Development of a Statistical-Analytical Approach for Assessing Coal Bump Potential

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ABSTRACT

Coal bumps are defined as sudden failures of rock and coal near entries that are of such a magnitude that they expel large amounts of material into a mine opening. Coal bumps are influenced by geologic conditions, the geometric design of coal mine excavations, and the sequence and rate of extraction. Researchers from private industry and the National Institute for Occupational Safety and Health have studied mechanisms of violent failure and have identified individual factors that contribute to coal bumps. In an attempt to develop tools for assessing coal bump potential, the authors initiated a comprehensive study using information from 25 case studies undertaken in U.S. mines. Multiple linear regression and numerical modeling analyses were used to identify the most significant variables contributing to coal bumps (excluding bumps related to fault-slip).

Twenty-five geological, geometrical, and geomechanical variables were considered initially. The most important of these variables were then identified as (1) energy as calculated using the mechanical properties of the strata, depth of overburden, and joint density, (2) mining method, (3) pillar factor of safety, and (4) stress gradient and yield characteristics.

INTRODUCTION

Coal bumps are not only a safety concern in U.S. coal mines, but have also affected safety and resource recovery in other countries, including Germany, England, Poland, France, Mexico, China, India and South Africa. Gradual or progressive failure, which is commonly experienced in coal mines, has less effect on mining continuity and safety and is generally controlled by timely scaling, cleaning, and bolting.

Researchers from private industry, government, and academia have studied the mechanisms of coal bumps *(1-4)* and mine seismicity *(5-6)* and have identified individual factors that contribute to coal bump occurrence, including rapid changes in stress over a short distance or time, stiffness and strength of near-seam strata, and dynamic effects associated with failure of surrounding rocks. In an attempt to identify the most significant variables contributing to coal bumps, the authors analyzed information from 25 sites in mines in Colorado, Utah, Virginia, and Kentucky.

RESEARCH RATIONALE

The need for an analytical methodology for assessing coal bumps has been indicated in conference proceedings *(4)* and by accident statistics gathered by the Mine Safety and Health Administration (MSHA).

Underground coal mines have a higher incidence of accidents relative to surface coal mines (figure 1). Of particular concern is the potential for an increased number of bumps in mines using the longwall mining method, especially because trends indicate more extensive use of this method. Energy Information Administration data show that longwall production has risen from 20% in 1983 to 45% in 1995 as a percentage of all underground coal production *(7)*. Although room-and-pillar operations are more prone to bumps, it is anticipated that as easily recovered reserves are mined, the trend will be toward deeper mines and those in less stable geologic settings. Both conditions are known to increase bump potential. In addition, new advances in longwall mining technology, such as longer panel length (up to 5,500 m in a mine in Colorado), are creating the need to better understand bump potential so that the problem may be addressed in new mine designs.

MSHA statistics for 1978 through 1995 were analyzed by National Institute for Occupational Safety and Health (NIOSH) personnel using the U.S. Bureau of Mines' Accident Data Analysis (ADA) program *(8)*. No field in the MSHA database specifically indicates injuries resulting from coal bumps, so ADA code categories designated as "fall of roof," "fall of rib-side-face," "falling material," or "entrapment" were compared to the remain-

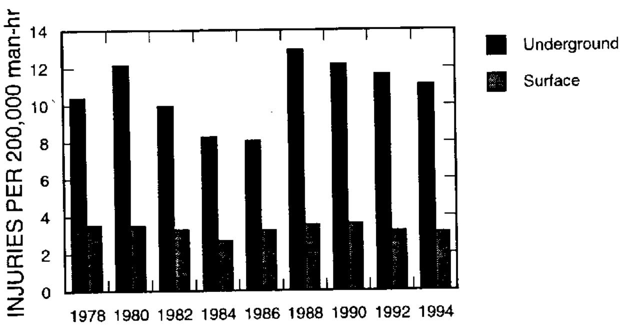

Figure 1.—Accident incident rates in underground and surface coal mines in the United States, 1978-1994

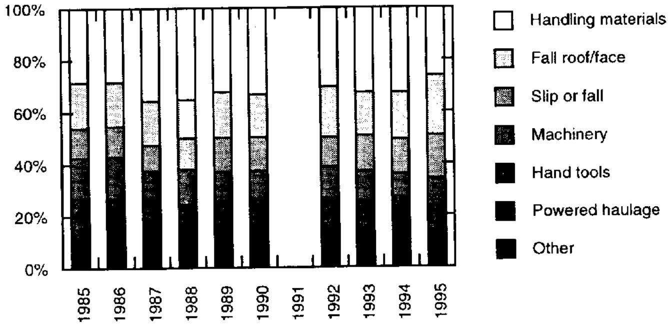

Figure 2.—Accidents in U.S. longwall mines by category, 1985-1995

ing accident injury categories (figure 2). "Materials handling" appeared as the largest contributor to accidents, but the great diversity of causes of these accidents would require a significantly larger research effort than would addressing the second largest contributor, "falls of roof and rib."

