Design of primary roof support systems in US coal mines based on the analysis of roof fall rates

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ABSTRACT

Each year, about 2,000 falls of supported roof occur in the more than 800 underground U.S. coal mines. Therefore, to help improve the design of primary support systems, the National Institute for Occupational Safety and Health (NIOSH) conducted a nationwide study of roof falls in over 2,500 km of roadways at 37 coal mines. Information on the roof falls as well as other geotechnical, mining, geologic and roof bolting factors were collected and quantified. Then a multi variate statistical analysis was conducted on the data with the roof fall rate being the outcome variable. The results were used to derive preliminary design guidelines for predicting the roof bolt length, capacity, and pattern required to effectively reduce the roof fall rate. The equations are fairly limited by a relatively high statistical variance in the data. Also reported is a recent survey of U.S. roof bolt manufacturers that shows a significant change in bolt types used over the last ten years.

ZUSAMMENFASSUNG

Jedes Jahr erfolgen über 2000 Steinfälle in den mehr als 800 Kohlenbergwerken der USA. Um die Gestaltung des ersten Ausbausystems zu verbessern, hat daher das National Institute for Occupational Safety and Health (NIOSH) eine landesweite Untersuchung auf 37 Bergwerken mit mehr als 2500 km Strecke zum Steinfall durchgeführt. Dabei sind Informationen zu Steinfall, zur Geotechnik, Bergtechnik. Geologie und Ankertechnikfaktoren gesammelt und quantifiziert worden. Danach wurde eine statistische Multivarianzanalyse mit diesen Daten durchgeführt, die die Steinfallraten als Resultat ergaben. Die Ergebnisse wurden zur Ableitung vorläufiger Gestaltungsrichtlinien für die Bestimmung der Ankerlänge, Tragfähigkeit und des erforderlichen Schemas genutzt, um wirksam die Steinfallrate zu senken. Aufgrund der relativ hohen statistischen Abweichungen in den Daten sind die Formeln nur begrenzt anzuwenden.

Der Vortrag gibt ebenfalls einen Überblick über amerikanische Ankerhersteller, der einen wesentlichen Wandel der benutzten Ankertypen in den letzten zehn Jahren aufzeigt.

INTRODUCTION

In a typical year, there are approximately 2,000 roof falls reportable to the Mine Safety and Health Administration (MSHA) that are distributed through about 800 operating underground U.S. coal mines. Over 95 pct of these falls are reported because they go above the depth of the primary roof bolt anchorage. These falls impact mining operations but more importantly they create a hazard or a potential hazard to the underground miners.

This large number of roof falls highlight the present state of roof support systems and the state of the art in roof support system design that is used in the U.S. In general, there is a lack of an adequate and accepted support system design for primary roof support systems. The design of primary support systems is based on trial and error and on previous mining experience. To an extent this has worked but this method does not provide for a rational approach for improved design and the elimination or reduction of roof falls. Also, the primary support systems used in the U.S. coal mines can be considered relatively light compared to that used in some other countries [5]*. This may reflect the generally better ground control conditions seen in a majority of U.S. mines. However, when more difficult ground conditions are encountered problems in the form of increased roof instability and roof falls result. Further, changes in support system design and approaches to the roof support requiring more extensive primary support are often not acceptable because of the cost and impact on development mining.

Because of the large number of roof falls that occur each year, the National Institute for Occupational Safety and Health (NISOH) researchers decided that an empirical approach to the design of primary roof support systems could be developed for U. S coal mines where the roof falls could be considered as tests of the roof support system. This empirical approach would be based on a statistical analysis of parameters that affect the number of roof falls that occur. Because of the wide range of conditions and the large number of U.S. coal mines, this approach to be successful required a sufficient database as well as the identification and quantification of parameters relevant to the roof falls. Therefore, a national database on roof falls and relevant geotechnical parameters was developed. This paper discusses that database and the

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*The number in square brackets are related to the reference list at the end of the text.

statistical analysis used in evaluating that database as well as the development of preliminary design guidelines for primary roof support based on the database.

Another aspect of this investigation was the determination of the support types and usage in the U.S. coal mines. This information was obtained from a survey U.S. roof bolt manufacturers and is also presented in this paper.

TRENDS IN U.S. ROOF BOLT USAGE AND ROOF FALL RATES

To evaluate the roof bolt usage and trends in U.S. coal mines, NIOSH recently collected information from U.S. roof bolt manufacturers [2]. Figure 1 shows the results of this study for 1999. However, the data is not complete in every instance and the data are for all bolt usage, not just coal mines. Therefore the results shown in figure 1 should be considered estimates. In the figure, 5 bolt types are indicated: mechanical anchor, point anchor or speciality, torque tension, combination and the full grouted resin rebar bolts. Although this figure does not break down the bolt usage by commodity, the coal industry uses an estimated 80 pct to 85 pct of the reinforcement. Therefore, the percentage of the different types of bolts used are probably very representative of the distribution of the type of bolts used in coal mines.

