A HYBRID STATISTICAL-ANALYTICAL METHOD FOR ASSESSING VIOLENT FAILURE IN U.S. COAL MINES

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ABSTRACT

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 government agencies around the world have studied mechanisms of violent failure and have identified individual factors that contribute to coal bumps. To develop predictive 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 of geological and mining conditions were used to identify the most significant factors contributing to stress bumps in coal mines.

Twenty-five factors were considered initially, including mechanical properties of strata, stress fields, face and pillar factors of safety, joint spacings, mining methods, and stress gradients. In situ strength was estimated in 12 coal seams where uniaxial compressive strength exceeded 2,000 psi. 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.

This work identified the most important variables contributing to coal bumps. These are (1) mechanical properties of strata, including local yield characteristics of a mine roof and floor, (2) gate pillar factors of safety, (3) roof beam thickness, joint spacing, and stiffness characteristics, which influence released energy, (4) stress gradients associated with the approach of mining to areas of higher stress concentrations, and (5) the mining method. By combining the strength of both analytical and statistical methods, new capabilities were developed for predicting coal bump potential and for building confidence intervals on expected damage.

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INTRODUCTION

Coal bumps are sudden failures near mine entries that are of such a magnitude that they expel large amounts of coal and rock into the face area. These destructive events have resulted in fatalities and injuries to underground mine workers in the United States. Coal bumps are not only a safety concern in U.S. coal mines, but also have affected safety and resource recovery in other countries, including Germany, the United Kingdom, Poland, France, Mexico, the People's Republic of China, India, and the Republic of 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 [Crouch and Fairhurst 1973; Salamon 1984; Babcock and Bickel 1984; Iannacchione and Zelanko 1994; Maleki et al. 1995] and mine seismicity [Arabasz et al. 1997; McGarr 1984]. Seismic events are generated as mining activities change the stress field; they often result in either crushing of coal measure rocks (strain bump) or shearing of asperities along geological discontinuities (fault-slip). Sudden collapse of overburden rocks [Maleki 1981, 1995; Pechmann et al. 1995] has also been associated with large seismic events, triggering coal bumps in marginally stable pillars.

To differentiate between stable and violent failure of rocks, Crouch and Fairhurst [1973] and Salamon [1984] proposed a comparison of postpeak stiffness of a coal seam and the loading system (mine roof and floor). Linkov [1992] proposed an energy criterion emphasizing that violent failure results when kinetic energy is liberated above that consumed during fracturing of the coal. In practice, it is difficult to estimate postpeak stiffness of coal for any geometry [Maleki 1995] or to calculate fracture energies. This led some practitioners to use either stored elastic strain energy or changes in energy release [Cook et al. 1966] to evaluate the likelihood of violent failure.

In view of limitations for unambiguous calculations of postpeak stiffness, many researchers have attempted to identify individual factors influencing coal bumps using the data from single-field measurement programs. Using such data analyses and in the absence of rigorous statistical treatment of all case studies, it is very difficult to identify geotechnical factors that influence coal bumps, to assign confidence intervals, and to develop predictive capabilities.

To identify the most significant factors contributing to coal bumps, the authors analyzed geometric and geologic data using both computational and statistical analysis techniques. The data included information on both violent and nonviolent failures from 25 mine sites in Colorado, Utah, Virginia, and Kentucky, where detailed geotechnical and in-mine monitoring results were available.

DATA ANALYSIS

The first step in developing a statistical model was to create suitable numerical values that express geologic, geometric, and geomechanical conditions. The second step was to reduce the number of independent variables by combining some existing variables into new categories and identify highly correlated independent variables. Reducing the number of variables is needed when there are too many variables to relate to the number of data points. The presence of highly correlatable variables influences which procedures are selected for multiple regression analyses. The third step was to develop a multivariate regression model and identify significant factors that contribute to coal bumps.

Some geologic variables were readily available in numerical format; other geomechanical factors had to be calculated using numerical and analytical techniques. These activities involved:

(1) Obtaining mechanical property values for roof, floor, and coal seams through laboratory tests of samples of near-seam strata. In situ strength of coal seams was estimated using the procedures suggested by Maleki [1992].

(2) Calculating both maximum and minimum secondary horizontal stresses using overcoring stress measurements from one to three boreholes [Bickel 1993].

(3) Calculating pillar and face factors of safety for individual case studies using both two- and three-dimensional boundary-element techniques [Maleki 1990; Crouch 1976; Zipf 1993]. Results were compared with field data when such data were available.

