ANALYSIS OF ROOF BOLT SYSTEMS

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ABSTRACT

Despite more than half a century of experience with roof bolting, no design method has received wide acceptance. To begin to improve this situation, National Institute for Occupational Safety and Health (NIOSH) conducted a statistical study of roof bolt performance at a number of mines throughout the U.S. Case histories were collected from 37 mines with a variety of roof bolt types and patterns in a wide range of geologic environments. Performance was measured in terms of the number of roof falls that occurred per 10,000 ft of drivage. The study found that roof falls are rare when the roof is strong and the stress is low, even with light roof bolting patterns. The focus of this paper is on the more difficult conditions, where the roof is weaker and/or the stress is higher.

Analysis of the results led to guidelines that can be used to make preliminary estimates of the required bolt length, capacity, and pattern. The guidelines are based on the depth of cover (which correlates with stress) and the roof quality (measured by the Coal Mine Roof Rating (CMRR), and the intersection span. Another contribution is a formula for estimating the horizontal stress level in the eastern U.S. coalfields as a function of the depth of cover. The design guidelines are currently being implemented into a computer program called Analysis of Roof Bolt Systems (ARBS).

INTRODUCTION

Roof bolts are the first line of defense protecting mineworkers from the hazards of ground falls. Because roof bolts utilize the inherent strength of the rock mass, they have many advantages when compared with earlier standing support systems. Due to of their central importance, roof bolts have received more research attention than any other ground control topic, with the possible exception of coal pillars.

Roof bolt design consists in specifying the proper bolt type, capacity, length, and pattern for a particular roof rock, stress level, and application. The interactions between these variables are very complex, and our understanding of their mechanics remains imperfect. Numerous roof bolt design methods have been proposed over the years, but none has gained widespread acceptance by the coal mining industry (1). This is unfortunate, because more than 1,500 roof falls occur each year in U.S. coal mines (2).

To help develop scientific guidelines for selecting roof bolt systems, the National Institute for Occupational Safety and Health (NIOSH) conducted a study of roof fall rates at 37 U.S. mines (3). The study evaluated five different roof bolt variables: Length, tension, grout length, capacity, and pattern. Roof spans and the Coal Mine Roof Rating (CMRR) were also measured. Stress levels could not be measured directly, but the depth of cover was used as a stand-in for stress. The outcome variable, which measured the success of the roof support system, was the number of Mine Safety and Health Administration (MSHA)-reportable roof falls that occurred per 10,000 ft of drivage.

In all, nearly 100 case histories were collected. Areas that were affected by longwall mining, multiple seam interactions, or major faults were excluded, as were roof falls that took place more than 18 months after development. Details of the data collection procedures and the case history data base have been published elsewhere (2).

Analysis of the entire data set led to some preliminary roof bolt design guidelines (1). This paper will focus on the subset of more difficult conditions, those with weaker roof and higher stress. The first step is to define those difficult conditions, based on the mechanism of roof bolt support.

ROOF GEOLOGY AND THE REINFORCEMENT MECHANISM OF ROOF BOLTS

The principle objective of roof bolting is to help the rock mass support itself. Some researchers have ascribed different support mechanisms to different types of roof bolts. For example, mechanical bolts were originally thought to work in suspension, while resin bolts primarily built beams (4). Others have described the beam-building mechanism of tensioned bolts, and the frictional support of fully grouted bolts (5).

It seems, however, that the reinforcement mechanism is actually dictated to the bolts by the ground, rather than the other way around. Four mechanisms can be identified, depending on the geology and the stress regime:

- <u>Skin Control</u>: In strong, massive roof that is essentially self-supporting, cracks, joints, crossbeds, or slickensides can create occasional hazardous loose rock at the skin of the opening (figure 1a). In this environment, the function of the bolts is to prevent local rock falls, not to prevent a major collapse. A pattern of relatively light, short roof bolts is usually sufficient. Skin control is also an important secondary function of roof bolts in weaker ground.

- Suspension: In many mines, a stronger unit that is largely self-supporting overlies a weak immediate roof layer (figure 1b). In these circumstances, roof bolts act to suspend the weaker layer. Experience has shown that roof bolts are extremely efficient in the suspension mode (6, 7, 8), though suspension becomes more difficult if the weak layer is more than 3 ft thick. The Coal Mine Roof Rating (CMRR) somewhat quantifies this effect through the Strong Bed Adjustment (9). The traditional dead-weight loading design approach is generally appropriate for suspension applications (1).

