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A case study of multi-seam coal mine entry stability analysis with strength reduction method

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ABSTRACT

In this paper, the advantage of using numerical models with the strength reduction method (SRM) to evaluate entry stability in complex multiple-seam conditions is demonstrated. A coal mine under variable topography from the Central Appalachian region is used as a case study. At this mine, unexpected roof conditions were encountered during development below previously mined panels. Stress mapping and observation of ground conditions were used to quantify the success of entry support systems in three room-and-pillar panels. Numerical model analyses were initially conducted to estimate the stresses induced by the multiple-seam mining at the locations of the affected entries. The SRM was used to quantify the stability factor of the supported roof of the entries at selected locations. The SRM-calculated stability factors were compared with observations made during the site visits, and the results demonstrate that the SRM adequately identifies the unexpected roof conditions in this complex case. It is concluded that the SRM can be used to effectively evaluate the likely success of roof supports and the stability condition of entries in coal mines.

1. Introduction

Since the introduction of roof bolts in the coal mines during the late 1940s and 1950s, roof bolts promised to dramatically reduce roof fall accidents [1]. However, ground falls still remain a significant factor in underground coal mine injuries and fatalities. In 2013, ground falls accounted for 4 of the 14 fatalities and 166 of the 1577 reported lost-time injuries in underground coal mines.

The design of appropriate support systems requires the understanding of: (1) the variable nature of the rock mass, (2) the performance and characteristics of the roof support, (3) the interaction between the rock mass and the installed support system, and (4) the in-situ and mine-induced stress distribution around the excavation. Over the past 25 years, multiple design approaches have been used in coal mine ground control. The approaches include empirical mechanistic methods, empirical statistical analysis, rules of thumb, and numerical methods [2]. In the U.S., Analysis of Roof Bolt Systems (ARBS) can be given as an example of an empirical method. ARBS uses relatively simple equations to calculate the intensity of support provided by a roof bolt system and compare it with a suggested ARBS value [3]. The suggested ARBS design equation is derived from an analysis of 100 case histories. The ARBS design equation is dependent on two parameters: depth of cover and Coal Mine Roof Rating (CMRR). More recently, a probabilistic design approach was developed by Canbulat and van der Merwe in South Africa [4]. In this method, the variability of the rock mass, the mining geometry, and support characteristics are included in the analytical models. The major advantages of these two methods are: (1) they can be applied rapidly and easily, (2) complex rock mass/roof support interaction mechanisms are represented with simple equations, and (3) they are supported by large databases. However, both methods generally ignore mining-induced stress distribution, details of the roof support system, details of the geological setting, and the interaction between the support system and the rock mass.

To evaluate such complex interactions during support design, numerical models can be used. In general, experience-based design backed by empirical and analytical methods have found more application in the industry than numerical methods. The preference for empirically based methods may be related to the difficulty of selecting appropriate input parameters and interpreting success or failure when using numerical models. Recently, procedures

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were developed by Esterhuizen et al. to address these two concerns related to modeling [5,6].

2. Entry stability analysis with the strength reduction method (SRM)

The strength reduction modeling technique has a long history in numerical model analysis in rock slope stability engineering [7]. This modeling technique was adapted to underground coal mine entry analyses by Esterhuizen [8] to address the need for a method to compare the effectiveness of different support systems when designing ground control support in coal mines. The focus of the method is on large stress-driven roof falls that extend more than 1.00 m above the entry roof line. The SRM calculates a stability factor of the entry roof by gradually reducing the rock strength until failure is indicated. The stability factor is expressed as the inverse of the strength reduction factor. For example, if collapse occurs when the strength is reduced by a factor of 0.5, the entry stability factor will be 2.0.

Esterhuizen et al. [5] also developed an approach to systematically derive initial input parameters for modeling coal-measured rocks based on the field methods used in the Coal Mine Roof Rating (CMRR). Sedimentary rocks can contain weak bedding structures that have a significant impact on their stability. Anisotropic rock strength in the numerical models is achieved by user-defined functions.

The numerical models for determining the SRM stability factors are created using the FLAC3D finite difference code. Details of the model layout and input selection are described in Esterhuizen et al. [5]. Model calibration and validation studies were conducted to ensure that the developed modeling technique provides realistic estimates of the stability of mine entries. As part of the validation studies, model-calculated stability factors were compared to the results of the empirically based ARBS method [3]. Outcomes of the validation studies are presented by Esterhuizen et al. [6,9].

