Gate Entry Design for Longwalls Using the Coal Mine Roof Rating

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ABSTRACT

Successful longwall mining requires a stable tailgate entry. Gate entry performance is influenced by a number of geotechnical and design factors, including:

- Pillar size and pillar loading;
- Roof quality;
- Floor quality;
- Entry width; and,
- Artificial support (primary and secondary).

This paper describes a comprehensive, practical, design methodology, based on statistical analysis of a nationwide data base of longwall ground control experience.

Geotechnical surveys were conducted at 44 U.S. longwall mines, and underground observations of site geology, entry conditions, and support design were recorded at each mine. The observations were combined with discussions with mine personnel to identify 69 longwall gate entry designs as satisfactory, unsatisfactory, or borderline. Only conventional longwall designs, in which the pillars are expected to carry the full abutment loads, were included in the data base. Designs which employed yield pillars only were excluded.

The case histories were characterized using five descriptive parameters. Pillar design was described by the Analysis of Longwall Pillar Stability Factor (ALPS SF). A major new contribution is the Coal Mine Roof Rating (CMRR), a rock mass classification system that quantifies the structural competence of bolted mine roof. Other quantitative measures were developed for primary support, secondary support, and entry width.

Multivariate statistical analyses indicated that in 84% of the case histories the tailgate performance could be correctly predicted using just ALPS and the CMRR. Most of the misclassified cases fell within a very narrow borderline region. The analyses also confirmed that primary support and gate entry width are essential elements in successful gate entry design. The relative importance of the floor and of secondary support could not be determined from the data.

Based on these results, a simple equation was developed to guide the design of longwall pillars and gate entries:

$$\text{ALPS SF}_R = 1.76 - 0.014 \text{ CMRR}$$

Where: ALPS SF_R = ALPS SF suggested for design.

Guidelines for entry width and primary support density, as related to the CMRR, are also provided.

INTRODUCTION

During the past decade, longwall mining has become the predominant mining method at large underground coal mines. Average face productivity has nearly quadrupled, and now stands near 2,400 clean tons per unit shift. In 1991, 76 longwall mines accounted for nearly 40% of all underground coal production in the U.S. (Combs, 1993; Merrits, 1993; Energy Information Administration, 1992).

Ground control has been an important element in improved longwall performance. Fifteen years ago there were no reliable guidelines for designing either gate entries or chain pillars. Tailgate failures occurred frequently, and the literature of the time describes many instances when roof falls, floor heave, or pillar sloughage impeded face advance and ventilation. The safety implications of tailgate blockages were further underlined by the 1984 Wilberg mine disaster, and regulations introduced by the Mine Safety and Health Administration (MSHA) in 1988 required that roof control plans address the issue of maintaining safe travelways on the tailgate side of the longwall (U.S. CFR 30, 1988).

Responding to the need for better conditions, ground control researchers focussed initially on the design of longwall chain pillars. Many mines had found by trial-and-error that tailgate conditions could improve significantly when pillar sizes were increased. Data published by Mark

(1992) confirmed the correlation between pillar design and tailgate stability. Of 46 case histories of unsatisfactory tailgate designs, only one occurred when the ALPS SF was greater than 1.3.

While the various pillar design formulations proposed during the 1980's built upon this correlation, it was also evident that pillar design is not the only factor affecting tailgate stability. Indeed, experience and common sense strongly suggested that roof quality and entry support play a significant role. As Carr and Wilson (1982) noted, studies conducted as early as the 1960's 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."

Yet researchers were unable to successfully move beyond pillar design. In part, their narrow focus may have been due to the force of tradition. Before longwall mining, the greatest danger for pillars was the regional failure of many pillars at once. The classic approach of determining "safety factors" from estimates of pillar strength and load worked well in predicting such squeezes or collapses. It was natural, though not necessarily appropriate, to transfer the same methodology to longwalls.

Another reason for the focus on pillars was that traditional, deterministic rock mechanics, involving analytical or numerical models, is not yet well suited to the complex problem of gate entry stability. The mechanisms of gob formation, abutment load transfer, pillar yielding, and roof behavior are largely unknown, making model formulation difficult. Also central to the problem is the immense variety of geologic sequences and features that collectively determine the structural integrity of coal mine roof. Even the most sophisticated numerical models strain credulity when critical material properties and structural features must be guessed or ignored.

Fortunately, deterministic methods are not the only ones available for the solution of complex ground control problems. The method of back-calculation relies instead on the scientific interpretation of actual mining experience. More than 100 longwall panels are mined in the U.S. each year, and each one is a full-scale test of a longwall gate entry design. Back calculation builds upon this wealth of experience, focussing directly on the variable of interest--tailgate performance.