- Beam Building: Where no self-supporting bed is within reach, the bolts must tie the roof together to create a "beam" (figure 1c). The bolts act by maintaining friction on bedding planes, keying together blocks of fractured rock, and controlling the dilation of failed roof layers (5, 10). In general, roof bolts have to work much harder in beam building than in suspension, and higher densities of support are required. However, it is these applications (and those in the next category) that have been most troublesome for design.

- Supplemental Support: Where the roof is extremely weak, and/or the stress extremely high, roof bolts may not be able to prevent roof failure from progressing beyond a reasonable anchorage horizon (figure 1d). In these cases, cable bolts, cable trusses, or standing support may be necessary to carry the dead-weight load of the broken roof, and the roof bolts act primarily to prevent unraveling of the immediate roof (11).

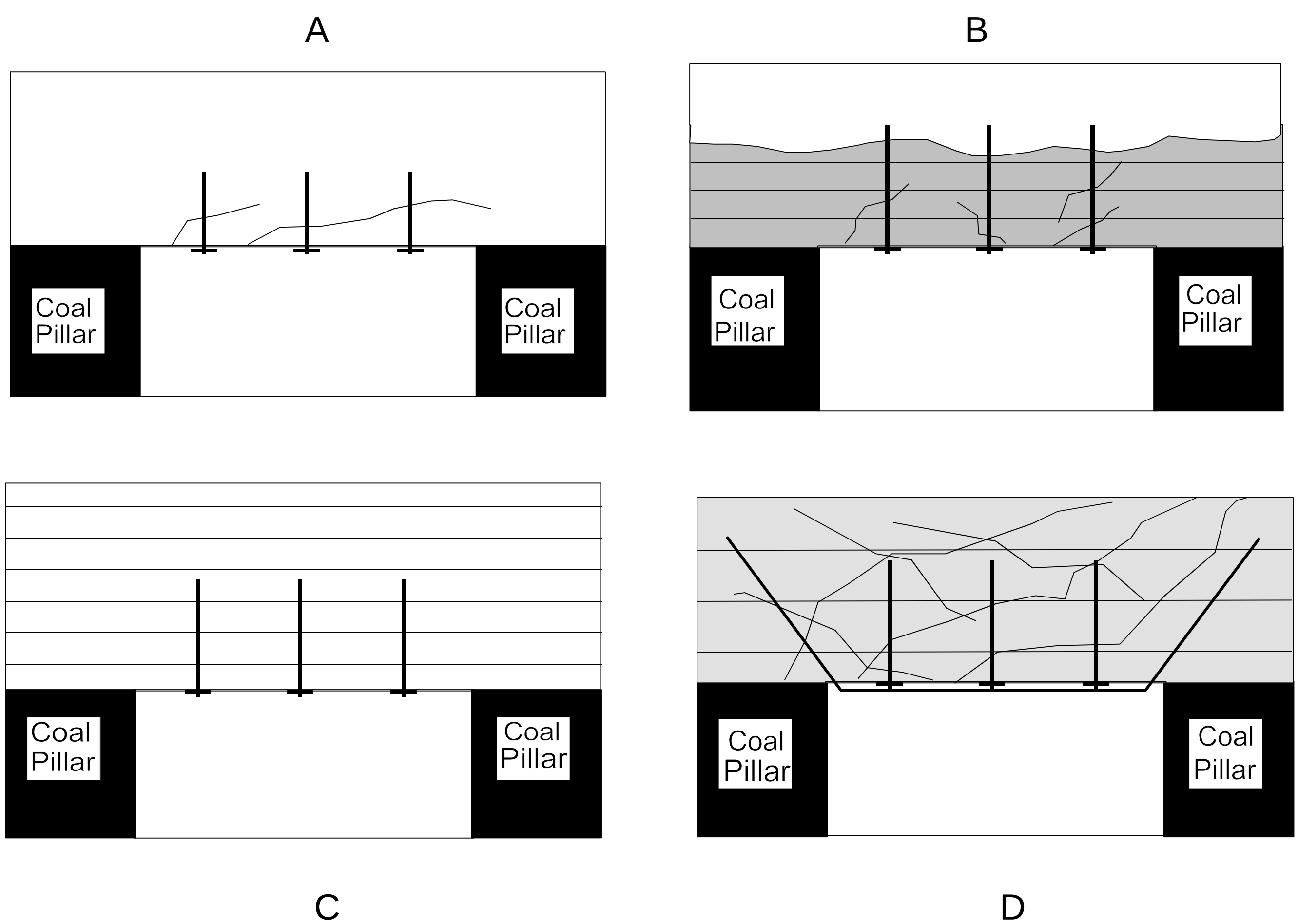

Figure 1. Roof bolt support mechanisms: (A) simple skin support, (B) suspension, (C) beam building, and (D) supplemental support in failing roof.