3. Case study

In this paper, the stability of the entries in a multiple-seam mine in central Appalachia is evaluated with the strength reduction method. The case study mine had unexpected stress-related ground conditions due to topography and multiple-seam effects [10]. Stress mapping and observation of ground conditions were used to quantify the success of entry support systems in the affected areas. In this paper, the SRM-calculated SF values are compared with the field observations.

3.1. Mining and geotechnical parameters at the case study mine

The Darby Fork No. 1 Mine is operated by Lone Mountain Processing, Inc., and is located in Harlan County, KY. The mine produces bituminous coal from the Darby and Kellioka coal beds by the retreat room-and-pillar mining method. In this paper, performances of the Nos. 1 and 5 entries in the L-6, L-5, and L-4 panels along the cross section *A*–*A*′ in the Kellioka seam are evaluated with the SRM (Fig. 1).

The workings on the Kellioka coal bed are accessed from the Darby coal bed by a set of three slopes which connect to the L-7 Right panel. The Kellioka, Darby, and previously mined Owl panels have been stacked vertically so that the panel edges and barrier pillars between panels are superimposed. The depth of cover varies between 90 and 610 m, and the thickness of interburden between the Kellioka and the Darby coal beds varies between 9 and 15 m. In the Kellioka, the L-7 panel was developed first to provide access from the Darby coal bed. The operator developed and retreat-mined

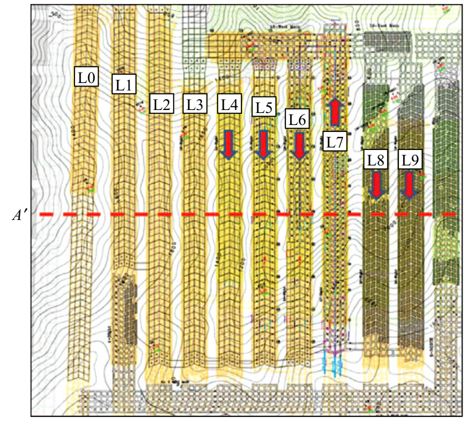

Fig. 1. General layout of the panels in the area of interest.

the L-8 and L-9 panels to the east followed by the L-6, L-5, and L-4 panels to the west. The L-7 panel was mined in a northward direction, and the L-8, L-9, L-6, L-5, and L-4 panels were mined southward. Pillars in the L-7 panel were not extracted to provide access to the remainder of the Kellioka workings and to provide intake ventilation.

The production pillars are designed to 24 m × 24 m centers with 70° crosscuts. Panel width is 98 m, with slab cuts of 9 m taken on both sides of the panel during retreat mining. Entries and crosscuts are mined at 5–5.5 m wide. The mining height varies between 1.8 m and 2.1 m, while the coal bed thickness varies around 0.9–1.2 m. Details about the case study mine are published by Tulu et al. [10].

3.2. Unexpected stress-related damage in the case study mine

During development of the L-6 panel, advancing to the south (Fig. 1), unexpectedly the No. 5 entry (western) experienced symptoms of stress-related damage, while the other four entries and the cross cuts were unaffected. The roof damage in the No. 5 entry appeared to be classic horizontal stress-related damage with the formation of roof cutters along the length of the entry [10]. The cutters were mostly located along the eastern corner or along the center of the No. 5 entry. Some floor heave occurred near the center of the entry. The conditions in the No. 5 entry deteriorated to such an extent that it became necessary to install timber cribs to support the roof. Roof cutters and poor conditions continued to be experienced as the L-6 panel development advanced towards the south, with an improvement in roof conditions towards the end of the panel, after crosscut 41. The stress-related damage observed in the No. 5 entry of the L-6 panel was unexpected because the No. 1 entry was expected to be subject to horizontal stress-related damage, as shown in Fig. 2. The No. 5 entry was actually expected to be in a favorable situation because it was supposed to be in a zone of relieved horizontal stress.

In an attempt to explain the occurrence of the failure in the No. 5 entry of the L-6 panel, two-dimensional finite element stress analyses were conducted [10]. The stress analysis models included the effects of the initial horizontal stress, the effect of the variable topography on vertical stress, and the details of the mined panels and entry development. The results indicated that the unusual stress damage was most likely related to the effect of the mountainous topography, which produced a rotated stress field at the location of the current workings. The rotated stress resulted in asymmetrical interactions between the upper and lower workings, explaining the baffling damage observations [10]. To remedy the situation, the No. 5 entry in the subsequent panels was developed