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ScienceDirect

Procedia Engineering 191 (2017) 82 – 88

Procedia Engineering

www.elsevier.com/locate/procedia

Symposium of the International Society for Rock Mechanics

Analysis of Geomechanical Factors Affecting Rock Bursts in Sedimentary Rock Formations

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Abstract

Rock bursts are defined as sudden, violent failures of rock mass that are of such a magnitude that they expel large amounts of coal and rock into the face area during longwall or pillar extraction in sedimentary rocks. In an attempt to develop tools for assessing stress bump potential, the first author initiated a comprehensive study using site specific information from 25 case studies undertaken in U.S. mines. This effort builds on an initial study while expanding the data base and including additional variables and analyses. 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 (mechanical properties of strata, stress fields, face and pillar factors of safety, joint spacings, mining methods, and stress gradients, among others). 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 in case studies having experienced both violent and nonviolent failures.This work identified the most important variables contributing to coal bumps and violent failure of near seam strata. These are [1] mechanical properties of strata, including local yield characteristics of a mine roof and floor, [2] gateroad geometry and/or gate pillar factors of safety, [3] stress gradients associated with the approach of mining to areas of higher stress concentrations such as abutment stresses from multiple seam mining, and [4] roof beam thickness, joint spacing, and stiffness characteristics, which influence cave conditions and dynamic loading. The latter variables, combined together to form a new variable called "strata rigidity-cavability", reflect some of the most important aspects of violent failure, i.e. having massive and stiff near-seam stratigraphic units capable of absorbing high strain energy, forming high stress on mine structures and poor cave conditions, and thus the potential for dynamic loads.

Peer-review under responsibility of the organizing committee of EUROCK 2017

Keywords: Rock burst; coal bump; seismicity; multi-variable regression; cavability

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Peer-review under responsibility of the organizing committee of EUROCK 2017
doi:10.1016/j.proeng.2017.05.157

1. Introduction

Rock bursts are defined as sudden, violent failures of rock mass that are of such a magnitude that they expel large amounts of coal and rock into the face area during longwall or pillar extraction in sedimentary rocks. Typical ejected material varies from 5-100 tons filling up the pan at the longwall face. Rock bursts and coal bumps are an important safety concern in U.S. coal mines. However, U.S. experiences reflect just one part of what is really an international problem; Safety and resource recovery have been affected in many 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.

The occurrence and mechanism of these failures have been studied for decades in both hard rocks and coal mines [1–5]. While unstable slip along geologic discontinuities is known to be associated with many large seismic events in hard rock mines [6], many coal bump events in the U.S. coal fields are related to the failure of marginally stable structures under high stress conditions (stress bumps) triggered by dynamic energy resulting from failure of stiff enclosing stratigraphic units in the overburden and underburden [7, 8]. These stress bumps (the focus of these investigations) are influenced by geologic conditions, the geometric design of coal mine excavations, and the sequence of extraction.

In spite of significant progress in understanding the mechanics of violent failure within the last fifty years, there is still an urgent need to develop practical, predictive techniques for assessing coal bump potential. Cook [9] suggested comparing the stiffness of the testing frame to post-failure modulus of coal samples to determine whether a test sample will fail violently or nonviolently. Salamon [2] proposed a criterion for assessing mine stability (not coal bump potential) using the concept of mine stiffness. For a discussion of other criterion including Energy Release Rate, the interested reader is referred to Maleki [10]. Many practitioners have suggested simple indices for assessing coal bump potential using either near seam mechanical properties or energy concepts. For instance, Maleki [5] proposed a strata stiffness index, the ratio of strata stiffness-strength to that of the coal seam, for identifying bump-prone conditions. However because coal bumps are influenced by a number of geologic and mining factors, these indices have limited usefulness in a preliminary evaluation of burst-prone nature of mining properties.

Advancements in numerical modeling has made it possible to back analyze both static and dynamic (i.e., excess shear stress [11]) conditions leading to violent failure. However, most applications are challenged by poor availability of complete data sets regarding geologic, geometric and geotechnical data which include post-failure behavior of coal pillars and cave conditions [7, 12, 13]. Statistical techniques, on the other hand, are powerful tools for studying failure mechanisms where there is good data but poor understanding of the contributing factors.

By combing the strength of computational and statistical techniques, it is possible to advance the understanding of violent failure mechanisms through identification of the significant factors affecting the failure. This is the approach undertaken in this research. This research utilizes the first author’s observations and back analyses of violent failure in twenty five US operations including both single- and multiple-seam operations in flat lying and dipping seams. Although not all data could be collected at the exact location of failures, the existing data base is the closest to the source of the event as feasible. Where possible, field activities included coring and mechanical property testing of rocks with stress measurements within 50-ft of coal bump events. Back analyses of stress conditions from case studies provided additional insights regarding poor, cyclic cave conditions [7, 8] influenced by stiff strata.