These broad categories can be seen in the data collected in this study. Figure 2 shows the roof fall rates for all the case histories, divided into three groups:

- *Failures* (more than 1.5 roof falls per 10,000 ft of drivage)
- *Intermediate* (the roof fall rate is between 0.4 and 1.5 falls per 10,000 ft)
- *Successes* (the roof fall rate is less than 0.4 falls per 10,000 ft)

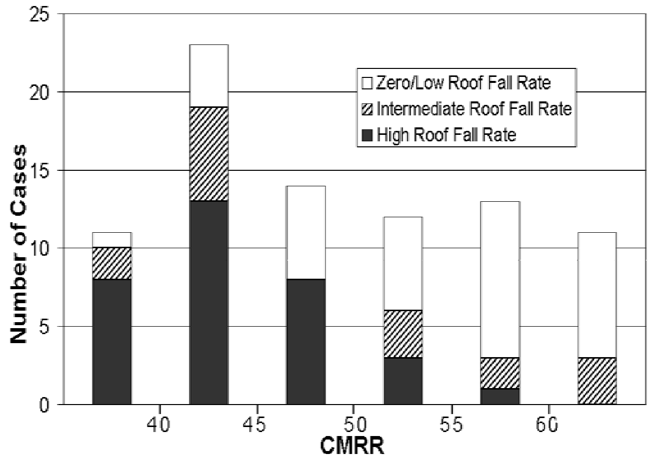

Figure 2. Roof fall rates for different CMRR values

It is clear that mines with weaker roof were much more likely to encounter roof falls. When the CMRR was less than 50, 29 cases fell in the Failure category, while there were just 16 Successes. When the CMRR was 50 or greater, the proportions were more than reversed, with Successes outnumbering Failures by 6-to-1.

HORIZONTAL STRESS AND DEPTH OF COVER

Geology is not the only factor that determines the reinforcement mechanism, however. The transition between suspension and beam building depends heavily on the level of stress. The same roof bed that is self-supporting in a low stress environment may require substantially more reinforcement when subjected to higher stresses.

Worldwide research over the past 20 years has shown that the horizontal stress is usually two or three times larger than the vertical stress. In addition, the horizontal stress attacks the roof directly, while the pillars carry most of the vertical stress.

In U.S. coal mines, horizontal stresses are rarely measured underground. However, a comprehensive data base collected by Mark and Mucho (12) shows a strong correlation between increasing depth and greater levels of maximum horizontal stress in the eastern U.S. (figure 3). Two regression equations are shown, linear and logarithmic:

$$\sigma_H = 1.23\ H + 1306 \quad (1a)$$

$$\sigma_H = 2250 \log_{10}(H) - 4075 \quad (1b)$$

Where: σ_H = In situ horizontal stress (psi)
H = Depth of cover (ft)

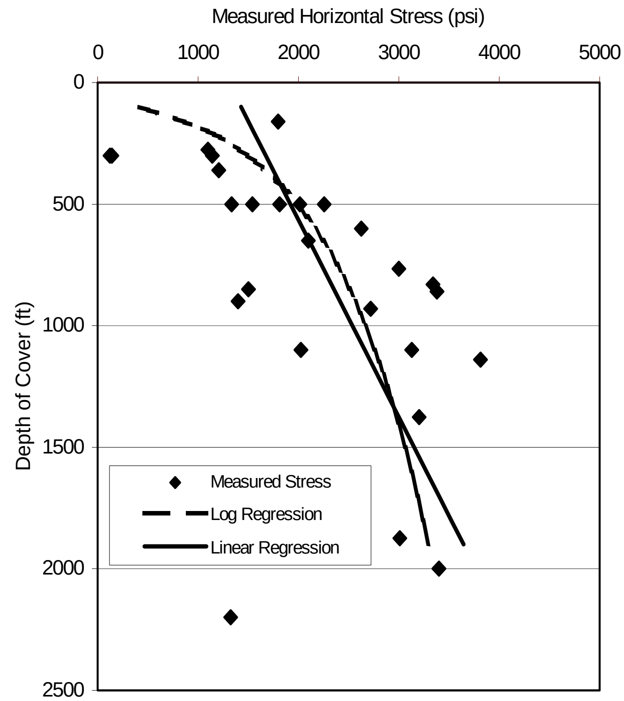

Figure 3. Horizontal stress in eastern U.S. coal mines. Actual stress measurements from Mark and Mucho (9).