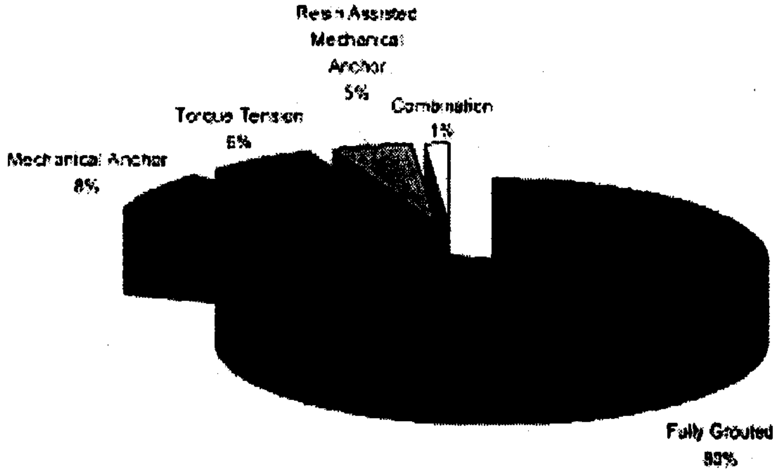


Figure 1: Percentage of a bolt type used in underground coal mines, 1999

In 1999, approximately 100 million bolts were used in the U.S. mining industry. Fully grouted resin rebar (headed) comprise about 80 pct of these bolts. For the grouted rebar, 80 pct were 1.6-cm diameter, # 5 rebar , and nearly all the remaining were a 1.9-cm diameter #6 rebar. The #5 rebar are usually installed in a 2.5 cm diameter hole. Mechanical anchor bolts comprise only about 8 pct of the supports.

Surveys on bolt usage were also conducted in 1988 and 1991 representing all mine types [10], [11]. Table 1 shows a comparison between the percentage of each bolt type for these years and 1999. An estimate of the distribution of bolt types for 1976 is also given in the table [4]. For the periods from 1976 to 1991 and again from 1991 to 1999, there has been a substantial shift away from mechanical anchor bolts to the fully grouted resin rebar.

Of interest is what if any changes in roof stability has occurred with this shift in the type of roof support over the last 10 or even 25 years. The number of reportable roof falls that occur each year can be used to assist in evaluating the overall affects of the change that may have occurred in roof stability with the changing bolt trend. However, to compare the data for each year, the roof fall rate based on production must be used. Figure 2 shows the roof fall rate per million tons of coal for the years from 1989 to 1998 for both longwall and room and pillar mining.

	Percentage			
Bolt Type	**1976**	**1988**	**1991**	**1999**
Mechanical Anchor	80	35.3	34.1	7.7
Fully Grouted	20	40	48.2	83.1
Torque Tension		3.5	4.6	5.6
Point Anchor		14.1	11.5[1]	2.3
Combination		3.5		1.3
Friction Stabilizer		2.4		
Other		1.2	1.5	
Total	100	100	100	100

[1] Includes both torque tension and combination bolts. The two systems were classified as point anchor tension rebar in the survey.

Table 1: **Bolt usage by type in US mines given in percent**

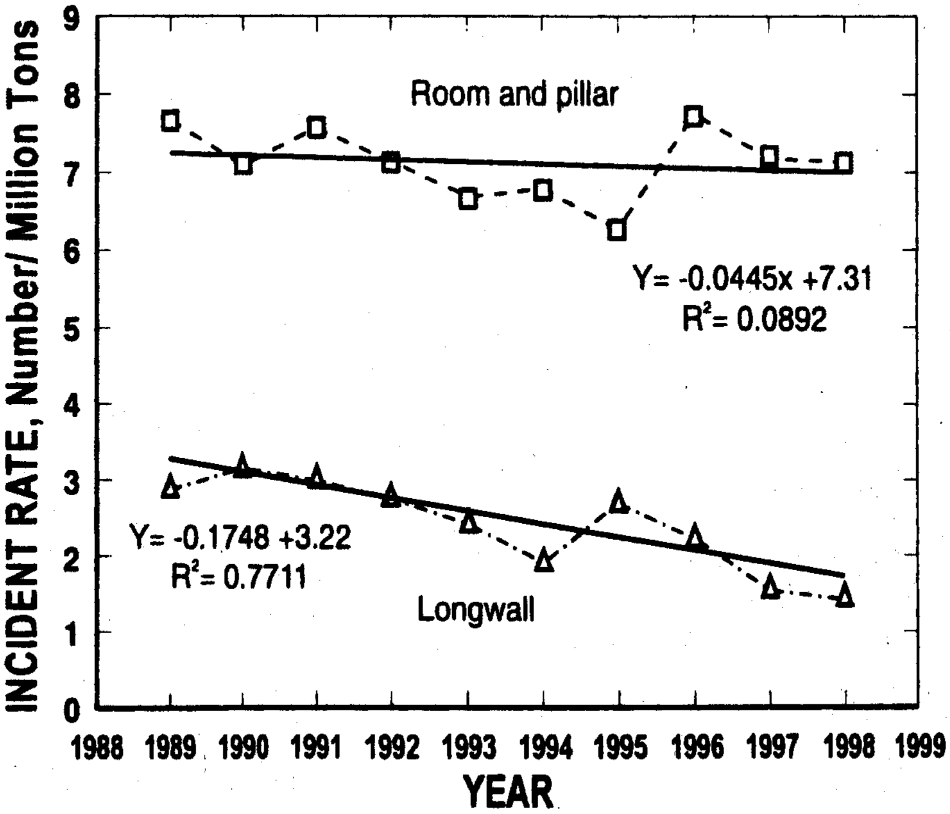


Figure 2: **Incident rate for reportable roof falls based on production from 1988 to 1999 for both longwall and room and pillar operations, including a regression analysis.**