(4) Calculating energy release from a potential seismic event using boundary-element modeling and analytical formulations suggested by Wu and Karfakis [1994] for estimating energy accumulation in both roof and coal and energy release [McGarr 1984] in terms of Richter magnitude (M_l) using the following formula:

$$1.5\, M_l = a \times \log(E) - 11.8, \qquad (1)$$

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

and a = coefficient depending on joint density.

(5) Assessing the severity of coal bumps using a damage rating developed by and based on the authors' observations of physical damage to face equipment and/or injury to mine 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; level 3 signifies damages to both face equipment and injuries to mine personnel.

The first step of the analyses involved the identification of 25 geologic, geometric, and geomechanical variables that had the potential to contribute to coal bump occurrence. Both violent (bump-prone) and nonviolent conditions in 6 room-and-pillar mines and 19 longwall mines were studied. Tables 1-3 summarize these data and include averages, ranges, and standard deviations. Typical frequency histograms are presented in figures 1-3 and indicate that these case studies provided good coverage of the variables.

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
In-seam partings.	1	0.9	0-3	21
Joint spacing, ft.	22	18	5-50	24
Rock Quality Designation (RQD).	77	18	50-100	15
Depth, ft.	1,640	440	900-2,700	25
Roof beam thickness, ft	14	11	5-40	25
Young's modulus, million psi	0.4-8	0.12	0.35-0.67	25
Young's modulus of roof and floor, million psi	3	1	1-4.8	25
Uniaxial strength, psi	3,240	750	2,000-4,600	25
Uniaxial strength of roof and floor, psi	14,700	3,460	8,000-22,000	25
Maximum horizontal stress, psi	1,920	1,100	100-3,800	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, ft.	63	34	30-140	23
Pillar height, ft	8.3	1	5.5-10	25
Entry span, ft.	19	1	18-20	25
Barrier pillar width, ft	165	90	50-240	6
Face width, ft.	550	130	200-800	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 (MJ)	3	0.5	2-4	22
Damage	1.4	1	0-3	25

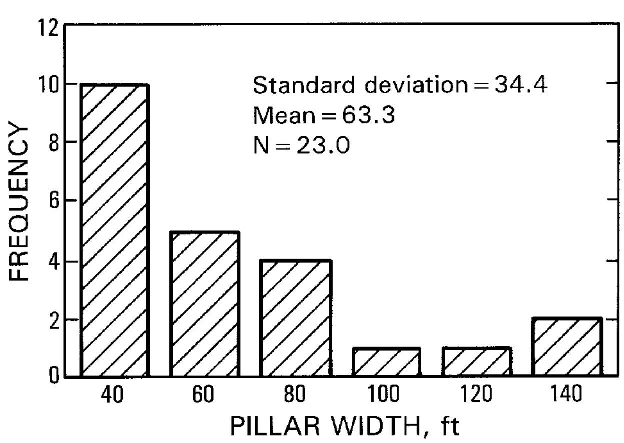

Figure 1.—Histogram frequency diagram for pillar width.

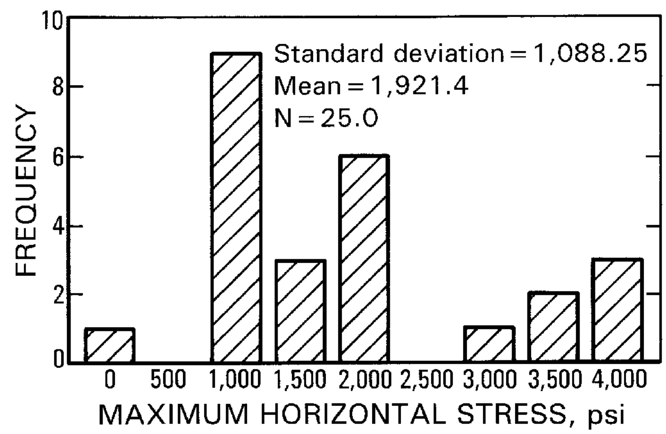

Figure 2.—Histogram frequency diagram for the maxiumum principal stress.