They both predict very similar values for the range of depths in the case histories. However, the logarithmic equation is preferred because other research suggests that the horizontal stress gradient tends to decrease at greater depths (13). In the western U.S., the horizontal stress is generally about equal to the vertical, but it is highly variable.

For the study described in this paper, it was impossible to measure the horizontal stress at any of the sites. However, based on the data shown in figure 3, the assumption will be made that the depth of cover can be used to estimate the stress level.

In figure 4, the case histories are plotted against the CMRR and the depth of cover. A discriminant line is shown separating the data into two groups:

$$CMRR = 9 + 17\ (\log_{10} H) \quad (2)$$

Roof falls are rare above the line, and this is the strong roof and/or low stress regime where roof bolts are apparently working by Skin Control or Suspension. Below the line roof falls were much more common, and roof support was clearly more difficult. This is the weak roof/high stress regime where the bolts apparently have to work by Beam Building or with Supplemental Support. The remainder of this paper will address roof support design for this regime.

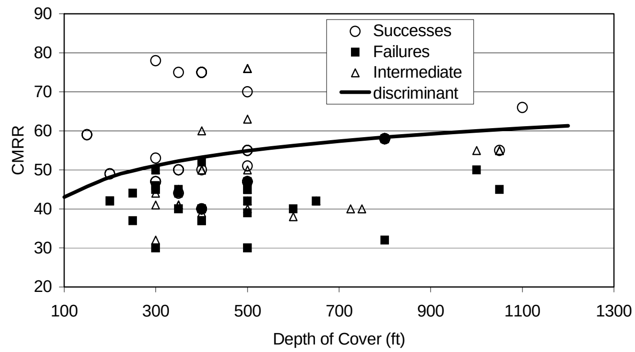

Figure 4. Support mechanisms in practice. Above the discriminant line is the skin support/suspension regime; below the line is the beam building/supplemental support regime.

INTERSECTION SPAN

After the CMRR and the depth of cover, the roof span is the next most important factor affecting roof stability. In coal mines, the greatest spans are encountered in intersections. Approximately 70% of all roof falls occur in intersections, though they account for just 20-25% of the total drivage (14). Clearly, roof falls are much more likely in wider spans. Any successful roof bolt design methodology must consider the span effect.

Figure 5 plots the case history spans (reported as the average of the sum-of-the-diagonals) against the CMRR. The best equation separating the Successful cases from the Failures is also shown as:

$$Is_G = 20 + 0.26\ (CMRR) \qquad (3)$$

Where Is_G = Suggested Intersection Span (average of the sum-of-the-diagonals, ft). Surprisingly, the correlation was not improved when either the depth of cover or the seam thickness were included.

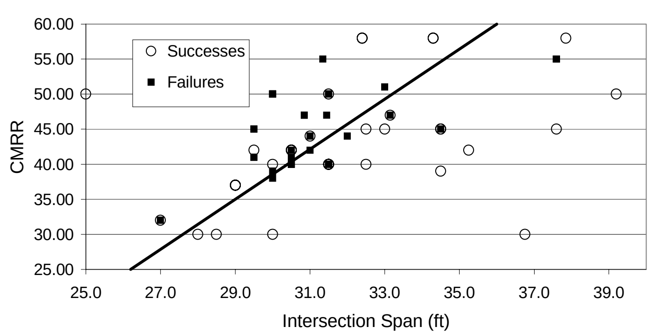

Figure 5. Effect of roof span on roof fall rate. Above the line spans are appropriate, below the line spans are generally too wide.

BOLT LENGTH

An original goal of the study was to determine which of the bolt design parameters (length, tension, pattern, capacity) were most important. Unfortunately, statistical analysis of the entire data set did not reveal any significant correlations (3). However, bolt length was confirmed as a critical parameter in a separate analysis that used "paired data" from individual mines.

From the large data set, 13 pairs of case histories were extracted where two different lengths of roof bolts were used at the same mine. For a pair to be selected, the roof bolt lengths had to differ by at least one ft, and at least one of the roof fall rates had to be greater than zero. Figure 6 shows that in 11 of the 13 cases, the roof fall rate was less with the longer bolt. The average reduction in the roof fall rate was 65%. The greater effectiveness of the longer bolts was statistically significant at the 98% confidence level. Four of the pairs mixed shorter, pre-tensioned bolts with longer, fully-grouted bolts. In three of these pairs, the longer bolts had the lower roof fall rate. More details on the study can be found in Molinda et al. (3).

