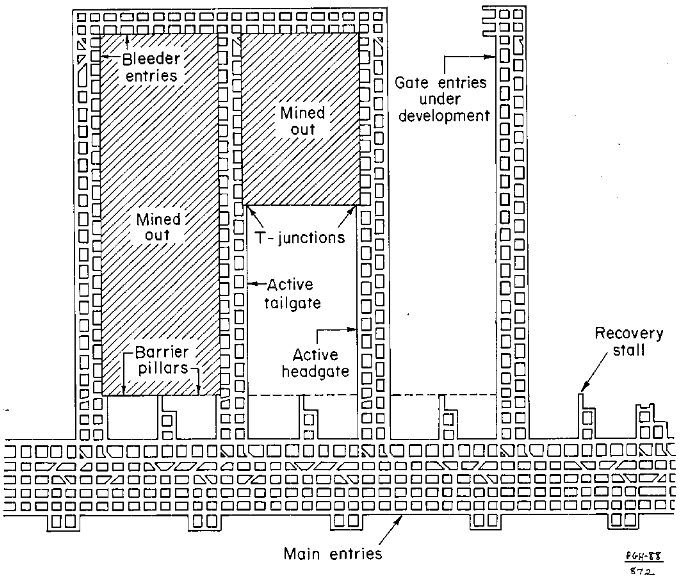

Figure 3. Plan view of a typical U.S. longwall mine.

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. 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 design in future panels. Satisfactory designs were used for at least three successive panels without significant ground control delays.

Each case history was described by several descriptive variables, including the ALPS stability factor (SF), the CMRR, entry width, and primary support rating. Multi-variate statistical analysis showed that when the roof is strong, smaller pillars can safely be used (Mark et al., 1994). For example, when the CMRR is 75, the an ALPS stability factor (SF) of 0.7 is adequate. When the CMRR drops to 35, the ALPS SF must be increased to 1.3 (figure 4). Significant correlations were also found between the CMRR and both entry width and the level of primary support.

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.

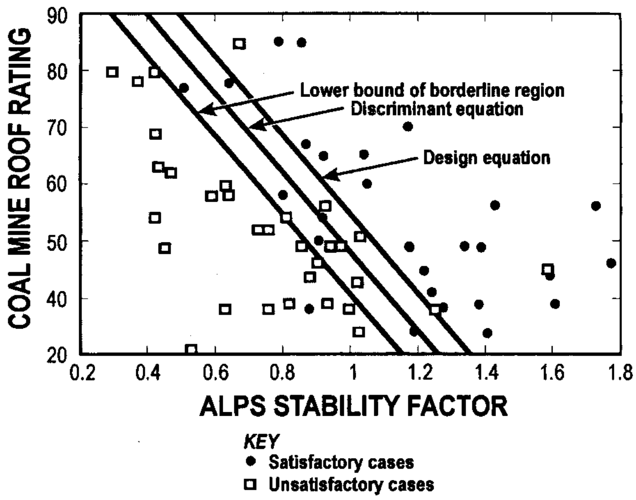

Figure 4. ALPS case history data base and design guidelines.

4 PILLAR DESIGN FOR RETREAT MINING

The classical empirical pillar strength formulas were all developed for room and pillar mining. However, none ever attempted to consider the abutment loads that occur during pillar recovery operations. The abutment load formulas used in ALPS provided a means to rectify that shortcoming.

The Analysis of Retreat Mining Pillar Stability (ARMPS) employs the same basic constructs as ALPS, adapted to more complex and varied mining geometries (Mark and Chase, 1997). The abutment load formulas have been adapted to three dimensions, to account for the presence of barrier pillars and previously-extracted panels. Features such as varied entry spacings, angled crosscuts, and slab cuts in the barrier can all be modeled (figure 5).

