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Applying robust design to study the effects of stratigraphic characteristics on brittle failure and bump potential in a coal mine

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ABSTRACT

Bumps and other types of dynamic failure have been a persistent, worldwide problem in the underground coal mining industry, spanning decades. For example, in just five states in the U.S. from 1983 to 2014, there were 388 reportable bumps. Despite significant advances in mine design tools and mining practices, these events continue to occur. Many conditions have been associated with bump potential, such as the presence of stiff units in the local geology. The effect of a stiff sandstone unit on the potential for coal bumps depends on the location of the stiff unit in the stratigraphic column, the relative stiffness and strength of other structural members, and stress concentrations caused by mining. This study describes the results of a robust design to consider the impact of different lithologic risk factors impacting dynamic failure risk. Because the inherent variability of stratigraphic characteristics in sedimentary formations, such as thickness, engineering material properties, and location, is significant and the number of influential parameters in determining a parametric study is large, it is impractical to consider every simulation case by varying each parameter individually. Therefore, to save time and honor the statistical distributions of the parameters, it is necessary to develop a robust design to collect sufficient sample data and develop a statistical analysis method to draw accurate conclusions from the collected data. In this study, orthogonal arrays, which were developed using the robust design, are used to define the combination of the (a) thickness of a stiff sandstone inserted on the top and bottom of a coal seam in a massive shale mine roof and floor, (b) location of the stiff sandstone inserted on the top and bottom of the coal seam, and (c) material properties of the stiff sandstone and contacts as interfaces using the 3-dimensional numerical model, FLAC3D. After completion of the numerical experiments, statistical and multivariate analysis are performed using the calculated results from the orthogonal arrays to analyze the effect of these variables. As a consequence, the impact of each of the parameters on the potential for bumps is quantitatively classified in terms of a normalized intensity of plastic dissipated energy. By multiple regression, the intensity of plastic dissipated energy and migration of the risk from the roof to the floor via the pillars is predicted based on the value of the variables. The results demonstrate and suggest a possible capability to predict the bump potential in a given rock mass adjacent to the underground excavations and pillars. Assessing the risk of bumps is important to preventing fatalities and injuries resulting from bumps.

1. Introduction

This paper is developed as part of an effort by the National Institute for Occupational Safety and Health (NIOSH) to identify risk factors associated with bumps in order to prevent fatalities and accidents in highly stressed, bump-prone ground conditions. The main objective of this study is to demonstrate the application of a robust design procedure by using factors affecting coal bumps based on the previous works by Lawson et al. as an example application [1,2]. The type of catastrophic failure in coal mines known as dynamic failure—also colloquially referred to as bumps, bounces, bursts, and others—is one of the most challenging and persistent safety and engineering problems associated with coal mining in highly stressed conditions. Coal pillar bursts involve the sudden expulsion of coal and rock into the mine opening. These events occur when stresses in a coal pillar, left for support in underground workings, exceed the critical strength capacity of the pillar, causing it to rupture without warning. Agapito and Goodrich investigate five common stress factors responsible for bump problems in

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Utah—depth of cover, sandstone channels, arching of strata, faults, and coal seam thickness—and find that these factors can concentrate or relieve stress to affect the potential for bumps [3]. In addition, floor failure in a coal mine often inhibits longwall mining when large displacement of floor strata, known as floor heave, interferes with travel, access, ventilation, and equipment. Aggson investigates floor heave in West Virginia where an underclay is relatively strong and high horizontal stress persists, and reported that the failure mode manifests mainly by buckling rather than by plastic flow [4]. Lawson et al. conduct a study of the effect of a stiff sandstone member in the near-seam overburden on the potential for shock bumps [1,2]. They find that the effect of the stiff sandstone unit on large-scale roof failure and potential for coal bumps depends on the location of the stiff unit in the stratigraphic column, the relative stiffness and strength of other structural members, and stress concentrations caused by mining. A correlation between bumping behavior and the ratio of stiff-to-compliant strata is observed empirically through examination of core logs, and it is shown that the relative influence of a stiff beam member is heavily impacted by the nature of the surrounding strata. However, a concise and broadly applicable relationship of coal bump potential to the ratio of the overall stiff-to-compliant strata alone is not clearly demonstrated by the investigation. Instead, the study suggests that site-specific modeling be conducted, using detailed local geology—a time-consuming approach that requires extensive modeling capability and geologic reconnaissance, which may or may not be practical for a given mine. Many uncertainties remain in the highly stressed coal seams associated with geologic structure and spatial redistribution of induced stress in coal pillars and adjacent to the mine openings due to coal extraction. Thus, to prevent fatalities in underground coal mining, a continuous effort is required to better understand the catastrophic failure mechanism in coal mines.