Coal bumps are of primary concern to miner safety in relation to falls of roof and rib. These categories do not specifically identify coal bumps, but provide a basis for understanding the level of problems associated with ground control that may be resolved with methods described in this paper.

FACTORS INFLUENCING COAL BUMPS

In an attempt to identify the most significant factors that contribute to coal bumps, the authors analyzed geologic, geotechnical, and in-mine monitoring data from 25 sites in 6 room-and-pillar coal mines and 19 longwall mines in Colorado, Utah, Virginia, and Kentucky. Both computational and statistical techniques were used in the analyses. The first step involved the identification of 25 geologic, geometric, and geomechanical variables that might have had the potential to contribute to coal bump occurrence (tables 1, 2, and 3). Typical frequency histograms are presented in figures 3, 4, and 5 and show the range of coverage provided by the selected variables.

In situ strength was estimated in 12 coal seams where uniaxial compressive strength exceeded 14 MPa. Allowances were made for favorable local yielding characteristics of mine roof and floor in reducing damage severity. Pillar and face factors of safety were calculated using displacement-discontinuity methods for specific geometries.

Some of the variables used in the first step of the analysis are described below.

- *Mechanical property values.* Mechanical property values for roof, floor, and coal seams were originally obtained through laboratory tests of samples of near-seam strata. The in situ strength of coal seams was estimated using procedures suggested by Maleki *(9)*.

Horizontal stresses. Maximum and minimum secondary horizontal stresses were originally obtained using overcoring stress measurements from one to three boreholes *(10)*.

Pillar and face factors of safety. Pillar and face factors of safety were obtained in individual case studies using both two- and three-dimensional, displacement-discontinuity techniques *(11-13)*. Results were compared with field data when such data were available.

Energy release. Energy release from a potential seismic event was calculated using both boundary-element modeling and analytical formulations as suggested by Wu and Karafakis *(14)* to estimate energy accumulation in both roof and coal, and energy release *(6)* in terms of Richter magnitude (M_l) using the following formula:

$$1.5\, M_l = A \times \log (E) - 11.8,$$

where E = total accumulated energy in roof and seam, ergs,

and A = coefficient depending on joint density,

Damage rating. A damage rating to assess the severity of coal bumps was developed by and based on the authors' observations of physical damage to face equipment and/or injury to personnel, as well as observations by other researchers as cited in the literature. Damage levels were assigned a ranking between 0 and 3. Level 1 signifies interruptions in mining operations while level 3 signifies damage to both face equipment and injuries to mine personnel.

Roof beam thickness. Roof beam thicknesses varied between 1.5 and 12 m. The thickness chosen for evaluation was the strongest beam of the near-seam strata located between 1 and 4 times the total seam thickness in the immediate mine roof. Although there is some evidence that massive upper strata have contributed to coal bumps in some mines *(4)*, their influence was not directly evaluated in this study because of the lack of geological and mechanical property data.

Local yield characteristics. Local yield characteristics of immediate roof and floor strata influence coal pillar failure and the severity of coal bumps. This factor varied from 0 to 2, where 0 indicates insignificant yielding in the roof and floor and 2 indicates favorable, gradual yielding.

Stress gradients. Stress gradients varied from 0 to 2, depending on whether or not mining proceeded toward an area of high stress (resulting either from previous mining or rapid changes in topography) and/or abnormal geologic conditions such as occasionally found near faults or grabens.