For room and pillar mining, the roof fall rate trend from 1989 to 1998 can be evaluated by fitting a linear regression to the data. The results indicate that there has been no change in the roof fall rate for the last 10 years in room and pillar mines. For 1975 and 1976, the roof fall rate per million tons was 5.7 and 6.8, respectively.

For longwall mining, there was a decrease of about 1.6 roof falls per million tons or a reduction of about 50 pct in the roof fall rate between 1988 and 1998. However, other factors such as increased face width, increased seam height and a decrease in the number of gateroad entries have caused much of this change by reducing the amount of development mining [3], [9]. In 1990 about 26 pct of the production from a longwall mine was from development [1]. In 1999, an estimated 15 to 18 pct of production came from development. Essentially, any change the roof fall rate can be accounted by the changes in these parameters.

NATIONAL ROOF FALL DATABASE

To evaluate the performance of the primary roof support systems a national roof fall database was created from data obtained from visits to a number of U.S. coal mines [7]. Study mines were selected by computing the roof fall rate from the MSHA accident database. Drivage was estimated by converting annual production (excluding longwall production) into linear feet of advance, assuming an average seam height. Reportable roof falls were then divided by drivage to arrive at the roof fall rate (figure 3). Mines were then selected for study from this distribution to represent the entire range of roof stability from high, medium, to low roof fall rates. Mines were also selected to represent a wide range of roof geologies.

Through extensive interviews with mine operators and underground reconnaissance, NIOSH collected and quantified information on the number of roof falls, roof geology, depth, primary support parameters and opening geometry during each mine visit. Ultimately 41 mines in 10 states were visited, representing over 2,500 km of drivage in most of the major coal basins where underground mining occurs (figure 4).

At each of the mines, one or more "case histories" was collected. A case history was a portion of the mine that could be defined by a number of descriptive parameters and an outcome parameter. The database ultimately included information from 37 of the 41 mines, but actually contained 109 "cases." The outcome parameter was based on the number of reportable roof falls that occurred above the anchorage of the primary support in that portion of the mine.