A robust design (the Taguchi method [5,6] along with FLAC3D [7]) is used in this study to predict bump potential associated with plastic dissipated energy in a highly stressed coal pillar with respect to the stratigraphic characteristics of sedimentary formation, such as thickness, engineering material properties, and location. Because the inherent variability of the significant factors is substantial and the number of influential parameters in determining a parametric study is large, it is impractical to consider every simulation case by varying each parameter individually. Statistical experimental design is widely used to assist in data acquisition, decrease experiment error, and provide statistical analysis tools to describe the degree of errors. In statistical experimental design, two basic principles—replication and randomness—are required. Replication means that the same results can be obtained by the same experimental conditions. Randomness is required to ensure objectivity by putting the experimental objects into different conditions or by randomly arranging their experimental order. Furthermore, it is necessary to have a homogeneous experimental environment when applying the probability theory [8,9]. The Taguchi method was developed based on orthogonal array experiments. This gives a much reduced variance for the experiment with optimum settings of control parameters.

Orthogonal arrays provide a set of well-balanced (or minimum) experiments and serve as objective functions for optimization. The aim is to reduce the number of experiments in order to minimize the resources such as equipment, materials, manpower, or time. However, doing all of the factorial experiments is suitable when conducting experiments is cheap and quick but measurements are expensive and take too long, and when the experimental facility will not be available later to conduct the verification experiment. Conducting separate experiments for studying interactions between factors is not desirable. The general steps involved in the Taguchi method are as follows: (1) define the process objective, or more specifically, a target value for a performance measure of the process, and (2) determine the design parameters affecting the process. The number of levels that the parameters should be varied at must be specified in order to: (1) create orthogonal arrays for the parameter design indicating the number of and conditions for each experiment. The selection of orthogonal arrays is based on the number of parameters and the levels of variation for each parameter, and will be expounded; (2) conduct the experiments indicated in the completed array to collect data on the effect on the performance measure; and finally (3) complete data analysis to determine the effect of the different parameters on the performance measure.

The effect of many different factors on the performance characteristic in a condensed set of experiments can be examined by using the orthogonal array experimental design. The levels at which these parameters should be varied must be determined. Determining what levels of a variable to test requires an in-depth understanding of the process, including the minimum, maximum, and current value of the parameter. Orthogonal arrays created by the robust design are used to define the combination of the (a) thickness of a stiff sandstone inserted on the top and bottom of a coal seam in a massive shale mine roof and floor, (b) location of the stiff sandstone inserted on the top and bottom of the coal seam, and (c) material properties of the stiff sandstone and contacts as interfaces using FLAC3D. When there are many parameters to be studied, the main effect of each parameter and some of the reciprocal actions are estimated, while other reciprocal actions are disregarded to reduce the number of tests. The benefits of orthogonal array design are that it calculates the parameter changes from experimental or field-mapping data, facilitates the easy preparation of input data for analysis of variance, and accommodates many parameters in experiments or simulations without increasing the test scale [8,9]. Assuming that there is an orthogonal array presented as $L_{25}(5^6)$, this means that six parameters can be used in the experiment, and there are five stages in which the parameter values can be varied. In this case, 15,625(=5^6) experiments in total are required to obtain results that are statistically significant and representative. If the orthogonal array is used, however, only 25 experiments are needed. After completion of the numerical experiments, multivariate analysis, such as principal component analysis and multiple regression, is performed using the calculated results from the orthogonal arrays. The effect of each variable on the intensity of dissipated plastic energy and consequent retained potential energy are investigated and quantified in order to predict the bump potential in the roof, floor, and pillars. In short, this method provides an efficient, practical way to estimate the amount of energy retained in the rock mass that may be subsequently released in the form of a dynamic failure event.

The next section introduces stochastic simulation for the estimation of engineering properties of the rock masses and describes the FLAC3D modeling approach, including assumptions and conditions. Finally, methodologies appropriate to evaluate the bump potential adjacent to the underground excavations and in the coal pillar are explained and demonstrated by means of the robust design and numerical modeling technique.

2. Assumptions and conditions for FLAC3D modeling for evaluation of the bump potential

2.1. Stochastic simulation for estimation of engineering properties of coal

For this study, the engineering material properties for the sandstone, the coal seam, and other lithologies which are modeled as an elasto-plastic model are estimated using the geological strength