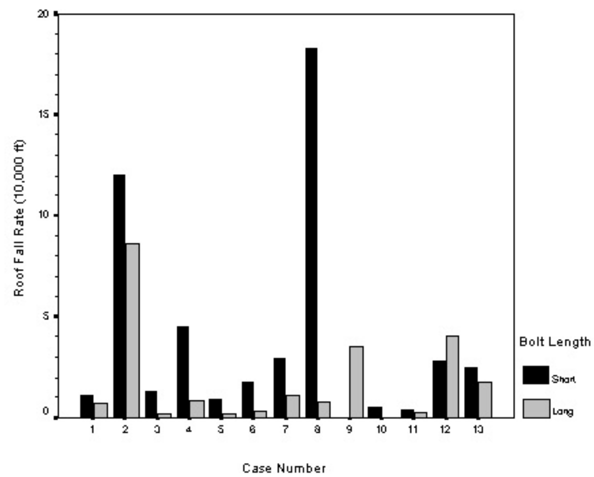

Figure 6. Paired cases of long and short bolts showing benefits of long bolts in decreasing roof fall rates.

Building upon these results, an equation was developed to guide the selection of the proper bolt length (L_B). Equation (4) incorporates the major factors that should affect the required bolt length, namely the span, the stress level, and the roof quality:

$$L_B = (Is/13)\ (\log_{10} H)\ ((100\text{-}CMRR)/100)^{1.5} \qquad (4)$$

Where Is = the actual intersection span (average of the sum-of-the-diagonals, ft).

The roof quality term in equation (4), $((100\text{-}CMRR)/100)^{1.5}$ is based on the relationship originally proposed by Unal (15), but it has been adjusted to magnify the effect of the weak roof.

Figure 7 compares the bolt lengths predicted by equation (4) with the actual bolt lengths in the case histories. For the successful cases, the mean bolt length was very close to the equation's prediction. In the unsuccessful cases, on the other hand, the mean bolt length was 8 in too short. Moreover, of the 13 cases when the actual bolt length was shorter by 1.5 ft or more than the length recommended by equation (3), 77% were failures. These data further confirm the importance of proper bolt length in preventing ground falls.

It should be noted, however, that good anchorage is necessary to ensure that the entire length of a fully grouted bolt is working. In weak rock, the anchorage factor of a typical 13-ton capacity No. 6

rebar bolt may be less than 0.5 tons per grouted inch (5), meaning that the upper 26 in will pull out before that portion of the bolt achieves its yield load. In other words, a 6-ft bolt with a low anchorage factor might provide less support than a 5-ft bolt with a good anchorage factor. Smooth holes, a large annulus, and/or poor resin quality can also reduce the anchorage factor and the effective bolt length. If the anchorage is questionable, short encapsulation pull tests should be used to identify the problem and make adjustments (1, 16).

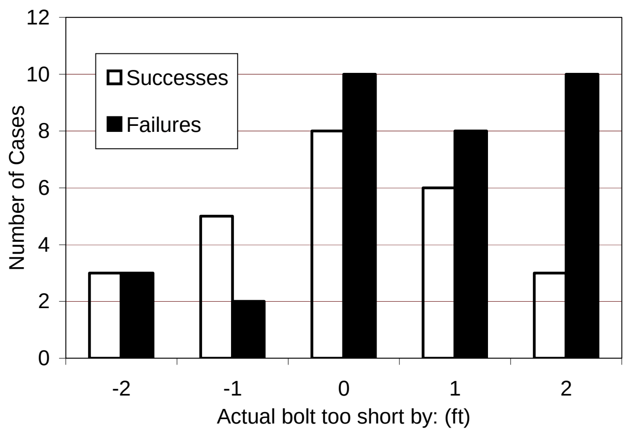

Figure 7. Comparison between the actual bolt lengths from the case histories with the bolt length predicted by equation (4). When the X-axis value is positive, the actual bolt length was shorter than the equation (4) prediction.

PATTERN AND CAPACITY OF ROOF BOLT SYSTEMS

The intensity of support provided by a roof bolt system is determined by:

- The load-bearing capacity of the individual bolts;
- The density of the bolt pattern, and;
- The length of the bolts.

The capacity of the roof bolt is normally determined by the diameter and the grade of the steel. One obvious advantage of stronger bolts is that they can carry more broken rock. They can also produce more confinement in the rock and accept higher pre-tension loads. The capacity of a bolt can also depend on the anchorage, however, as noted above.