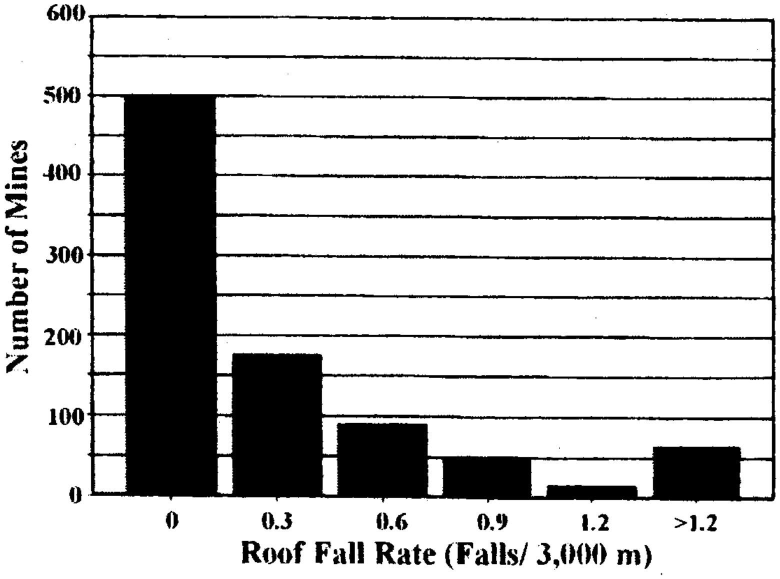


Figure 3: **Distribution of roof fall rates in U. S. coal Mines.**

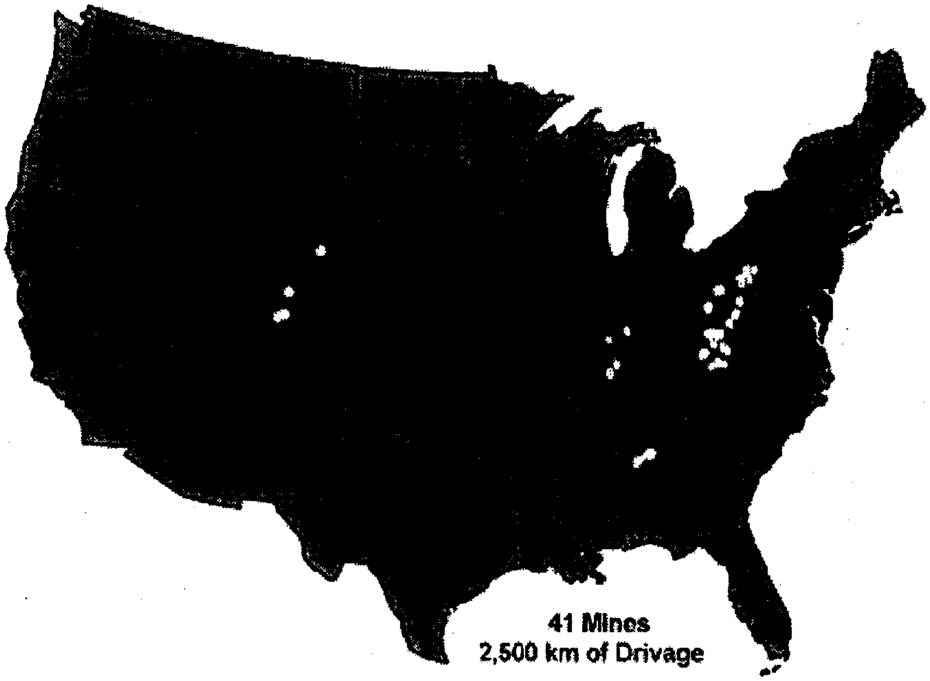


Figure 4: **Location on mines in study (41 mines and 2,500 km of drivage).**

In the study, geotechnical parameters that were evaluated and quantified included the immediate roof geology and the depth of cover. The roof geology was quantified by using the Coal Mine Roof Rating (CMRR). [8]. Mine design parameters that were collected included the entry width and the intersection span. The intersection span was calculated as the sum of the two intersection diagonals.

For the primary support, six bolt variables were quantified that included the bolt capacity (yield), bolt length, applied tension, grout column length, number of bolts per row and row spacing. A summary support variable was calculated from these parameters as a measure of the roof bolt density:

$$PRSUP_m = \frac{Lb * Nb * C}{Sb * We} \tag{1}$$

where Lb = Length of the bolt (m),
Nb = Number of bolts per row,
C = Capacity (kN),
Sb = Spacing between rows of bolts (m),
We = Entry width (m).

The roof fall rates were calculated as the outcome variable in each case. This rate was calculated based on the total number of roof falls divided by the total drivage for a given case. A 4 way intersection fall rate was also calculated based on the number of falls in the 4-way intersections divided by the total number of 4-way intersections. Figure 5 shows the roof fall rate distribution by number of cases for the study.

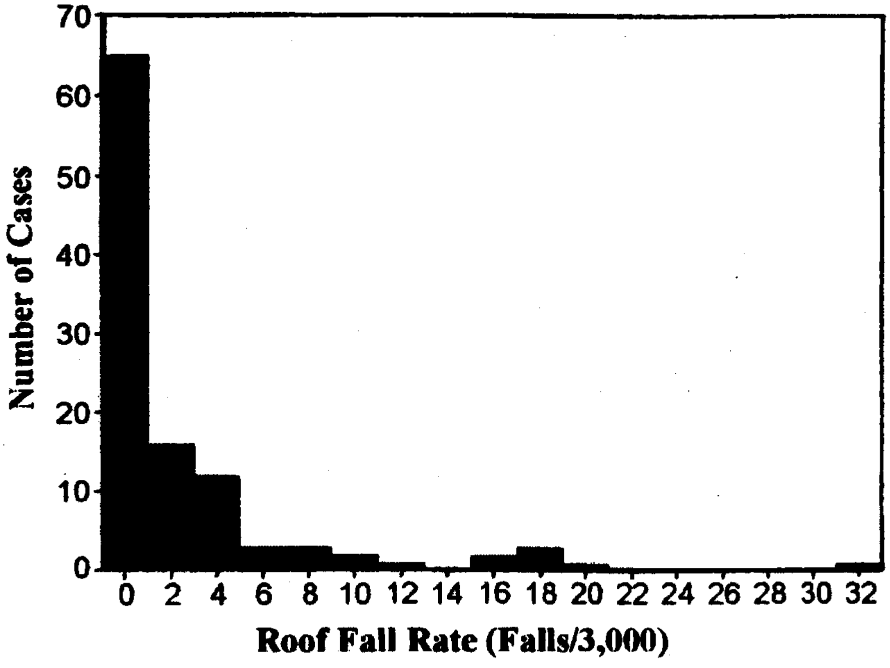


Figure 5: **Distribution of roof fall rates in the study sample**

STATISTICAL ANALYSIS

One of the goals of the study was to determine if there was a universal design equation which would utilize all or some of the geotechnical variables to predict the roof fall rate. A multivariate linear regression was performed which included all the significant geotechnical variables, including overburden, bolt length, grout length, density, entry width, CMRR, intersection span, tension, and bolt capacity (yield). The resultant regression equations at best could explain only 29.9 pct of the variation of the 4-way intersection fall rate and much less for the overall roof fall rate. In part this is caused by the uncontrolled nature of the experiments or cases where for each case a number of factors were varied. Another issue is the correlation between individual parameters.

