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Analysis of global and local stress changes in a longwall gateroad

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ABSTRACT

A numerical-model-based approach was recently developed for estimating the changes in both the horizontal and vertical loading conditions induced by an approaching longwall face. In this approach, a systematic procedure is used to estimate the model's inputs. Shearing along the bedding planes is modeled with ubiquitous joint elements and interface elements. Coal is modeled with a newly developed coal mass model. The response of the gob is calibrated with back analysis of subsidence data and the results of previously published laboratory tests on rock fragments. The model results were verified with the subsidence and stress data recently collected from a longwall mine in the eastern United States.

1. Introduction

In 2015, there were 40 longwall mines operating in the United States, each producing an average of 4.5 million tons of coal per year, and they supplied 60% of the U.S. underground coal production. This represents a substantial increase from 50% over the previous three years [1]. During this period, reportable roof fall rates in U.S. longwall mines also increased. Large roof falls that can block the gateroads are not only a ground-fall hazard; they can disrupt the ventilation system, block the escape ways, and increase the potential for elevated methane levels in the gob. To address these hazards, the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Mining Research Division (PMRD) is conducting research to improve the design of ground control systems in longwall gateroads.

Gateroad layout is primarily determined by the longwall pillar design. Generally, the required dimensions of the pillars around a longwall panel are determined first, which dictates the location of the gateroads relative to the mined panel. The analysis of longwall pillar stability (ALPS) method is the most accepted design procedure in the United States [2]. The ALPS method accounts for local roof geology in the gateroad stability assessment by including the coal mine roof rating as an input parameter [2]. The key assumption in the ALPS method is that unstable pillars will result in unstable gate entries. However, experience provides examples of mines where pillar stability and gateroad stability are loosely correlated [3].

Gateroad support design is largely empirical, often based on a trial-and-error approach. Gateroad stability and safety can be improved by introducing an engineering-based design approach that specifically considers the rock mass and support response to changes in both the horizontal and vertical loading conditions induced by the approaching longwall face. Such complex stress changes during a longwall retreat can be evaluated with calibrated numerical models, allowing support systems to be designed that can accommodate the expected loading conditions.

2. Longwall model development and calibration

Esterhuizen et al. developed a modeling approach that can be used to provide realistic stress and deformation results along the gateroad chain pillars [4]. In this approach, an "equivalent element" method is used to capture the stress/strain response of the pillars and the immediate roof and floor rocks to model large-scale, three-dimensional retreat mining layouts. One limitation of this approach is that the response of the immediate roof to horizontal stress change during the retreat mining cannot be investigated because only the vertical stress is solved within the equivalent elements. Recently, this approach has been updated for estimating the changes in both the horizontal and vertical loading conditions in the immediate roof of the gateroads [5]. The modified approach uses standard elements to model the pillars, roof, and floor, which provides the full stress tensor, including horizon-

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tal stress components in the roof of the coal bed. In addition, interface elements are introduced between main geologic units to more accurately model shear and bending of the overburden strata.

2.1. Pillar strength modeling

Recently at NIOSH, Mohamed et al. developed a coal material model. In this model, the peak strength of the coal is evaluated by the generalized Hoek-Brown failure criterion [6–8]. The residual stiffness and strength are evaluated by the Fang and Harrison local degradation model [9]. The dilation of the coal material is defined by the Alejano and Alonso peak-dilation model [9,10].

Mohamed et al. indicated that the Mohr-Coulomb constitutive model provides a method for describing the dilation behavior of rocks, and it is available in the majority of numerical codes [7]. Therefore, in this model, the equivalent Mohr-Coulomb model parameters derived from the Hoek-Brown criterion are used. This model simulates the peak and post-peak behaviors of the coal material by using a strain-softening, ubiquitous joint model available in the FLAC3D software.

The input parameters used for coal in this paper are summarized in Table 1. In Table 1, "σci" is the intact unconfined compressive strength of the coal, and m, s and a are the peak strength scaled parameters of coal. The parameter σc represents peak, and σcr is the residual of the field-scale unconfined compressive strength. Nd is a scaled coal degradation parameter. This degradation parameter is used to reduce the strength and stiffness of the coal from peak values to residual values in the coal model. $\Upsilon pcrit$ is the critical plastic shear strain that controls the rate of material degradation. The strength of the coal material is reduced until plastic shear strain reaches to this critical value. Coal material fracturing is simulated by adding an implicit cohesion-less ubiquitous joint within the material. Fractures are initiated in those elements that have plastic shear strain equal to or greater than the "fracture plastic shear strain" parameter detailed in Table 1. The coal model was originally developed to simulate the stress/strain behavior of coal pillar ribs. This model also simulates the stress/strain behavior of full coal pillars satisfactorily, as demonstrated in Fig. 1.