The density of a roof bolt pattern depends on the number of bolts per row and the spacing between rows. In the U.S., support density does not vary much. With the advent of dual-head roof bolting machines, four bolts per row have become the near universal standard. Bolt spacing is limited by law to 5 ft, but is seldom less than 4 ft. With entries varying in width from about 15 to 20 ft, bolt densities range from one bolt per 12 to 25 ft^2.

To measure the bolt intensity, a summary variable, ARBS, was developed that includes all three factors:

$$ARBS = \frac{(L_b)\,(N_b)\,(C)}{(S_b)\,(W_e)} \qquad (5)$$

Where L_b = Length of the bolt (ft)
N_b = Number of bolts per row,
C = Bolt capacity (1000's of pounds, (or kips))
S_b = Spacing between rows of bolts (ft),
W_e = Entry width (ft)

Figure 8 shows that the necessary ARBS increases as the CMRR decreases. The prediction becomes even better if the depth of cover is included in the equation:

$$ARBS_G = (5.7 \log_{10} H) - 0.35\ CMRR + 6.5 \qquad (6)$$

Where $ARBS_G$ is the suggested value of ARBS for the given CMRR and depth of cover.

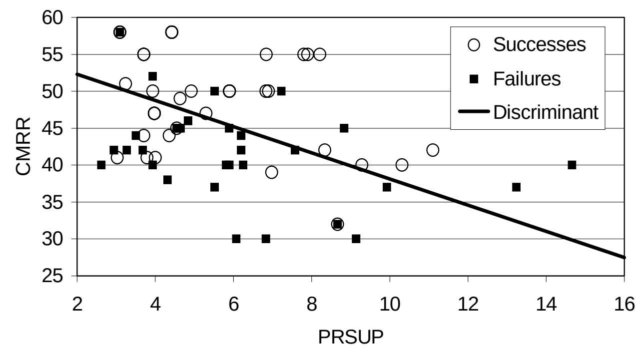

Figure 8. Effect of ARBS on roof fall rate. Above the discriminant line the ARBS was generally adequate, below the line it generally was not.

VERIFICATION

Figure 9 shows the performance of the design methodology represented by equations 2 through 6. All of the 71 case histories that fell below the line in figure 4 are plotted. The two axes are:

- The difference between the suggested $ARBS_G$ and the actual ARBS, and;
- The the difference between the suggested Is_G and the actual Is.

Therefore, a positive value on the x-axis means that the span was too large. A negative value on the y axis means that the ARBS was inadequate.

The lower right-hand quadrant of the graph contains 19 cases in which the equations predict that both the span was too large and the bolt intensity was too low. Of these, 16 were in fact failures, and only one was a success.

The upper left-hand quadrant contains 18 cases in which the equations predict that both the span and the bolt intensity were adequate. Of these, 9 were successes and 4 were failures. Therefore, for these two groups of cases, the design equations predicted the actual outcome 83% of the time.

For the case histories in the other two quadrants, one of the parameters was within the guidelines, while the other was not. It seems reasonable that if the actual span were less than the suggested