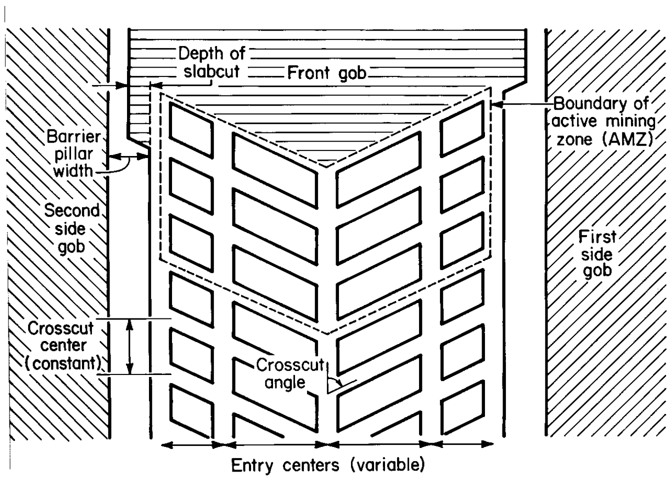

Figure 5. Model of a room-and-pillar mining section used by the ARMPS program

To evaluate the validity of ARMPS, more than 200 retreat mining case histories were obtained from field visits throughout the U.S. 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 (figure 6). When the data set was limited to cases where the depth of cover (H) was less than 200 m, the accuracy improved to 83%. The conclusion seems to be that ARMPS works quite well at shallow depth and moderate width-to-height (w/h) ratios (Mark, 1999). Research is currently underway to determine what other factors need to be included when designing squat pillars at great depth.

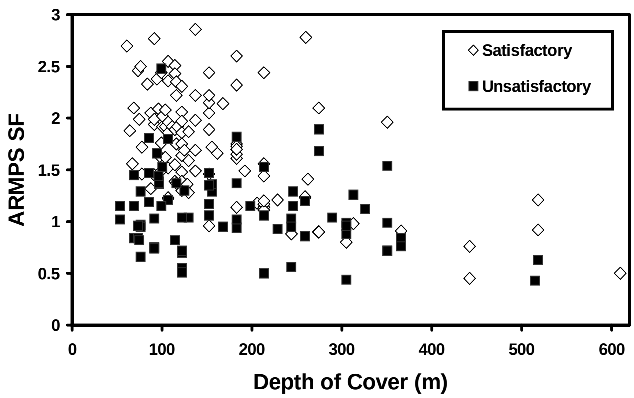

Figure 6. The ARMPS case history data base.

The study also answered some ancient questions regarding the value of laboratory tests to determine the UCS of coal specimens. The analyses clearly showed that UCS was of no value whatever in predicting the strength of coal pillars, thus confirming the results of an earlier study (Mark and Barton, 1996). It also found that the best results are achieved with ARMPS when the in situ coal strength is assumed to be 6.2 Mpa. The study 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.

5 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 15 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 that 1.5 in every case, and was less that 1.2 in 81% of the cases. What really distinguished the sudden collapses from the slow squeezes, however, was the pillar's w/h ratio (figure 7). Every massive pillar collapse involved **slender** pillars whose w/h was less than 3. Laboratory tests have shown that slender pillars typically have little residual strength, which means that they shed almost their entire load when they fail. 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).

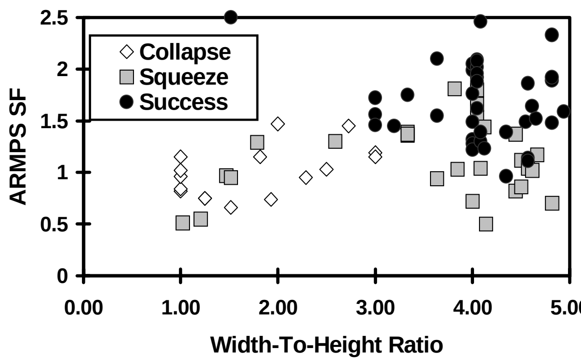

Figure 7. Pillar collapse case histories in the U.S

Two alternative strategies were proposed to prevent massive pillar collapses. Prevention requires increasing either the SF of the pillars, or their w/h ratio.