Table 2 (Pearson correlation) is a test of the codependence of the geotechnical variables. There is only a significant correlation to roof fall rates for the CMRR, capacity ($PRSUP_m$, density) and grout index. The bolt capacity shows the strongest correlation to the roof fall rate. However, the relationship between bolt capacity and the roof fall rate is positive where the bolt capacity went up with the roof fall rate. This may be the result of higher capacity bolts being used when roof conditions deteriorate (increased roof fall rates) but the relationship is not useful in a design equation. The CMRR shows the highest correlation with the correct expected relationship (negative) to the roof fall rate. The lack of significant correlation between the roof fall rates and a number of the other factors results in a low overall fit to the data.

As expected there is correlation between several bolt parameters such as tension and grout indices, capacity and density, and bolt tension and capacity (table 2). Intersection span and entry width are naturally related. The CMRR and the bolt length are also related. As the roof gets stronger (higher CMRR), operators install shorter bolts. These types of intercorrelations of variables further confound the overall effect of any one variable on the roof fall rate.

Statistically, in the database, the correlation between the depth and fall rate is relatively weak though positive. However, it seems likely that in the data, depth of cover is an indirect measure, or surrogate, for horizontal stress level. Other studies show significant evidence of increasing horizontal stress with depth [6]. Horizontal stresses are seldom measured directly because of the difficulty and expense. Using this assumption, the case histories were divided into two groupings by depth of cover. The relationship between CMRR and $PRSUP_m$ is shown in figure 6a for shallow depth (less than 120 m) and in figure 6b for deeper cover (greater than 120 m). The original discriminate line that can be used to classify the data as well as a design equation line are shown on both figures. The discriminate line mis-classifies about 45 pct of the high fall rates for the shallow cover and about 30 pct of the high fall rates for the deeper cover. With the more conservative design equation line, the misclassification of the high fall rates is greatly reduced. The equation for this design line is presented later in the paper.

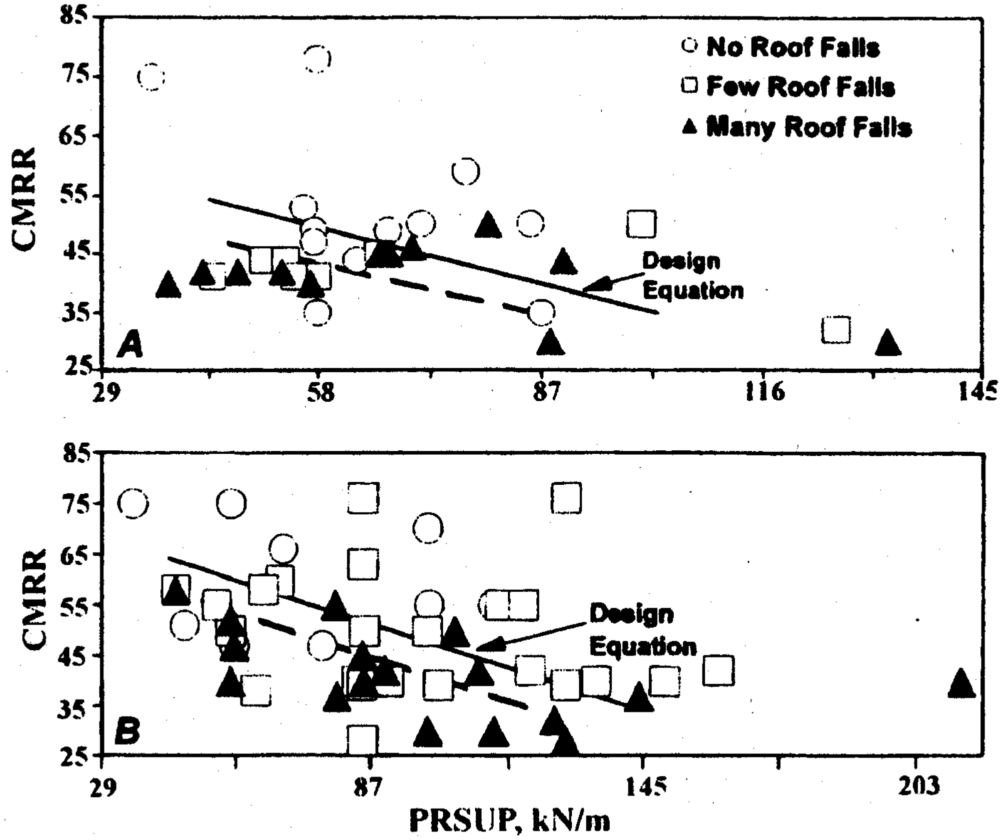
Geotechnical variable	CMRR	Bolt length selected, ft	Tension index	Grout index	Capacity, kips	Bolts per row	Row spacing, ft
CMRR	1.000	-.329	-.020	-.081	-.166	.037	-.147
Bolt length selected, ft	[1]-.329	1.000	.251	-.059	.134	-.116	.038
Tension index	-.020	.251	1.000	[1]-.811	.326	-.161	.070
Grout index	-.081	-.059	[1]-.811	1.000	-.196	.131	-.012
Capacity, kips	-.166	.134	[1].326	[2]-.196	1.000	-.178	-.084
Bolts per row	.037	-.116	-.161	.131	-.178	1.000	.000
Row spacing, ft	-.147	.038	.070	-.012	-.084	.000	1.000
Entry width, ft	.089	[2]-.215	-.107	.123	.086	.167	.041
Density	-.134	.161	.271	-.169	[1].907	-.076	-.375
PRSUP$_m$	-.282	.738	.356	-.176	.686	-.132	-.232
Intersection span, ft	[1].233	-.067	-.204	.124	.043	.042	-.089
Overburden index	[2].249	-.039	-.188	.127	[1].234	-.097	-.248
4-ways rate	-.257	.091	.217	-.192	.442	.079	.182