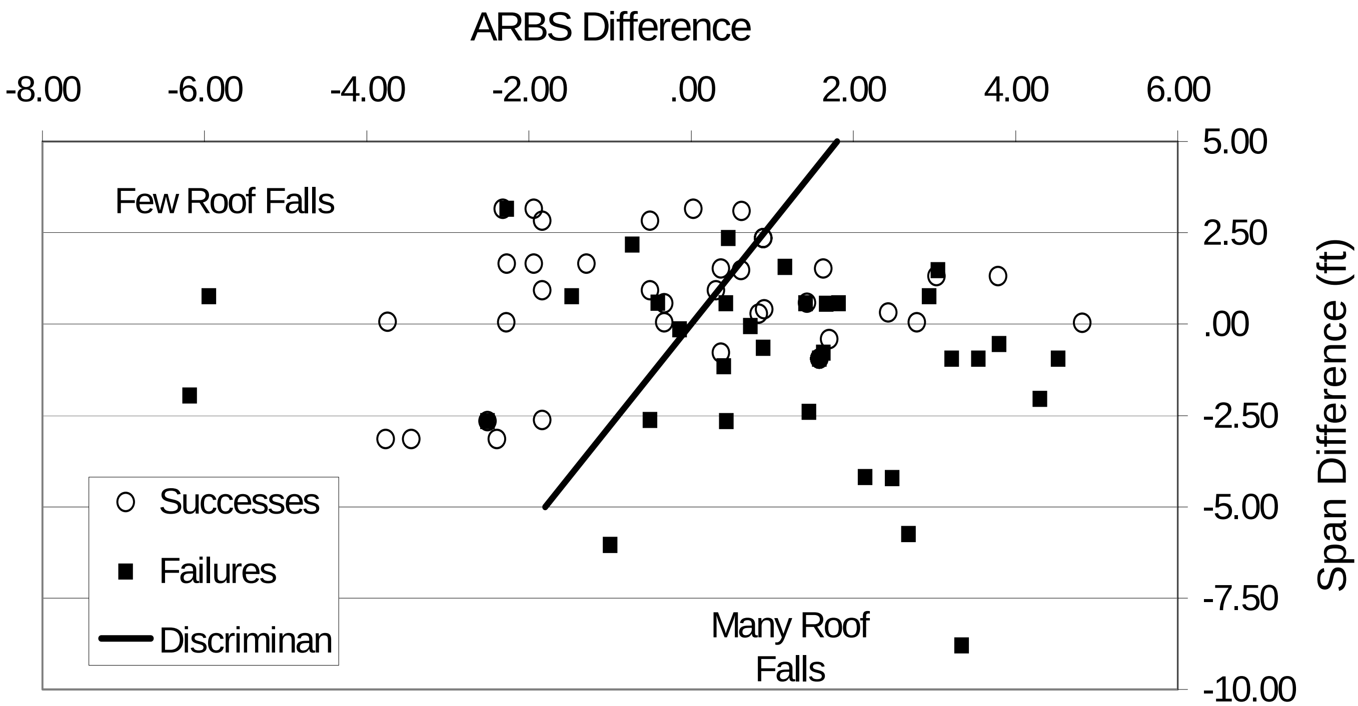

Figure 9. Verification of the design equations (3), (6), and (7). The case histories are plotted according to the difference between the actual ARBS and the calculated ARBS (X-axis), and between the actual span and the calculated span (Y-axis). The discriminant line is equation (7)

span, then it might be possible to reduce the required ARBS. Similarly, if the span was larger than recommended, a higher ARBS might compensate for it.

The discriminant equation shown on the graph reflects an adjustment to the suggested ARBS as follows:

$$ARBS_{Gadj} = ARBS_G - 0.3\ [Is_G - Is] \qquad (7)$$

Equation (7) correctly predicted 76% of the successful and failed case histories. Only 6 successes were mis-classified, and all but one of these was very near the line. Of the 8 mis-classified failures, 5 also fell close to the line. The 3 further away represent mines that installed high densities of support and still had many roof falls. They serve as reminders that roof bolt design remains an imperfect science and there may be regimes where roof bolts may not be adequate. Nevertheless, the overall results are sufficiently promising that the following step-by-step guidelines can be proposed.

ANALYSIS OF ROOF BOLT STABILITY (ARBS)

1. *Evaluate the Geology.* The CMRR should be determined either through underground observation or from exploratory drill core. Zones of markedly different CMRR should be delineated. If the thickness of individual beds varies within the bolted horizon, this effect should be noted. Special features, such as faults or major geologic transition zones, should be treated separately.

2. *Evaluate the Stress.* It is unusual for stress measurements to be available, so the design procedures use the depth of cover as a rough estimator. One warning is that the case histories were purposely chosen to be away from stress intensifiers like retreat mining or multiple seam interactions. Where such intensifiers are expected, it might be prudent to increase the "effective depth" used in the equations.

3. *Determine the Roof Bolt Reinforcement Mechanism* using equation (2). If the actual CMRR exceeds the one calculated by equation (2), then the support mechanism is probably skin control and/or suspension, and the traditional, dead-weight loading design technique is probably appropriate. Otherwise, the support mechanism is probably "beam building," and the ARBS technique may be used (continue with the steps 4 through 8.)

4. *Determine the Intersection Span.* Equation (3) should be used to determine the recommended maximum span. Where available, actual measurements of the diagonal spans should be made, and the real values used in the equations.

5. *Determine the Bolt Length* using equation (4), and rounding to the nearest half-ft.

6. *Determine Required Roof Bolt Intensity.* The design equation is based on equations 6 and 7:

$$ARBS_G = (SF)\ (0.3\ (Is_G - Is))\ [(5.7 \log_{10} H) - (0.35\ CMRR) + 6.5] \qquad (8)$$

Where SF= Stability Factor (1.2 recommended)

The minimum recommended ARBS is approximately 3.0.