Back-calculation is similar to the empirical/statistical approach that is widely used in other fields, such as medicine, where the scientific understanding of the physical problem is incomplete, but a large quantity of data is available. Because the solutions are so firmly linked to reality, they are particularly well-suited for solving practical problems. Perhaps the best example of the method of back-calculation in ground control is the Salamon and Munro pillar strength formula, which has been so convincing it has been used to size more than one million South African pillars (Salamon and Wagner, 1985).

Effective back-calculation requires, as Salamon (1989) points out, "a reasonably clear understanding of the physical phenomenon in question." Without prudent simplification, the complexity of the problem will overwhelm the method's ability to discern relationships between the most important variables. But a key advantage of the approach is that critical variables may be included even if they are difficult to measure directly. Usually a "rating scale" is developed as a meaningful, repeatable measure of semi-quantitative data.

In the longwall tailgate design problem, the simplified conceptual model assumed that tailgate performance was determined by six factors:

- Pillar design and loading;
- Roof quality;
- Floor quality;
- Entry width;
- Primary support; and,
- Supplemental support.

The sections that follow describe how the data was collected and how the necessary rating scales were derived.

DATA COLLECTION

Data for the study were collected during a series of mine visits conducted between October 1988 and June 1992. A total of 44 mines were included, representing approximately 55% of all U.S. longwall mines in operation during the time period. The mines were selected to represent a geographic and geologic cross-section of the U.S. longwall experience. Every state with an operating longwall, with the exception of Ohio, was included (figure 1).

At each mine, information was collected through underground geotechnical surveys and discussions with mine personnel. The underground surveys documented geology, support, and gate entry conditions. Standardized data sheets were used to record rock mass properties observed in underground exposures, usually roof falls and/or overcasts. Other data sheets were used at coalbed and floor exposures, and at the headgate and tailgate corners of the longwall.

The discussions with mine personnel focussed on past experience with gate entry ground control. Panels in which conditions had been satisfactory were identified, as were locations where conditions were unsatisfactory. Where conditions were considered unsatisfactory, the steps taken by management to prevent reoccurrence were documented.

DESCRIPTION OF THE DATA BASE

A total of 69 individual longwall case histories were distilled from the data. The data base was limited to conventional designs, where the pillars were sized to carry the full abutment loads (Mark, 1990). Total yielding pillar designs were