Geotechnical variable	Entry width, ft	Density	PRSUP$_m$	Intersection span, ft	Overburden index	4-ways rate	Roof fall rate
CMRR	.089	-.134	-.282	[1].233	[2].249	-.257	-.215
Bolt length selected, ft	-.215	.161	.738	-.067	-.039	.091	.105
Tension index	-.107	.271	.356	-.204	-.188	.217	.187
Grout index	.123	-.169	-.176	.124	.127	-.192	-.044
Capacity, kips	.086	[1].907	.686	.043	[1].234	.442	.322
Bolts per row	.167	-.076	-.132	.042	-.097	.079	.031
Row spacing, ft	.041	-.375	-.232	-.089	-.248	.182	.075
Entry width, ft	1.000	-.172	-.245	[1].359	[1].124	.063	-.011
Density	-.172	1.000	.767	.016	[2].248	.341	.294
PRSUP$_m$	-.245	.767	1.000	-.049	.154	.273	.266
Intersection span, ft	[1].359	-.016	-.049	1.000	[1].600	.060	-.053
Overburden index	[1].124	[2].248	.154	[1].600	1.000	.089	.004
4-ways rate	.063	.341	.273	.060	.089	1.000	[1].661
Roof fall rate	-.215	.105	.187	-.044	.322	.031	.075

[1] Correlation is significant at the 0.01 level (2-tailed).

[2] Correlation is significant at the 0.05 level (2-tailed).

Table 2: Correlation between geotechnical variables in the study



A, shallow cover (depth < 120m)

B, deep cover (depth > 120m)

Design equations for selecting bolt pattern and capacity (PRSUP $_m$) is a solid line and the original discriminate line used to fit the data is a dashed line.

Figure 6: **Relationship between PRSUP $_m$, CMRR and roof fall rate.**

An alternative to the multivariate statistical analysis was to conduct an analysis using "paired data" from individual mines. In these cases, only a single variable changes.

The most successful of these analyses was on roof bolt length. From the large data set, 13 pairs of data where two different lengths of roof bolts were used at the same mine were extracted. The roof bolt lengths differed by at least 0.3 m in the pairs. The data show that in 11 of 13 cases, the roof fall rate was less with the longer bolt (figure. 7). The roof fall rates for the paired data range from 0.0 to 18.3/3,000 and the decrease in roof fall rate (avg. 65 pct, n=13) with increasing bolt length holds true even in the high roof fall rate range. So, through a range of CMRR (30-58), an increase of at least one foot in bolt length can be expected to result in a decrease in the roof fall rate.

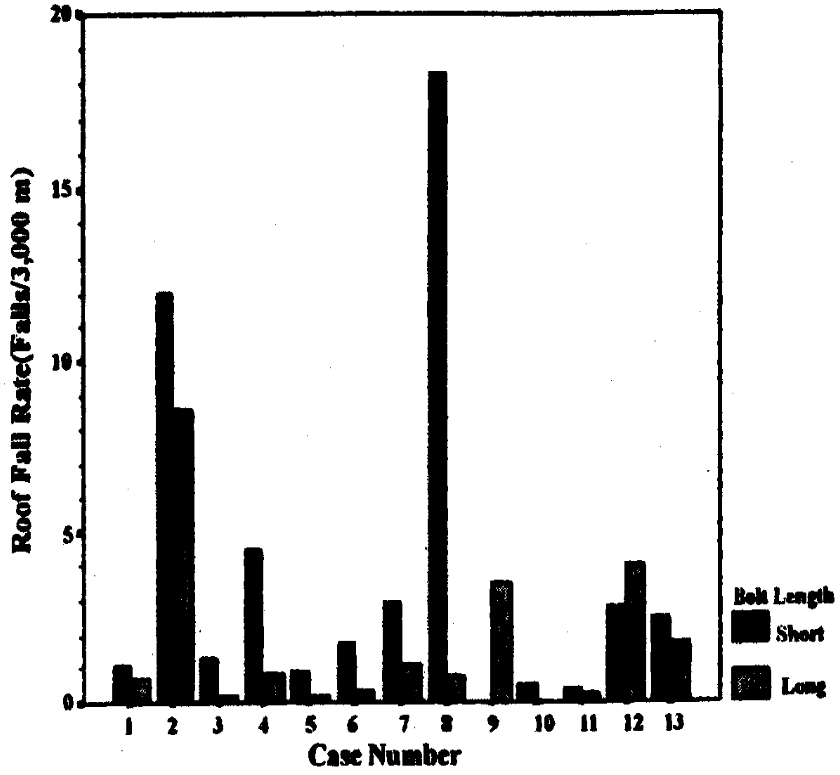


Figure 7: **Paired cases of long and short bolts showing benefit of long bolts and decreasing roof fall rates.**

The relationship between CMRR and intersection span was also analyzed. The data was partitioned by 4-way intersection fall rate into low, moderate and high. Additionally, only fully grouted bolts were used in the analysis. By logistic regression a line (solid) was fitted to the data and presented in figure 8. There are no cases with high roof fall rates which fall below the regression line. Based on the data there is also a likelihood that intersection falls will be reduced by a decrease in intersection span. Also shown on the figure is a less conservative regression line (dashed) that might be an appropriate first approximation of the intersection span.