To compare the stress-strain behavior of the pillars generated with the coal model of Mohamed et al. to results obtained by Esterhuizen et al., numerical models were created in which portions of the roof strata, the coal pillar, and the floor strata were simulated [4,7]. The same boundary conditions and model geometries used by Esterhuizen et al. were modeled [4]. Fig. 1 shows the resulting stress-strain curves obtained from the coal models with different pillar width-to-height ratios. The stress-strain behavior presented in Fig. 1 is similar to the results published by Esterhuizen et al. [4]. The new coal model can simulate the fracture development in coal pillar [7]. Post-peak stress/strain behavior was slightly different. For the width-to-height ratios below 8, the pillars exhibit a strain-softening behavior. For the width-to-height ratios above 8, the pillars exhibit a strain-hardening behavior. The peak pillar strengths simulated by the numerical models are compared with the empirical Bieniawski pillar strength equation in Fig. 2. The results show good agreement between the model calculations and the empirical equation.

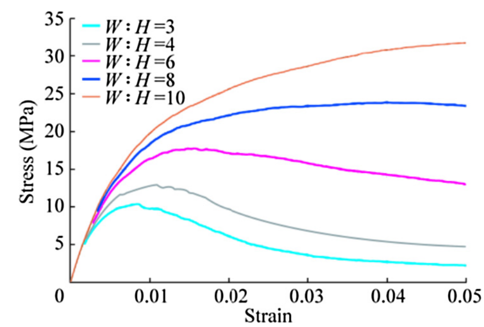

Fig. 1. Stress-strain curves obtained from a calibrated coal model.

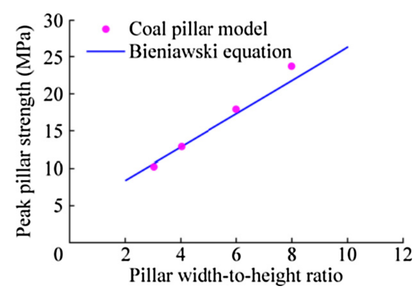

Fig. 2. Pillar strength results obtained by numerical models after calibrating the models to the empirical pillar strength equation.

2.2. Gob response modeling

It is important to simulate the gob response accurately to simulate the load distribution along the gateroad entries. Esterhuizen et al. indicated that gob modeling can follow two approaches: (1) explicitly model the gob formation process so that variations in geology and loading conditions can be studied, (2) implicitly model the gob compaction and load distribution to accurately model load redistribution to gateroad pillars and surrounding rock. As in Esterhuizen et al., the second approach is used in this paper to simulate the behavior of the gob [4].

As indicated by Pappas and Mark, laboratory tests on shale and sandstone fragments showed that the stress-strain response of caved material should follow a strain-hardening curve [11]. Pappas and Mark used the hyperbolic function derived by Salamon to fit test results, and they found that this function sufficiently simulates the strain-hardening gob response [11,12].

$$\sigma = (a \times \varepsilon)/(b - \varepsilon) \qquad (1)$$

where σ is the vertical gob stress, MPa; ε the vertical gob strain, and $\varepsilon = b/2$, MPa; b the maximum strain parameter related to void ratio; and a the gob stress.

Esterhuizen et al. calibrated the hyperbolic equation (Eq. (1)) by matching the model results with subsidence profiles that were calculated from the surface deformation prediction software (SDPS) [4,13]. To assist selecting appropriate gob parameters, they followed the same approach used by SDPS, in which the gob is char-

Table 1
Input parameters for coal material.

Elastic property		Strength parameter						Degradation parameter		Ubiquitous joint friction angle	Fracture plastic shear strain
Modulus (GPa)	Poisson's ratio	σci (MPa)	m	s	a	σcr (MPa)	σc (MPa)	Nd	$\Upsilon pcrit$		
3	0.25	20	1.52	0.013	0.5	0.3	2.28	0.503	0.26	25	0.0275

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