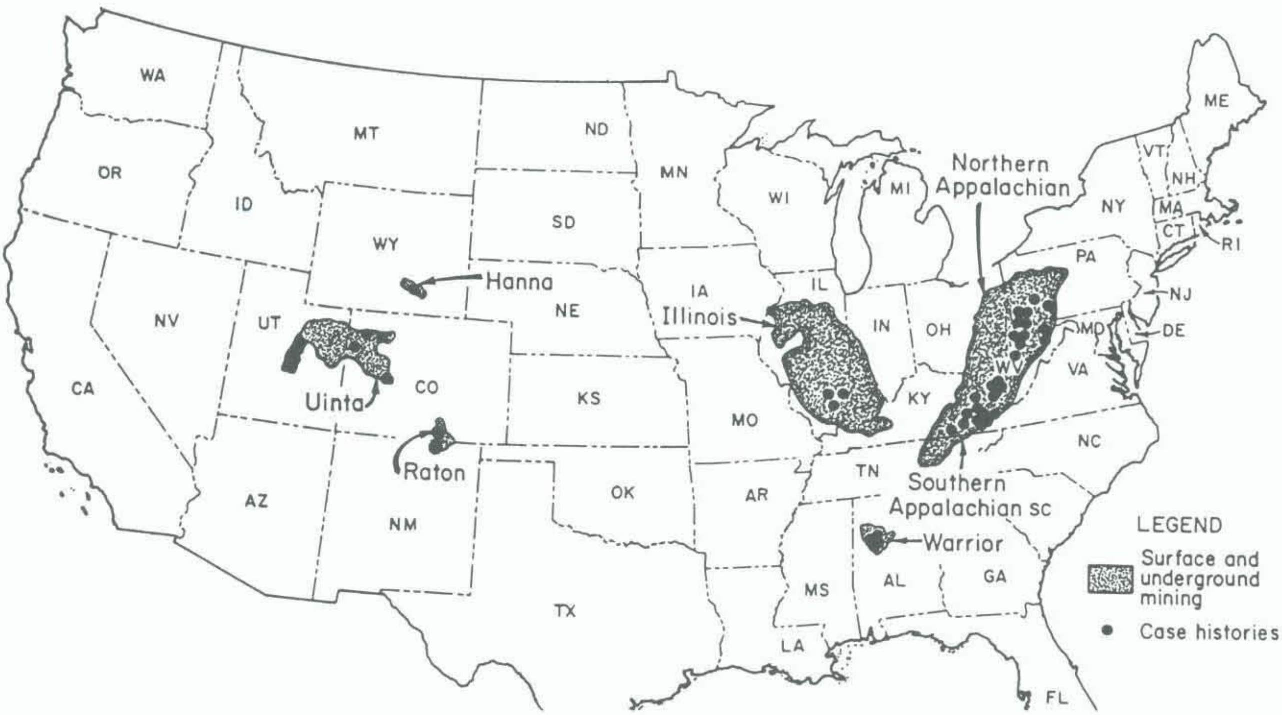

Figure 1–Location of the geotechnical surveys.

excluded. Each complete case history was defined by approximately 50 individual data fields, which were in turn used to define 7 summary variables. The first of these variables is Design Performance, which is the "outcome," or "dependent" variable in the analysis. The other 6 are "explanatory," or "dependent" variables.

Design Performance

The case histories were each classified as "satisfactory" (30 cases), "unsatisfactory" (32 cases), or "borderline" (7 cases). Unsatisfactory conditions almost always included roof deterioration and falls, though floor heave and pillar sloughage were often cited as well. To be classified as unsatisfactory, a case had to meet one of four criteria:

- Management changed the pillar design or the entry support in response to the poor tailgate conditions (25 cases);
- The panel was abandoned due to poor conditions (2 cases);
- Unacceptable conditions developed in the areas of deepest cover (2 cases), or;
- Several falls above the bolt anchorage occurred in the tailgate, resulting in tailgate blockages and significant longwall delays (3 cases).

Satisfactory cases, in contrast, were those in which:

- The design was used for at least three successive panels;
- Tailgate blockages were very rare or nonexistent; and,
- Good conditions, with minimal delays attributable to ground control, were reported.

In some instances, a single satisfactory case represents as many as 50 extracted panels. Where the depth of cover varied, the deepest cover was used to characterize the satisfactory case. Because previous studies had indicated that failures were very rare when the ALPS SF exceeded 1.3, no cases were included where the ALPS SF exceeded 2.0.

Borderline cases were defined as those in which conditions were considered less than satisfactory, but which did not meet any of the four criteria for unsatisfactory designs. Figure 2 shows the regional distribution of the satisfactory and unsatisfactory designs.

Pillar Design

Pillar design was characterized using the ALPS SF. The ALPS SF is defined as:

$$\text{ALPS SF} = \frac{\text{Estimated load-bearing capacity of pillar system}}{\text{Estimated load applied to pillars at tailgate corner}}$$

The estimated load-bearing capacity is determined by the width-to-height ratios, and the total load-bearing area, of the pillars comprising the pillar system. The estimated load is determined by the depth of cover, the panel width, and the extraction ratio within the gate entry system. Details on calculation of the ALPS SF have been published elsewhere (Mark, 1990; Mark, 1992). The distribution of the ALPS SF within the data base is shown in figure 3.

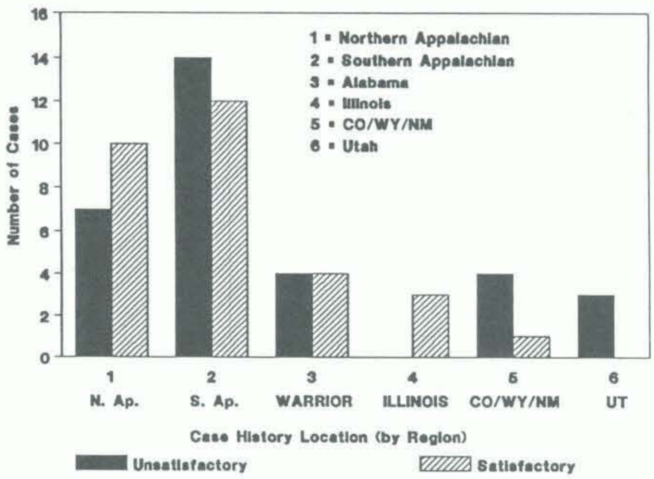

Figure 2–Case location distribution.