Containment is used if barrier pillars are used to separate compartments in which high extraction is practiced. The small pillars may collapse within a compartment, but because the compartment size is limited, the consequences are not great. 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).

6 LAMODEL: A NUMERICAL MODEL FOR MULTIPLE SEAM DESIGN

Multiple seam situations and other complex mining geometries do not lend themselves readily to simplistic empirical models like ALPS and ARMPS. Numerical methods are the alternative approach, but to be useful they must realistically portray the behavior of large volumes of rock. In addition, they must not require rock material properties that cannot be easily determined.

To address these concerns, NIOSH has developed the displacement-discontinuity model LAMODEL (Heasley and Salamon, 1996a). 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). 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. This technique of combining empirical pillar strength and abutment load formulas with the analytical mechanics of a displacement-discontinuity model capitalizes on the strengths of both the empirical and analytical approaches to pillar design. Using this technique, a displacement-discontinuity 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 (figure 8).

7 GUIDELINES FOR ROOF BOLT SELECTION

Despite more than half a century of experience with roof bolting, no design method has received wide acceptance. To begin to improve this situation, NIOSH evaluated the performance of roof bolt systems at 37 mines (Molinda et al., 2000). Success was measured in terms of the number of roof falls that occurred per 3,000 m of drivage with a particular roof bolt design when other geotechnical variables were held constant. A variety of statistical techniques were used to explore trends in the data.

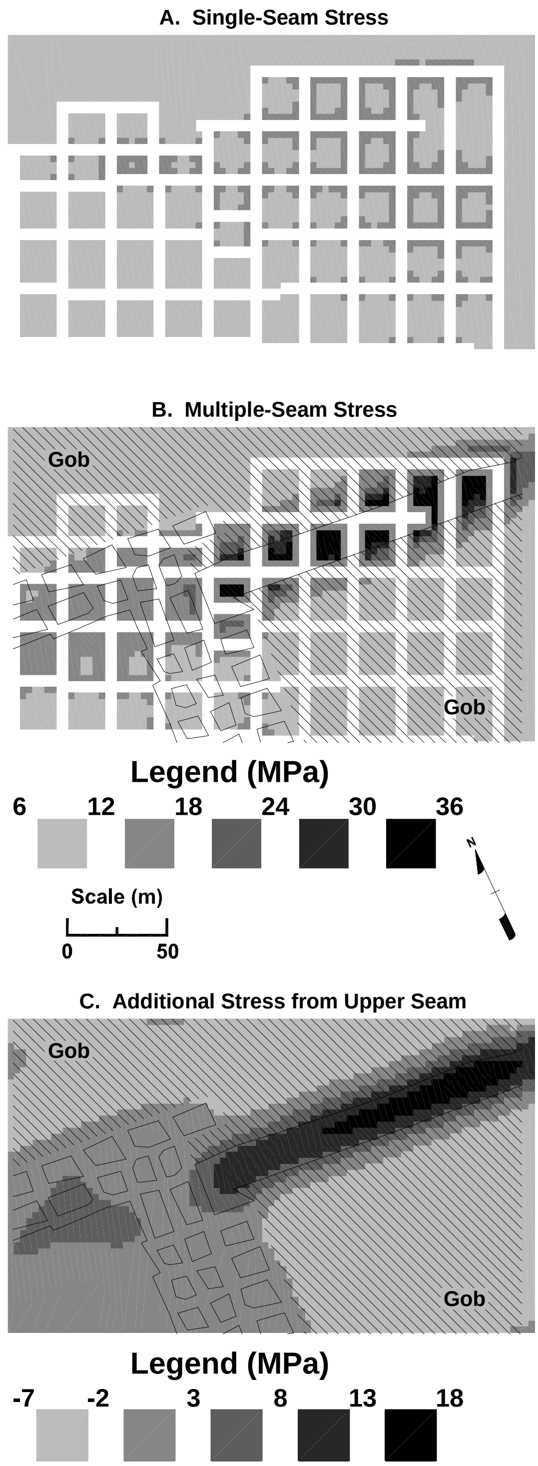

Figure 8. Stress analysis of multiple seam interaction using LAMODEL.