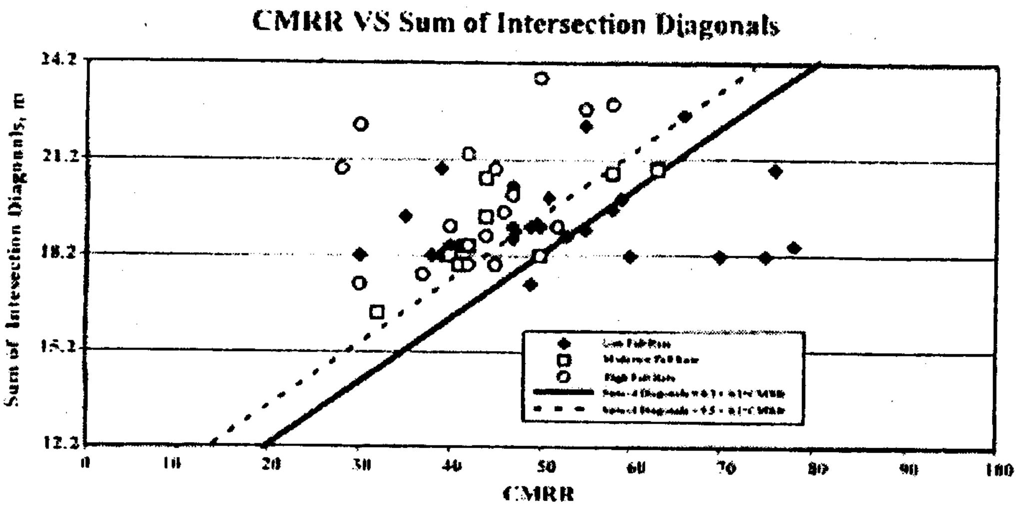


Figure 8: Relationship between CMRR, sum of intersection diagonals and roof fall rate.

Intersection diagonals are usually related to the entry width. The data were studied to determine t typical intersection spans that are encountered underground. Figure 9 shows the mean for t database of the sum-of-the-diagonals for 4.9, 5.5, and 6.1 m entries. It also shows that in dee mines, the sum-of-the-diagonals were 0.9-1.2 m wider than in the shallow mines, with the sa entry width probably because of greater rib sloughage.

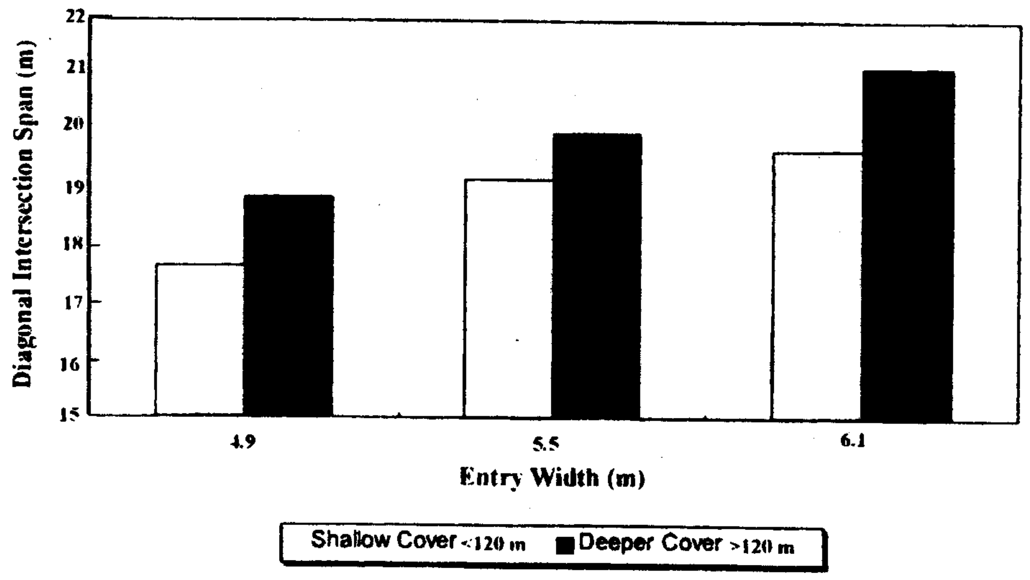


Figure 9: The effect of overburden on sum of intersection diagonals

GUIDELINES FOR ROOF BOLT DESIGN

Although it was not possible to develop a universal design equation with this statistical study of roof falls , some other relationships were established and found to be of value. It was not surprising that the geology, represented by the CMRR, was the most important variable. Although statistically, the effect of the depth of cover were relatively weak, with all else equal, deeper mines were more likely to have high roof fall rates. Horizontal stress could not be measured directly, but since it is known that the intensity of horizontal stress tends to increase with depth, the inference is that the depth of cover is a surrogate for the stress level. When the data were separated into a shallow cover group (<120 m) and a deeper cover group (>120 m), bolt design equations were determined for each. Based on these alternative relationships, a set of preliminary guidelines and limited design equations were developed from this investigation.