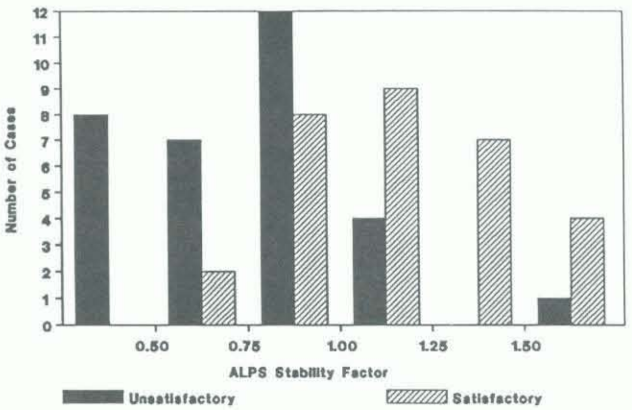

Figure 3–Alps SF distribution.

It may be noted that while data was collected at each site on the cleat, bedding, and other structural characteristics of the coal seams, no attempt was made to determine the in situ coal strength. As discussed elsewhere (Mark, 1992), there is little evidence that coal strength significantly affects tailgate entry performance.

Roof Quality

One of the keys to the success of this research was the development of the CMRR as a quantitative measure of the structural competence of coal mine roof. The CMRR weighs the importance of the geotechnical factors that determine roof competence, and combines these values into a single rating on a scale from 0 to 100. Three significant contributions of the CMRR are that it:

- Focusses on the characteristics of bedding planes, slickensides, and other discontinuities that determine the structural competence of sedimentary coal measure rocks;
- Is applicable to all U.S. coalfields, and allows a meaningful comparison of structural competence even where lithologies are quite different; and,
- Treats the bolted interval as a single structure, while considering the contributions of the different lithologic units which may be present within it.

The field data necessary for calculation of the CMRR are typically obtained from underground exposures of the roof strata in roof falls or overcasts. The following features of the roof rock are observed:

- Shear strength of discontinuities (roughness and cohesion);
- intensity of discontinuities (spacing and persistence);
- strength and weatherability of the rock;
- presence of a strong bed within the bolted interval;
- number of beds within the bolted interval;
- the quality of the rock overlying the bolted interval; and,
- the quantity of ground water inflow.

Full details on the collection of field data and the determination of the CMRR are presented in another paper in these Proceedings (Molinda and Mark, 1993).

The CMRR of the roofs observed at the longwalls varied from a low of 30 to a high of 85. Within this range three broad classes of roof emerged as follows:

<u>Weak Roof (CMRR<45)</u>: Roof typically consisting entirely of low strength (<8,000 psi), closely bedded, jointed, and/or slickensided rocks, usually shales and coals.

<u>Moderate Roof (45<CMRR<65)</u>: Bolted interval usually contains at least one competent unit, typically a siltstone or strong shale, that is at least 2 ft thick and contains few bedding planes or other discontinuities.

<u>Strong Roof (CMRR>65)</u>: Bolted interval typically contains at least one very competent, massive bed, at least 3 ft thick that exceeds 8,000 psi in strength, usually a sandstone or a limestone.

Figure 4 shows the geographic distribution of the CMRR in the data base. It can be seen that mines in the northern Appalachians (Pennsylvania, Maryland, and northern West Virginia) were characterized primarily by Weak Roof. Mines in Illinois and Alabama had mainly Moderate Roof, and in Utah the roof was usually in the Strong category. In the other two regions, the southern Appalachians (Virginia, eastern Kentucky, and southern West Virginia) and in Wyoming/Colorado/New Mexico, the roofs were distributed among all three classes.

Entry Width

No rating system needed to be developed to characterize entry width. For consistency, the entry width used in the analysis is as-mined, without considering the effects of rib sloughage. The range of entry widths within the data base is shown in figure 5.