2. Data Analysis

Twenty-five geologic, geometric, and geomechanical factors were first identified as having the potential to contribute to coal bump occurrence. Table 1 lists these variables excluding averages, ranges, and standard deviations due to limitations in this publication size; these case studies provided good coverage of the variables [6].

Table 1. Listing of geologic, geometric and geomechanical variables.

Geologic	Geometric	Geomechanical
Joint sets, number of	Pillar width, m	Pillar factor of safety
Cleat sets	Pillar height, m	Face factor of safety
Inseam partings	Entry span, m	Energy (M_1)
Joint spacing in strata, m	Barrier pillar width, m	Damage
Rock Quality Designation of roof/floor	Face width, m	
Depth, m	Mining method	
Roof beam thickness, m	Stress gradient	
Young's modulus coal, GPa		
Young's modulus of roof and floor, GPa		
Uniaxial strength of roof and floor, MPa		
Uniaxial strength of coal, MPa		
Max. horizontal stress, MPa		
Interacting seams, number of		
Local yield characteristics of roof/floor		

These variables include:

- Thickness of the roof beam: Roof beam thickness varied between 1.5-12 m and was chosen to be the strongest member of the near-seam strata, located between 1 and 4 times seam thickness in the mine roof. Although there is strong evidence [11], that massive upper strata have contributed to seismicity and possibly coal bumps in some mines [8], their influence was not directly evaluated in this study because of a consideration of reduced impacts because of attenuation of energy with distance.
- Near-seam strata and seam properties: Mechanical properties of roof, floor, and coal seams were obtained through laboratory tests of samples of near-seam strata. In situ strength of coal seams was estimated using the procedures suggested by Maleki [13] including both confinement-controlled and structurally controlled coal seams.
- Horizontal stress: Both maximum and minimum secondary horizontal stresses were obtained using overcoring stress measurements from one to three boreholes [14].
- Local yield characteristics: 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.
- Mining method: Both violent (bump-prone) and nonviolent conditions in six room-and-pillar mines and 19 longwall mines were studied.
- Stress gradients: Stress gradients near the rock burst varied from 0 to 2, depending on whether or not mining proceeded toward an area of high stress (resulting from previous mining or approaching topographic highs) and/or abnormal geologic conditions, such as occasionally found near faults or grabens. Stress gradient of zero reflected mining in virgin stress conditions and two reflected mining toward most severe multiple-seam solid-gob crossings [21]
- Factors of safety: Pillar and face factors of safety (strength to stress ratio) were calculated for individual cases studies using both two- and three-dimensional, boundary-element techniques [15, 16]. 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 suggested by Wu and Karafakis [17] for estimating energy accumulation in both roof and coal and energy release [18] in terms of Richter magnitude ($M_{1)}$ using the following formula:

$$1.5\, M_1 = A \times \log(E) - 11.8,$$

Where E - total accumulated energy in roof and seam, erg, and A - coefficient depending on joint density and expected cave conditions [7].

- Damage (severity): A damage rating was developed based on authors' observations of physical damage and citations by other researchers [6]. Damage levels varied between 0 and 3, depending on whether or not the result was significant damage to equipment and miners. Level 1 signifies interruptions in mining operations while level 3 signifies damage to both face equipment and injuries to mine personnel. The latter is considered significant because injuries often result where there is frequent damage to face equipment requiring presence of maintenance personnel for fixing the problem.

3. Bivariate Correlations and Data Reduction

The statistical analyses were first completed on the entire data set followed by data reduction and the introduction of new variables. The bivariate correlation of the entire data matrix, for instance, identified the following significant variables as related to "damage". Correlation was found to be significant at 0.05 level (2-tail) between the following variables and "damage", Yield (localized yielding of the roof and floor), Joint spacing, Barrier pillar width, Energy, Uniaxial strength of roof, Roof beam thickness. These findings are all logical, pointing to the significance of strong near-seam stratigraphic members in accumulating energy, joint spacing affecting regular cave conditions and load transference to the face, and the importance of barrier pillars in reducing inter-panel cantilevering as identified in the case studies [7, 8].

Following these 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 [19] 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	The 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* number of joints.
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 2 presents the bivariate correlation coefficients between the variable "damage" and selected geologic and geometric variables. Energy (M_1), stress gradient/yielding characteristics of mine floor, face/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 2. Bivariate correlation coefficients between damage and selected variables.