The study evaluated five different roof bolt variables, including length, tension, grout length, capacity, and pattern. Roof spans and the CMRR were also measured. Stress levels could not be measured directly, but the depth of cover was used as a surrogate.

As expected, the competence of the roof rock, represented by the CMRR, was the single best predictor of the roof fall rate. More surprising was the importance of depth. The higher horizontal stresses encountered in deeper mines apparently require greater levels of roof support (figure 9). Important findings were also made regarding bolt length and intersection span. Unfortunately, the data was too sparse and too scattered to allow conclusions to be made regarding tension and other roof bolt variables.

The study's findings were used to develop guidelines for designing roof bolt systems (Mark, 2000). Building upon an equation initially proposed by Unal (1984), a formula for selecting bolt length was proposed:

$$L_B = 0.12\,(I_s)\,\log_{10}(3.25H)\left\{\frac{100 - CMRR}{100}\right\}$$

Where: L_B = Bolt Length (m)
I_S = Intersection span (average of the sum-of-the-diagonals, m)
H = Depth of Cover (m)

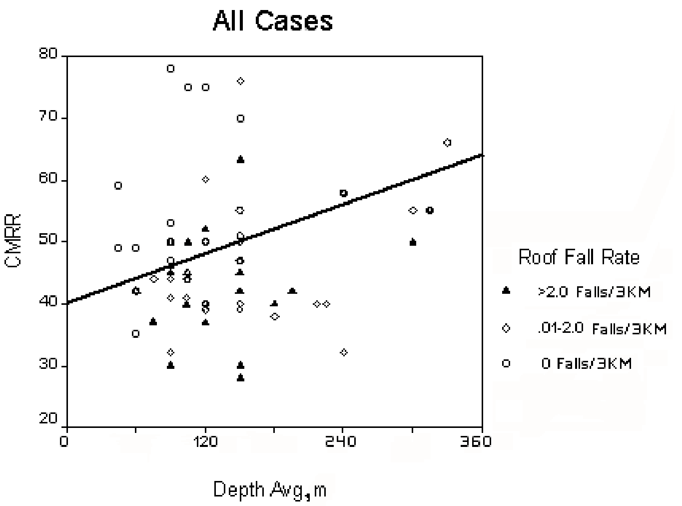

Figure 9. Roof bolt performance case histories.

Once the bolt length has been determined, the bolt pattern and capacity is determined using the following equation:

$$PRSUP = \frac{L_B\ N_B\ C}{14.5\ (S_B\ W_e)}$$

Where: N_B=Number of bolts per row
C=Capacity (kN)
S_B=Spacing between rows of bolts (m)
W_e=Entry width (m)

The suggested value of PRSUP depends on the CMRR and the depth of cover, as expressed in the following equations:

PRSUP = 15.5 - 0.23 CMRR (low cover)

PRSUP = 17.8 - 0.23 CMRR (high & moderate cover)

Figure 10 shows these equations together with the field data from which they were derived. The design equations are slightly more conservative than the discriminate equations that they are based on. The guidelines are currently being implemented into a computer program called Analysis of Roof Bolt Systems (ARBS).