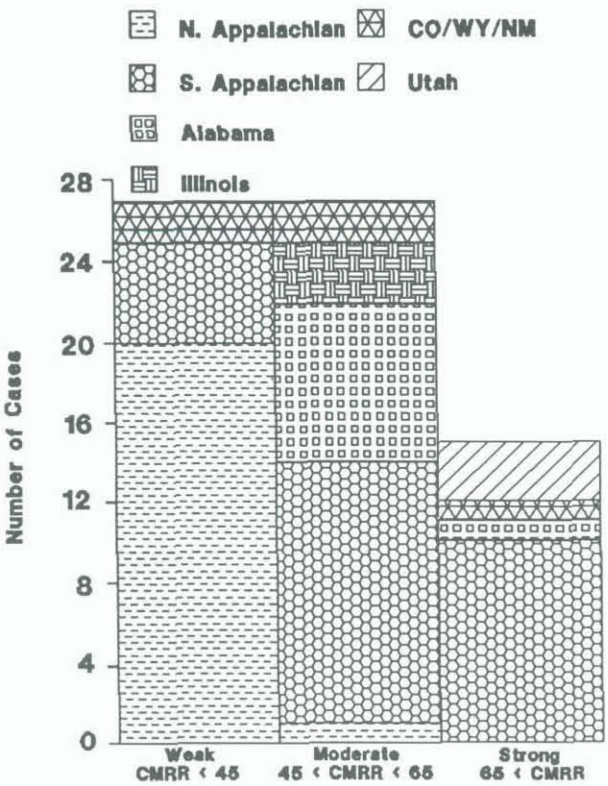

Figure 4–CMRR distribution.

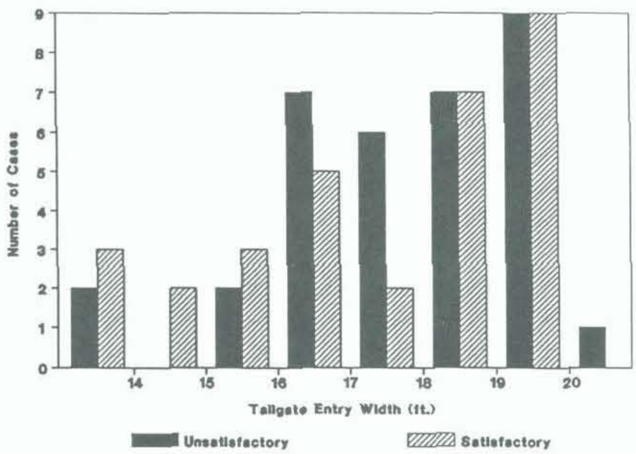

Figure 5–Tailgate entry width distribution.

Primary Support

A wide variety of primary (roof bolt) support fixtures and patterns were used in the longwall mines studied. Data collected underground included the type of bolt, bolt length and diameter, bolting pattern, plate type and dimensions, and additional support (mats, headers, mesh, etc.). The Primary Support Rating (PSUP) used in the analysis was developed as a rough measure of roof bolt density:

$$PSUP = \frac{Lb * Nb * Db}{Sb * We}$$

Where: Lb = Length of the bolt (ft)
Nb = Number of bolts per row
Db = Diameter of the bolts (inches)
Sb = Spacing between rows of bolts (ft)
We = Entry width (ft)

It should be noted that PSUP treats all bolts equally, without attempting to pass judgement on the relative reinforcement value of different types of fixtures. Figure 6 shows the distribution of PSUP in the data base, and table 1 provides examples of PSUP and its calculation.

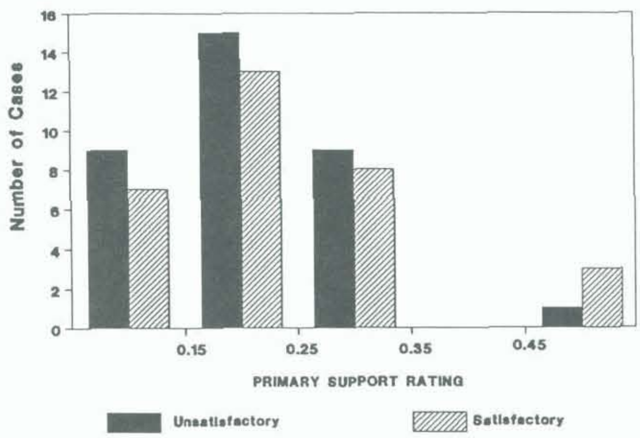

Figure 6–Primary support distribution.

Table 1. Typical primary support systems and values of PSUP

PSUP/We	Lb	Nb	Db	Sb
0.1	4	4	5/8	520
0.2	4	5	3/4	419
0.3	6	5	3/4	419

Secondary Support

By far, the most common type of secondary support used in the tailgates was wood cribbing. Concrete fibercrete cribs were used in just one case, and in three cases no secondary supports were installed. The secondary support rating, SSUP, is a rough measure of the volume of wood installed per unit length of the tailgate:

$$SSUP = \frac{Nc * Lc * Wc}{Sc}$$

Where: Nc = Number of rows of cribs installed
Lc = Length of the crib blocks (ft)
Wc = Width of the crib block (as installed, ft)
Sc = Center-to-center between cribs in each row (ft)

Figure 7 shows the distribution of SSUP, and table 2 provides sample values.