7. *Determine the Capacity and the Bolt Pattern.* Equation (5) is used to determine the remaining design variables. The bolt length was selected in step 5, and normally the entry width and the number of bolts per row are also fixed. The capacity and the row spacing the remaining variables, and they can be adjusted to achieve the suggested ARBS. Figures 10a and 10b may be useful in this process.

8. *Select Skin Support:* Plates, header, mats, or mesh should be specified to ensure that loose rock between the bolts does not pose a hazard.

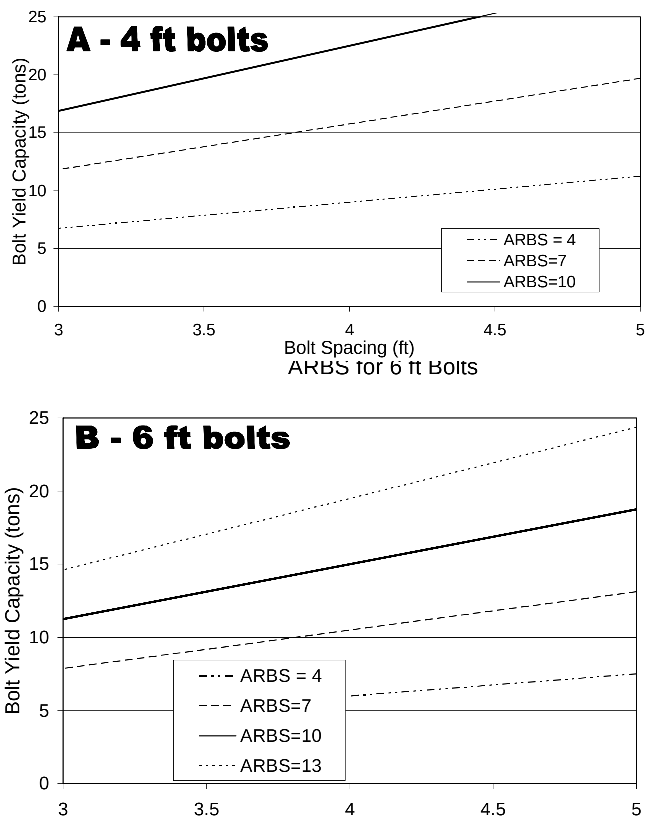

Figure 10. ARBS design charts relating the bolt spacing to bolt yield capacity. Based on 4 bolts per row and 18 ft wide entries. (A) Bolt length = 4 ft and (B) Bolt length = 6 ft

CONCLUSIONS

This paper has presented some first steps towards providing a scientific basis for roof bolt design. The design approach explicitly considers the most important factors that determine the performance of a roof bolt system. The two key input parameters are the roof quality and the stress level, and the outputs include suggested values for the intersection span, the bolt length, the bolt capacity and the bolt pattern. Each of the elements in the design technique is supported by extensive case history data.

A crucial finding was the importance of the depth of cover to roof bolt performance. The evidence clearly supports the proposition that in situ horizontal stresses tend to increase with depth, and make the job of roof support more difficult. An explicit connection between the depth of cover and the stress level is provided. Further research is necessary to refine the relationship.

It should also be noted that the design methodology was derived from the case histories based on the risk of roof falls in intersections. In some circumstances, it may be possible to reduce the level of support between intersections. On the other hand, the case histories were all from areas that were unaffected by retreat mining. Where elevated stresses are expected, the stress level could be adjusted by increasing the "effective depth" in the equations.

The field data also indicated that in very weak roof, it may be difficult to eliminate roof falls using typical U.S. roof bolt patterns. When the CMRR was less than 40 at shallow cover, and less than 45-50 at deeper cover, high roof fall rates could be encountered even with relativley high roof bolt densities. Faced with these conditions, special mining plans or routine supplemental support might have to be considered.

Much more remains to be learned to further improve the efficiency of roof bolt design. One important question is the interaction between primary roof bolts and the various supplemental supports that may be installed. Supplemental supports vary greatly in their stiffness and other characteristics, and they may not always be compatible with the primary support. The quality of roof bolt installation remains a critical issue. The effect of poor load transfer on resin bolts was discussed above, but there are many other ways in which the capability of a bolt may be defeated by improper installation (17). Installing supports with pre-tension may be one way to increase their efficiency, but a truly scientific study of the value of pre-tension remains to be published. With nearly 100 million roof bolts installed each year, the mining community has much to gain from continued roof bolting research.

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