Significant variables[1]	Coefficient	Insignificant variables	Coefficient
Damage	1	Mining method	0.26
Energy	0.65	Ratio of P to Q	0.1
Gradyield	-0.57	Young's modulus roof to coal	0.07
Jointrf	0.52	Pillar width	0.1
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		

[1] Two-tailed tests at .05 level

4. Initial 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 [20] 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 rock bursts.

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.

The multilinear regression procedure consisted of entering the independent variables one at a time into the equation using a forward selection methodology [19]. In this method, the variable having the largest correlation with the dependent 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, pillar factor of safety, energy and damage is evaluated and taken into account during every 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 (R2), which is a measure of goodness-of-fit, for the last step was 0.816.

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 [19]. The residual plot did not indicate the need for inclusion of nonlinear terms because there was no special pattern in the residuals [6].

5. Important Variables Contributing to Burst-Prone Conditions

Based on an examination of standardized regression coefficients (table 3), the following variables best explain the variations in damage and thus statistically have the most significant influence on coal bump potential.

- Energy release. This variable includes the effects of the mechanical properties of the roof and coal, depth, stress field, and joint density/cave conditions, and thus directly relates to damage.
- Method. Mining method has a bearing on coal bump potential. The room-and-pillar method is associated with a higher degree of risk 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, reducing the severity of damage particularly in properly designed mining systems using narrow "yield" pillars with limited confined core [21].

Table 3. Standardized 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	NA	0.234

NA Not applicable.

6. Additional Multiple Regression Analysis

In search of improving regression analyses and reducing computational requirements, new variables were added in the final analyses. These variables were based on field observations and structural considerations; they better reflected rigidity of near-seam strata and their potential for suddenly releasing the stored energy and forming a poor cave dependent on joint spacing. The intent was to exclude the energy calculations while still explaining variability in the outcome with sufficient regression coefficient. These variables were;

Rigidity Beam thickness* Young's modulus
RigidityJS Rigidity* Joint spacing, also referred to as "rigidity-cavability" index

Based on an examination of standardized regression coefficients (table 4), the following variables best explain the variations in damage and thus statistically have the most significant influence on violent failure potential. Themultiple correlation coefficient (R2), which is a measure of goodness-of-fit, for the last step was slightly reduced to 0.778 as the "energy" variable was intentionally excluded from the analyses. Thus, these additional analyses did not improve the goodness-of-fit. However, they were helpful in identifying a new "rigidity/cavability" index that is simpler to calculate and is correlated with the "damage".

- RigidityJS: This variable includes the effects of the stiffness of the roof beam, and the resistance of near seam strata to gradual caving and release of energy depending on joint spacing, and thus directly relates to damage.
- Method: Mining method has a bearing on coal bump potential. The room-and-pillar method is associated with a higher degree of risk than is longwall mining.
- Ratio of maximum to minimum horizontal stress: Implications are that there is higher coal bump potential in a hydrostatic stress field because of the negative standardized coefficient. This variable contributes to the statistical fit but in these authors' opinion it may not have real world relation to violent failure.
- Number of seams: Mining toward areas of high stress create a potential for coal bumps, a condition most experienced in multiple seam mines where mining in one seam approaches the solid-gob boundary in previously mined seams [21].

Table 4. Standardized regression coefficients and statistical significance for the additional analyses.

Variable	Standardized coefficient	T-significance
RigidityJS	0.565	0.000
Method	0.742	0.000
Pqratio	-0.601	0.020
No of seams	0.337	0.024
Constant	NA	0.005

NA Not applicable.

7. Conclusions

A statistical-analytical approach was used to identify the most significant factors contributing to coal bumps. By combining the strength of both computational and statistical methods, this study achieved new capabilities for 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 should be helpful to mine planners in identifying bump-prone conditions and in improving health and safety standards.

Important variables include Energy release, Pillar factor of safety, Mining method, Stress gradient and Yielding characteristics of immediate roof and floor. Other analyses reinforce the significance of beam rigidity and lack of jointing on promoting a poor cave, facilitating the sudden release of energy; this creates a potential for dynamic loading, forcing any marginally stable structures toward violent failure. The newly identified "rigidity-cavability" index reflects these conditions and effectively correlates with damage. In view of difficulties in assessing both the potential for violent failure and cavability of rocks [7], this is considered practically important.

Future research is focused on inclusion of complementary additional case studies to verify existing results and improve the understanding of violent failure.

Acknowledgements

This research was partially supported by a grant from the United States National Institute of Occupational Safety (NIOSH). It benefitted from numerous investigations implemented by the USBM, Maleki Technologies Inc. and mining companies.

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