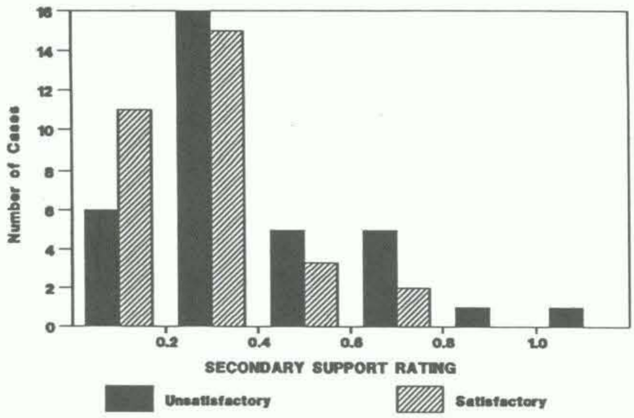

Figure 7–Secondary support distribution.

Table 2. Typical secondary support systems and values of SSUP

SSUP	Nc	Lc	Wc	Sc
0.1	1	3	0.5	15
0.3	2	3	0.5	10
0.5	2	3	0.5	6
0.7	3	3	0.5	7

Floor Quality

Characterizing the floor presented special difficulties. While attempts were made to collect data on the lithology and structure of the mine floors, good underground exposures were often unavailable. The floor has received relatively little research attention, so not all of the important information may have been collected. In the end, it was not possible to construct a meaningful floor rating system from the data available, and the floor could not be included in the analyses.

MULTIVARIATE STATISTICAL ANALYSIS

The goals of the statistical analysis were to:

- Determine which parameters are significantly related to tailgate entry performance;
- Classify each case history as a success or failure using a predictive model (or classification rule) based on those parameters; and,
- Develop an equation that can be used in design.

Two statistical techniques, discriminant analysis and logistic regression, were employed. Discriminant analysis is a regression method which classifies observations into two populations. It assumes that the predictor variables have a multivariate normal distribution, and that the covariance matrix is the same in both populations (Afifi and Clark, 1984). The longwall data set adequately met these two criteria. Logistic regression calculates the probability of a case belonging to a particular population, and does not require the assumption of multivariate normality for the predictor variables. In the longwall analyses, the results from logistic regression were nearly identical to those obtained from the discriminant procedure, so only the discriminant results will be discussed here. The statistical package SPSS was used in all computations.

The first step was to determine which variables were significant predictors of tailgate entry performance. Using a significance level of "alpha"=0.05, only two variables, ALPS SF and CMRR, were included in the model. The discriminant equation was calculated as:

$$Z = 4.10\ (\text{ALPS SF}) + 0.057\ (\text{CMRR}) - 6.83 \qquad (3)$$

Where Z = Discriminant.

When the discriminant (Z) value of a case is greater than zero, tailgate conditions are predicted to be satisfactory, while unsatisfactory conditions are predicted when Z is less than zero.

Equation (3) can be rearranged to relate ALPS SF to CMRR:

$$\text{ALPS SF} = 1.67 - 0.014\ \text{CMRR} \qquad (4)$$

The model represented by equations (3) and (4) successfully identified all but 10 cases, for an overall success rate of 84%. The misclassifications were evenly split between satisfactory and unsatisfactory designs. Figure 8 shows the complete data base, with equation (4) represented as the discriminant equation.

While equation 4 could be used directly in design, a more conservative equation that reduced the misclassification rate for unsatisfactory designs might be more appropriate. Moreover, it is evident from figure 8 that most of the misclassifications fall very near the discriminant equation. By designating a borderline region in which the outcome is uncertain, the total number of misclassifications is reduced to 4, for an overall misclassification rate of 7%. The upper bound of the borderline region is shown on figure 8 as the Design Equation:

$$\text{ALPS SF}_R = 1.76 - 0.014\ \text{CMRR} \qquad (5)$$

Where ALPS SF_R is the ALPS SF suggested for design.

The lower bound of the borderline region is defined by equation (6):

$$\text{ALPS SF} = 1.58 - 0.014\ \text{CMRR} \qquad (6)$$

Table 3 shows the performance of this model with the longwall data base.