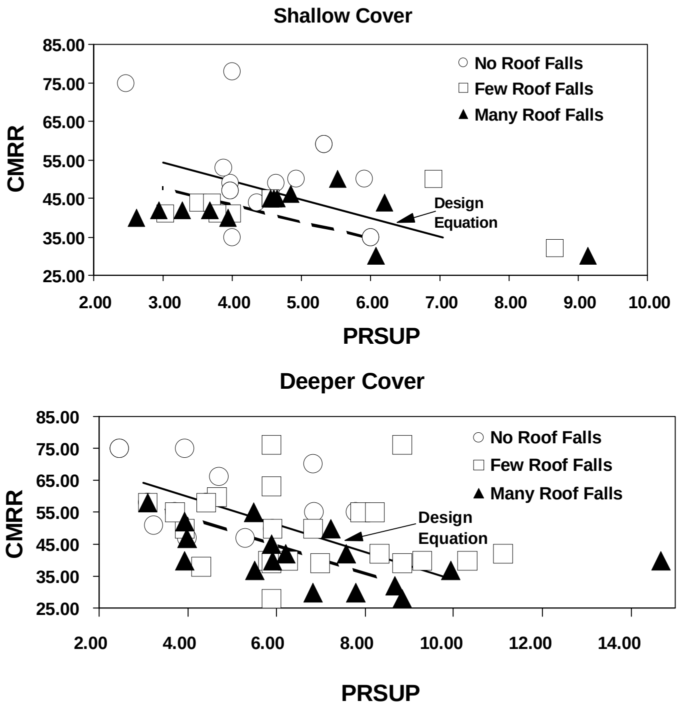

Figure 10. Design equations for roof bolts.

8 SUPPORT TECHNOLOGY OPTIMIZATION PROGRAM

The 1990's saw an unprecedented development of innovative supplemental roof support technologies for underground coal mines. Compared with the traditional wood posts and cribs, the new supports provide better roof control and material handling advantages. The new supports include both engineered wood products and novel concrete designs.

As new support systems are developed, they should be tested to determine their performance characteristics. NIOSH operates a world-class facility called the Safety Structures Testing Laboratory (Barczak, 2000a). During the past seven years, over

1,000 tests have been conducted on various support systems. As a result of this effort, 18 new support systems have been introduced to the mining community.

To facilitate the use of these new supports, NIOSH developed the Support Technology Optimization Program (STOP). STOP includes a complete database of the support characteristics and loading profiles obtained from the testing (Barczak 2000b). Using criteria introduced by the user, STOP can determine the support pattern that will carry the required load and provide convergence control. Comparisons among the various support technologies are easily made. STOP can also estimate material handling requirements and installation costs. Figure 11 shows a typical screen from the STOP program.

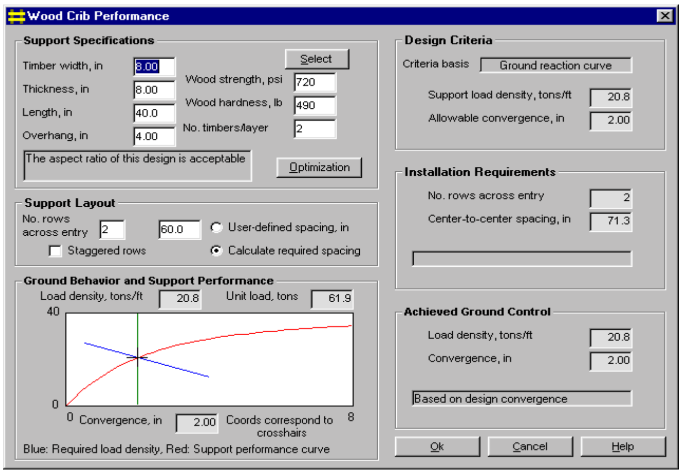

Figure 11. Typical Windows screen from the STOP program.

9 CONCLUSIONS

The NIOSH ground control program has focused on providing the mining community with practical tools for improving the safety of U.S. underground coal miners. Using these techniques, mine planners can optimize pillar design and support selection for a variety of mining techniques.

Transferring these tools to the industry is an integral part of the program. Traditional techniques, such as conference presentations and NIOSH publications, are employed extensively. But innovative methods are also employed to bring the research results directly to the end users. Open Industry Briefings are regularly held in numerous coalfield locations, to allow researchers direct access to their customers. Software packages are made available free of charge, and hundreds are distributed at meetings or in response to requests. Most recently, all the ground control software has been posted on the NIOSH mining website for easy access.

The technology transfer efforts have paid off in many ways. Large segments of the mining community uses NIOSH software routinely for many aspects of mine design. Mine operators and safety regulators both consider NIOSH as the central source for information ground control. While it is hard to measure directly, there is every reason to believe that our efforts have helped make underground coal mines safer places to work.

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