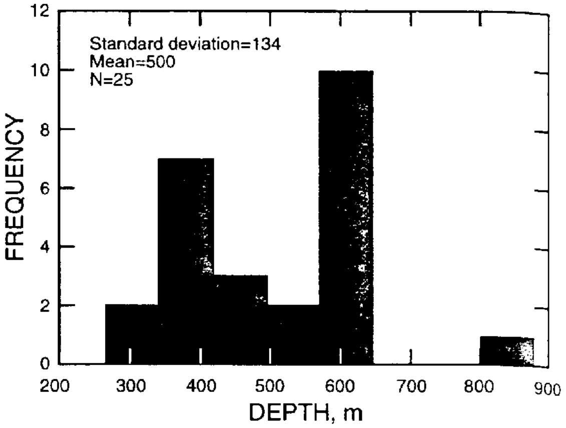

Figure 3.—Frequency diagram for depth

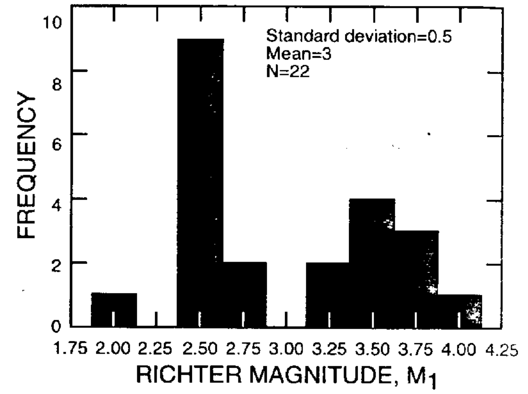

Figure 4.—Frequency diagram for released energy

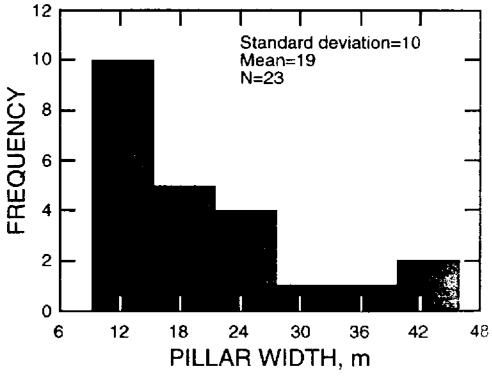

Figure 5.—Frequency diagram for pillar width

Table 1.—Statistical summary of geologic variables.

Variable	Mean	Standard deviation	Range	No. of cases
Joint sets	1.4	0.6	1-3	25
Cleat sets	1.8	0.4	1-2	25
Inseam partings	1	0.9	0-3	21
Joint spacing, m	6.7	5.5	1.5-15	24
Rock Quality Designation	77	18	50-100	15
Depth, m	500	134	275-820	25
Roof beam thickness, m	4.3	3.3	1.5-12.2	25
Young's modulus, coal, MPa	3310	830	2410-4620	25
Young's modulus, roof and floor, MPa	20,700	6900	6900-33,000	25
Uniaxial strength, MPa	22	5.2	13.8-32	25
Uniaxial strength, roof and floor, MPa	100	23.8	55-150	25
Max. horizontal stress, MPa	13	7.6	0.7-26	25
Interacting seams	1.2	0.4	1-3	25
Local yield characteristics	0.8		0-2	25

Table 2.—Statistical summary of geometric variables.

Variable	Mean	Standard deviation	Range	No. of cases
Pillar width, m	19	0	9-42	23
Pillar height, m	2.5	0.3	1.7-3	25
Entry span, m	5.8	0.3	5.5-6	25
Barrier pillar width, m	50	27	15-73	6
Face width, m	167	40	61-244	25
Mining method	1.2	0.4	1-2	25
Stress gradient	0.9	0.6	0-2	25

Table 3.—Statistical summary of geomechanical variables

Variable	Mean	Standard deviation	Range	No. of cases
Pillar factor of safety	0.8	0.3	0.5-1.4	23
Face factor of safety	0.9	0.2	0.6-1.5	22
Energy (M_1)	3	0.5	2-4	22
Damage	1.4	1	0-3	25

Bivariate Correlations and Data Reduction

In the next step of the analysis, "damage" was denoted as the dependent variable against which all other variables were tested to determine which of these variables were effective in deducing bump potential.

Based on preliminary bivariate correlations among all geologic, geometric, and geomechanical variables, the number of variables was reduced by combining some variables into new ones and eliminating those that were intrinsically interrelated. In addition, the cause-and-effect *(15)* structure in the data was identified, helping to tailor the procedures for multiple regression analysis using forward stepwise inclusion of variables. The new variables were as follows:

Pqratio Ratio of maximum principal horizontal stress (P) to minimum stress (Q).

Strenrc Ratio of uniaxial compressive strength of the roof to the coal.

Jointrf Joint spacing times roof beam thickness divided by mining height.

Table 4.—Bivariate correlation coefficients between damage and selected other variables

Significant variables[1]	Coefficient	Insignificant variables	Coefficient
Damage	1	Pillar width	0.1
Energy	0.65	Ratio of P to Q	0.1
Gradyield	-0.57	Young's modulus of roof to coal	0.07
Jointrf	0.52		
Pillar factor of safety	-0.44		
Uniaxial strength of roof to coal	0.36		
Face factor of safety	-0.33		
No. interacting seams	0.33		
Panel width to depth	-0.31		
Mining method	0.26		

[1] Two-tailed tests

Gradyield Ratio of roof and floor yield characteristics to stress gradient.

Panelwd Ratio of panel width to depth.

Youngrc Ratio of Young's modulus of the roof to the seam.

Table 4 presents the bivariate correlation coefficients between the damage variable and selected geologic and geometric variables. Energy (M_I), face factor of safety, stress gradient, pillar factor of safety, joint spacing, and uniaxial compressive strength of roof to coal were the most significant. Other variables were poorly correlated with damage, including the ratio of P to Q, pillar width, and Young's modulus of roof to coal.