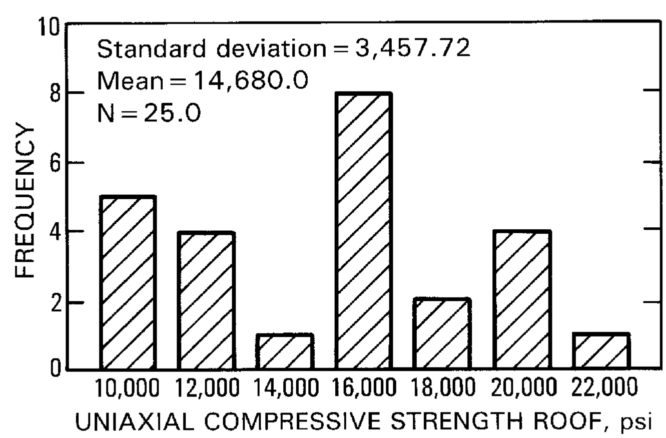

Figure 3.—Histogram frequency diagram for the uniaxial compressive strength of roof.

Roof beam thickness ranged from 5 to 40 ft. The beam chosen for the evaluation was the strongest beam of the near-seam strata located between one and four times the seam thickness in the mine roof. Although there is some evidence that massive upper strata have contributed to coal bumps in some mines [Maleki 1995], their influence was not directly evaluated in this study because of the lack of geological and mechanical property data.

Local yield characteristics of the 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 in both roof and floor.

Stress gradients varied from 0 to 2, depending on whether mining proceeded toward an area of high stress (resulting from previous mining) and/or abnormal geologic conditions, such as those occasionally found near faults or grabens.

BIVARIATE CORRELATIONS AND DATA REDUCTION

The second step in the analyses involved correlations and variable reductions. 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. In addition, the cause-and-effect structure in the data was identified, helping to tailor the procedures for multiple regression analysis using forward stepwise inclusion of dependent variables, as described later in this paper. The new variables were as follows:

Pqratio	Ratio of maximum principal horizontal stress (P) to minimum stress (Q)
Strenrc	The ratio of uniaxial compressive strength of the roof to the coal
Jointrf	Joint spacing × roof beam thickness ÷ mining height
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 variable "damage" and selected geologic and geometric variables. Energy, 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.

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

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

[1]Two-tailed tests.

MULTIPLE LINEAR REGRESSION ANALYSIS

The last step in developing predictive capabilities was to complete multiple regression analyses using the numerical values obtained through measurements and numerical modeling. This is a hybrid approach where the strengths of both statistical and computational methods are combined. 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, build confidence intervals, etc.

The multilinear regression procedure consisted of entering the independent variables one at a time into the equation using a forward selection methodology. 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 meets the criteria, the second variable with the highest partial correlation is 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 damage variable, however, resulted in the highest multiple regression coefficient. 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 4). Residual plot did not indicate the need to include nonlinear terms because there was no special pattern in the residuals.

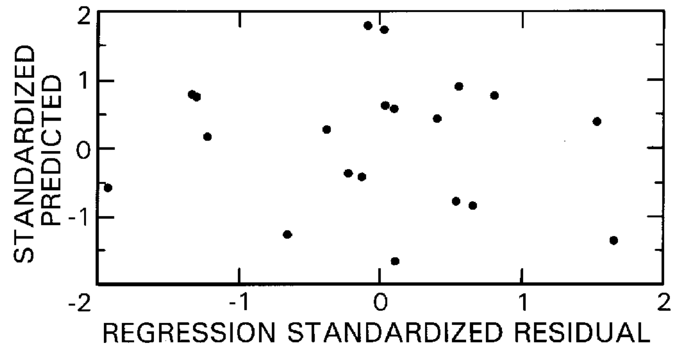

Figure 4.CStandardized scatterplot for the dependent variable "damage."

IMPORTANT VARIABLES CONTRIBUTING TO BUMP-PRONE CONDITIONS

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

$ *Energy release*.**C**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.

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

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

$ *Stress gradient and yield characteristics*.**C**Mining toward areas of high stress creates a potential for coal bumps; localized yielding roof and floor conditions encourage gradual failure, reducing the severity of damage.

Table 5.CStandardized regression coefficients and statistical significance

Variable	Standardized coefficient	T-significance
Energy	0.28	0.049
Pillar factor of safety. . .	−0.34	0.011
Method.	0.26	0.064
Gradyield.	−0.55	0.0004
Constant.	NAp	0.234

NAp Not applicable.

CONCLUSIONS

A hybrid statistical-analytical approach was developed to identify the most significant factors contributing to coal bumps. By combining the strength of both analytical and statistical methods, the authors achieved new capabilities for predicting coal bump potential and for building confidence intervals on expected damage. Because the method relies on an extensive amount of geotechnical data from 25 case studies in U.S. coal mines, it should be helpful to mine planners in identifying bump-prone conditions. This in turn will result in safer designs for coal mines.

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