The four remaining misclassifications can perhaps be explained by exceptional conditions. The two unsatisfactory cases which fell within the region of predicted satisfactory designs were also the only unsatisfactory cases in which <u>no</u> secondary support was installed in the tailgate. Conversely,

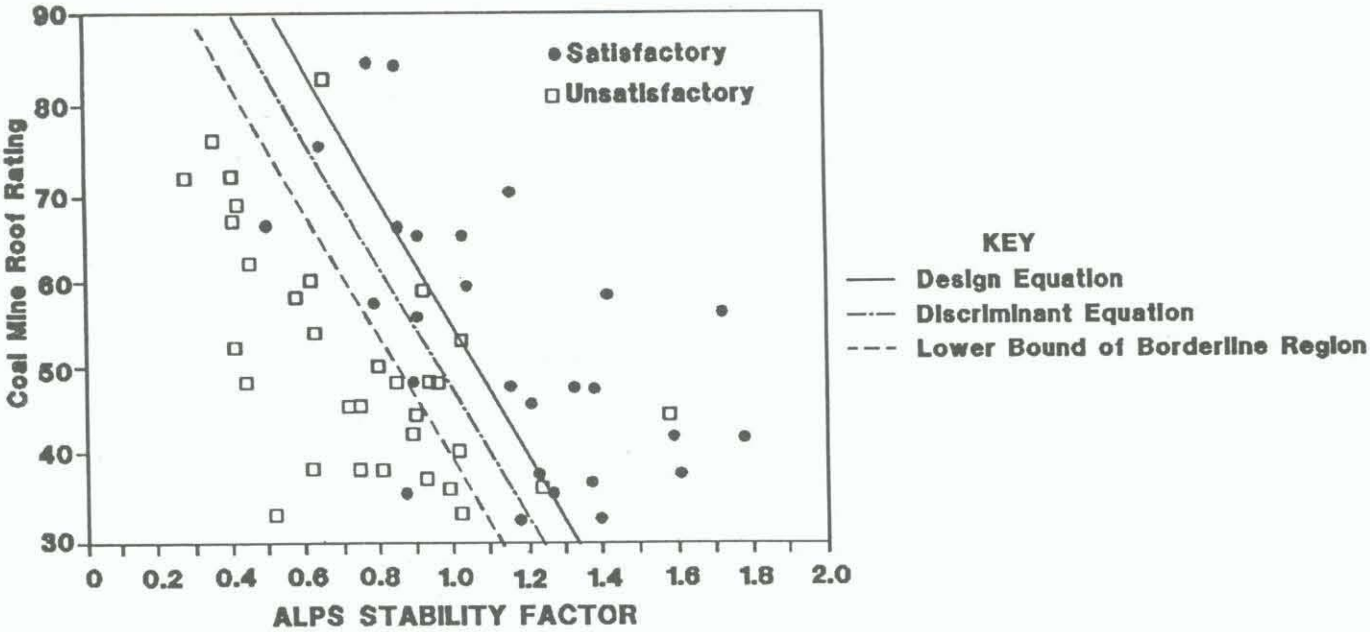

Figure 8–Scatter plot of case histories.

the two misclassified satisfactory cases used significantly more than the average amount of artificial support.

Table 3. Performance of the longwall design model

Region	Number of Successes	Number of Failures	Misclassification Rate
Satisfactory	25	2	7%
Borderline	3	3	-
Unsatisfactory	2	27	7%
Total	30	32	7%

Numerous other statistical analyses were performed on the complete data set on subsets. The most significant, and initially surprising, result was that including additional variables in the model did not improve the predictive capacity. The explanation is that primary support and entry width are correlated with the CMRR and the ALPS SF at a statistically significant level of "alpha"=0.05. Figure 9 shows the correlation between entry width and the CMRR. Of the 15 mines with weak roof (CMRR<45), all but one employed entries no more than 18 ft wide. Conversely, of 21 mines with CMRR>50, 20 used entry widths that were 18 ft or wider. It seems that mine operators have "naturally" adapted to weaker roof by using narrow entries. A similar, though less pronounced, correlation between primary support and the CMRR is evident in figure 10.

Figures 9 and 10 make clear that entry width and primary support <u>are</u> very important to gate entry stability. Including them in the model developed from this data set does not add predictive power, however, because their effects are already indirectly included in the CMRR term. An important

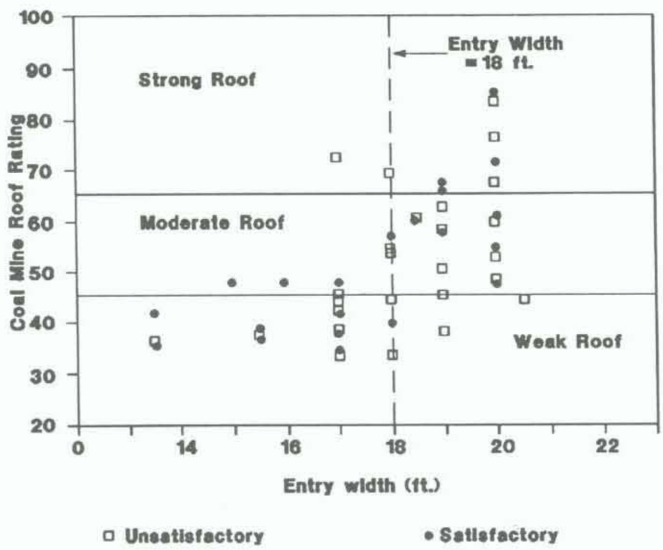

Figure 9–Entry width vs CMRR.