Multiple Linear Regression Analysis

There are two methods used by engineers and researchers as tools to help predict conditions in the future: statistical and computational. Starfield and Cundall *(16)* identify rock mechanics problems as "data-limited," that is, one seldom knows enough about a rock mass to use computational models unambiguously. Statistical methods, on the other hand, are uniquely capable of being applied where there are good data but a limited understanding of certain natural phenomena, such as coal bumps.

In this study, the authors combined the strength of both methods to identify important variables and to develop predictive capabilities. Computational methods have been used to assess the influence of a combination of geometric variables into single variables, such as pillar factor of safety and released energy. This was very useful for increasing goodness-of-fit and enhancing multiple regression coefficients. Statistical methods were used to identify significant variables, to build confidence intervals, and so forth.

In the final step in the analysis, a multilinear regression procedure was used, which involved entering the independent variables one at a time (table 4) into an equation using a forward selection methodology *(15)*. In this method, the variable having the largest correlation with the dependant variable is entered into the equation. If a variable fails to meet entry requirements, it is not included in the equation. If it does meet the criteria, the second variable with the highest partial correlation will be selected and tested for entering into the equation. This procedure is very desirable when there is a cause-and-effect structure among the variables. An example of the cause-and-effect relationship is shown when a greater depth reduces pillar factor of safety, contributes to an accumulation of energy, and ultimately results in greater damage. Using the above procedures, any hidden relationship between depth and pillar factor of safety, energy, and damage is evaluated and taken into account during each step of the analysis.

Several geomechanical variables (table 3) were initially used as dependent variables. The multiple correlation coefficient (R), which is a measure of goodness-of-fit, for the last step was 0.87.

The assumptions of linear regression analysis were tested and found to be valid by an analysis of variance, F-statistics, and a plot of standardized residuals (figure 6) *(15)*. Residual plots did not indicate the need for inclusion of nonlinear terms because there was no special pattern in the residuals.

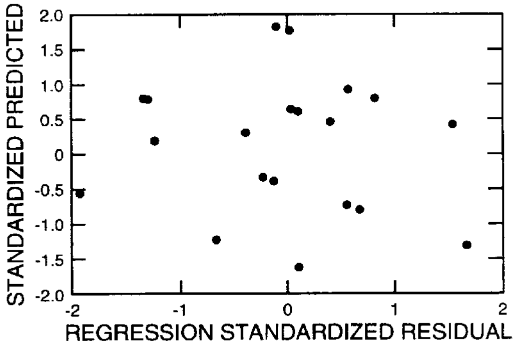

Figure 6.—Standardized scatterplot for dependent variable, "damage"

Table 5.—Standardized regression coefficients and statistical significance

Variable	Standardized coefficient	T-significance
Energy	0.28	0.049
Pillar factor of safety	-0.34	0.011
Mining method	0.26	0.064
Gradyield	-0.55	0.0004
Constant	NA	0.234

NA Not applicable.

Important Variables Contributing to Bump-Prone Conditions

Based on an examination of standardized regression coefficients (table 5), the following variables best explain variations in damage and thus statistically have the most significant influence on coal bump potential.

- *Energy.* This variable includes the effects of the mechanical properties of the roof and coal, depth, stress field, and joint density, and thus directly relates to damage.

- *Mining method.* Mining method has a bearing on coal bump potential. The room-and-pillar method is associated with a higher degree of damage than is longwall mining.

- *Pillar factor of safety.* Gate pillar geometry contributes directly to the severity of damage.

- *Stress gradient and yield characteristics.* Mining toward areas of high stress creates a potential for coal bumps, while localized yielding roof and floor conditions encourage gradual failure, which reduces the amount of damage.

CONCLUSIONS

A statistical-analytical approach was used to identify the most significant factors contributing to coal bumps. Twenty-five variables were initially considered (mechanical properties of strata, stress fields, face and pillar factors of safety, joint spacings, mining methods, and stress gradients, among others). Pillar and face factors of safety were calculated using displacement-discontinuity methods for specific geometries. The most important variables contributing to coal bumps were identified as (1) energy as calculated using the mechanical properties of the strata, depth of overburden, and joint density, (2) mining method, (3) pillar factor of safety, and (4) stress gradient and yield characteristics.

By combining the strength of both computational and statistical methods, the authors are making significant progress in predicting coal bump potential and for building confidence intervals. Since the method relies on an extensive amount of geotechnical data from 25 case studies in U.S. coal mines, it will be helpful to mine planners in selecting relevant variables for assessing bump-prone conditions, which in turn will result in safer designs for coal mines.

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