Following are step-by-step guidelines:

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 level.* It is unusual for stress measurements to be available, so the design procedures use the depth of cover as a rough estimator. However, horizontal stress can sometimes be intensified by stream valleys or by driving in an unfavorable orientation. Roof support may need to be increased in these areas.

3. *Evaluate mining-induced stress.* Vertical, and sometimes horizontal, stresses may also be intensified by retreat mining or multiple seam interactions. These areas are likely to require supplemental support.

4. *Determine the intersection span.* An equation was derived from the data which suggests that the appropriate diagonal intersection span (I_s) which is the average of the two diagonals is approximately:

$$I_s = \frac{95 + \left(0.2 * CMRR\right)}{2} \tag{2}$$

If the CMRR > 65, it should be set equal to 65 in equation 2. The intersection span can also be estimated from the entry width using table 3 where the typical spans are based on the field data. As table 3 shows, the field data indicated that for the same entry width, spans at deep cover (depth > 130 m) exceeded the shallow cover spans by an average of 0.6 m due to pillar sloughing.

Entry width, m	Ideal span, m	Typical diagonal intersection spans	
		Shallow cover, m	Deep cover, m
4.9	7.0	8.9	9.5
5.5	7.8	9.5	10.1
6.2	8.7	9.8	10.5

NOTE: The "ideal span" is determined by applying the Pythagorean theorem ($a^2 + b^2 = c^2$). "Typical" spans are based on actual measurements [7].

Table 3: Diagonal intersection spans (I_s)

5. *Determine the bolt length.* Where the roof geology is such that the suspension mode is appropriate, the bolt length should be selected to give adequate anchorage in the strong rock. For the beam building mode, a bolt length formula was derived by modifying the Unal [12] rock load height equation. The intersection span was substituted for the entry width, a depth factor was added, and then the constant was adjusted to fit the data:

$$L_B \text{Å}\ 0.12\left(I_s\right)\log_{10}(3.25H)\left[\frac{100\ \square\ CMRR}{100}\right] \tag{3}$$

where I_s = diagonal intersection span (m)

H = depth of cover (m).

6. ***Determine bolt pattern and capacity:*** As has already been stated, the data could not determine which bolt parameter was most important. Therefore, the design variable is $PRSUP_m$ which includes both, plus the bolt length is given by equation 1.

The suggested value of $PRSUP_m$ (metric) for shallow cover is determined as:

$$PRSUP_m = 225 - 3.33\ CMRR \qquad (4a)$$

and for deeper cover:

$$PRSUP_m = 258 - 3.33\ CMRR \qquad (4b)$$

Figure 6 shows these equations, together with the field data from which they were derived. The design equations are slightly more conservative than the discriminant equations on which they are based. 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 <40 at shallow cover and <45-50 at deeper cover, high roof fall rates could be encountered, even with high roof bolt densities. It should also be noted that these equations have been derived to reduce the risk of roof falls in intersections. In some circumstances, it may be possible to reduce the level of support between intersections. Finally, the minimum recommended $PRSUP_m$ is approximately 43.5.

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

8. *Monitoring:* The installation of telltales or other simple extensometers should be considered for critical intersections so that, if it becomes necessary, supplemental support can be installed in a timely fashion.

CONCLUSIONS

With the significant change in the type of bolts used in U.S. coal mines, there has been little change in the roof fall rate that can be linked to this trend for either the room and pillar or longwall mining. However, there are many other aspects to the design of a roof support system other than the support type while in many situations the roof falls may have been prevented only with the addition of supplemental support. Also, this is a general analysis where a number of factors may have changed including the number of mines, roof condition and accuracy of reporting roof falls though the affects of the roof support type did not overcome these factors.

Collecting and analyzing the national roof fall database that included information and cases from 37 mines did not lead to the development of a universal design equation for primary roof support systems in U.S. coal mines. There were a number of factors that confounded the results including the lack of experimental control where between most cases more than one factor was varied while only a few of the parameters investigated had a significant impact on the roof fall rate. However useful relationships were developed regarding the influence of specific factors such as bolt length, intersection span and mining depth. The mining depth was used as a surrogate for the horizontal stress.

Based on these specific relationships, preliminary guidelines for the design of primary support systems were developed. Formulas were presented that may be used to select appropriate intersection spans, bolt lengths and bolt capacity/patterns. The formulas require a determination of the roof quality (CMRR) and the stress level (depth of cover). The equations though, should be used with caution because the data used to derive them were highly scattered. However, these preliminary guidelines provide a start to the development of a more rational approach to roof support design out of the results of trial and error methods and of mining experience for roof support design that is still within the constraints of the U.S. mining industry.

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