corollary is that the two-parameter design equation (equation (5)) assumes that the same entry width/primary support/CMRR correlations will hold in the future. A mine with weak roof that employed a 20 ft wide tailgate might encounter difficulties, even if the ALPS SF satisfied equation (5). To help evaluate the role of entry width and primary support explicitly, a four-parameter model was determined from discriminant analysis:

$$\text{ALPS SF}_R = 1.63 - 0.018\ \text{CMRR} + 0.024\ \text{We} - 0.72\ \text{PSUP} \quad (7)$$

The lower bound of the borderline region for the 4-parameter model is:

$$\text{ALPS SF} = 1.47 - 0.018\ \text{CMRR} + 0.024\ \text{We} - 0.72\ \text{PSUP} \quad (8)$$

The misclassification rate of this model, 7%, is equivalent to that of the two-parameter model.

None of the predictive models presented thus far have included supplemental support. The reason is that the unsatisfactory case histories in the data base tended to use more supplemental support than did the satisfactory cases (see figure 7). The

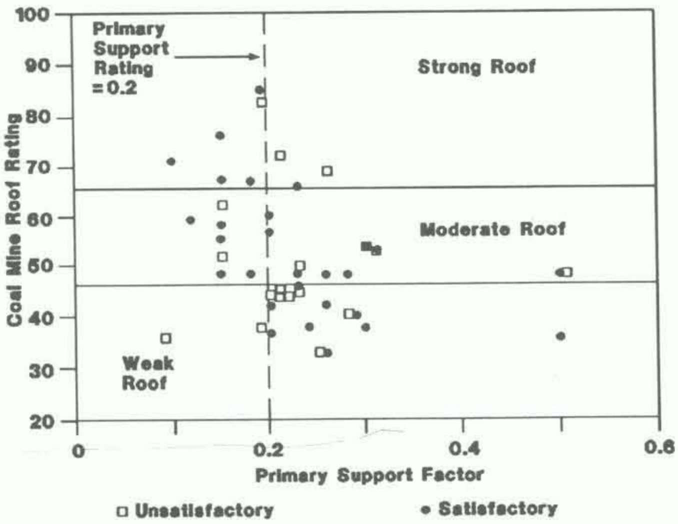

Figure 10—Primary support vs CMRR.

positive correlation between unsatisfactory conditions and heavy supplemental support arises because the installation of more cribbing is often the only available means of trying to save a troubled tailgate. In other words, the level of SSUP was often a consequence, not a cause, of the outcome. As a result, when SSUP was forced into a predictive model, the implication was that tailgate conditions would <u>improve</u> as tailgate support was <u>decreased</u>. Such a conclusion would obviously be incorrect. The inability of the data to help determine the role of supplemental support in tailgate performance points to a limitation of the back-calculation method. The data does suggest, however, that installing more supplemental support is not usually a satisfactory substitute for an adequate pillar design.

CONCLUSIONS

A comprehensive study of tailgate performance was conducted at 44 longwall mines. Statistical analysis of the data indicated that performance could be accurately predicted by the ALPS and the CMRR. The analysis also indicated that entry width and primary support are important, but they were not explicitly included in the predictive model because they were highly correlated in practice with the CMRR. The importance of floor quality and secondary support could not be determined from this data set.

The gate entry design methodology that resulted from the study should be a valuable aid to longwall mine planners. It is the first design methodology to focus on the tailgate entry itself, rather than on the chain pillars. More importantly, it is based on the scientific interpretation of the ground control experience obtained at more than half of all U.S. longwalls. The method thus makes the wealth of U.S. longwall experience available in a practical form.

The paper also illustrates the power of the empirical, back-calculation approach in deriving practical solutions to complex ground control problems. The CMRR makes a critical contribution by providing a meaningful, quantitative measure of the structural competence of bolted mine roof. Both back-calculation and the CMRR can be expected to figure prominently in future U.S. Bureau of Mines ground control research.

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