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Coal rib response during bench mining: A case study

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ABSTRACT

In 2016, room-and-pillar mining provided nearly 40% of underground coal production in the United States. Over the past decade, rib falls have resulted in 12 fatalities, representing 28% of the ground fall fatalities in U.S. underground coal mines. Nine of these 12 fatalities (75%) have occurred in room-and-pillar mines. The objective of this research is to study the geomechanics of bench room-and-pillar mining and the associated response of high pillar ribs at overburden depths greater than 300 m. This paper provides a definition of the bench technique, the pillar response due to loading, observational data for a case history, a calibrated numerical model of the observed rib response, and application of this calibrated model to a second site.

1. Introduction

Bench mining is an underground mining technique typically applied to room-and-pillar mines where full seam extraction on development presents an unacceptably high risk of injury from high pillar ribs or where the mining equipment is not designed to extract the full seam thickness. To mitigate the increased risk associated with high ribs and slender pillars, a more modest thickness is extracted from the top of the seam on development. This is followed by grading the floor and recovering the bottom of the seam with or without extraction of the pillars during retreat mining.

A mine located in Eastern Kentucky extracts two seams at depths ranging from outcrop to over 600 m. In some areas of the mine, Seam A and Seam B are close enough together to be mined simultaneously. Seam A (top) is mined on development 2–3 m high for the entire length of the panel. On retreat, as each pillar is extracted, the continuous miner is ramped down into the floor (Seam B), two pairs of mobile roof support (MRS) units are set, and the pillars are extracted at the full mining height of 4+ m. During the pillar recovery process, the floor is extracted in each entry, from a ramp initiated outby the retreat line, sequentially just prior to extracting the lifts from the pillars (Fig. 1).

Current rib support practices at the mine include the use of 1.5-m-long, 19-mm-diameter, grade 60, fully grouted tensioned rebar bolts installed with 20 cm × 40 cm steel bearing plates. Typically, one row of bolts is installed if the mining height is less than 3 m, two rows are installed if the mining height is from 3 to 4.5 m, and three rows are installed if the mining height is greater than 4.5 m. Row spacing for the top row is 1.2 m, while spacing for the second or mid-pillar row can be increased to 2.4 m if the bolts are anchored in the rock parting. Typically, the third row is installed just prior to retreat mining at a maximum 2.4-m spacing. During retreat, loose ribs are cut down and re-supported as necessary, which can include the installation of extended length (2.4-m) rib bolts if required [1].

2. Rib model development

Numerical modeling is a useful tool to help explain the stress distribution and extent of rib fracturing in coal pillars. In order to investigate the stress distribution and development of rib fractures at this mine, the finite difference software FLAC3D was used [2]. Fig. 2 shows the geologic column that was simplified into four coal layers and two stone layers for use in the FLAC3D model. The FLAC3D model for the first case history site is a three-dimensional model for a single pillar, 18 m wide and 30 m long, rib to rib. Three pillar configurations were considered in the initial model to better elucidate how each behaves during loading. The pillar models were monotonically loaded to failure. The short pillar represents development mining Seam A, which is labeled "Advance" in Fig. 2.

The slender pillar represents mining the full seam height of both seams at the full extraction thickness of 4+ m. Although this

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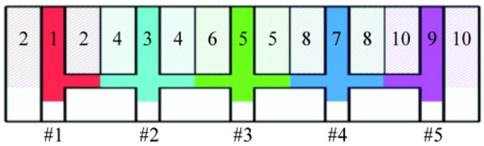


Fig. 1. Sequential floor removal in each entry prior to retreat mining.

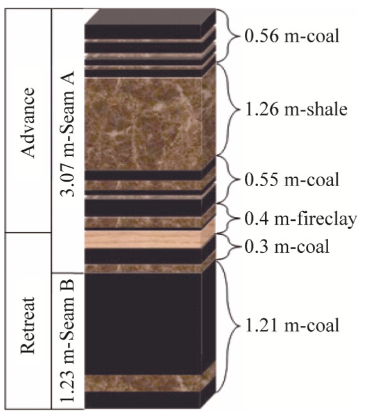


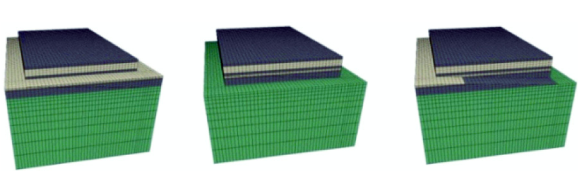
Fig. 2. Typical stratigraphic column simplified for the FLAC3D model.

configuration never occurs in the field, it was chosen to be modeled solely for comparison purposes. Finally, the third configuration modeled the benched pillar as close to the proposed design as possible with one entry ramped down into Seam B right before pillar extraction would begin (see Fig. 3). No rib supports were simulated in these models, and the benched model is capable of simulating retreat mining right to left or left to right simply by changing the orientation of the cleat system.

The bottom boundary of the model is constrained in the z-direction. Roller supports are assumed in the x-direction at both the left and right entries. Roller supports are also assumed in the y-direction at the inby and outby crosscuts. The element size in the pillar is about 25 cm in both the x and y directions. The smallest and largest element sizes in the z-direction of the modeled pillars are 15 and 30 cm, respectively.

Tables 1 and 2 show the rock and coal properties in the FLAC3D model. The field observations at Site 1 and Site 2 show that the immediate roof and floor strata were intact. Therefore, the roof and floor strata were modeled as elastic material models. Field inspection showed that a soft band located at the top of Seam A is extremely influential in the mode of failure and extent of rib deterioration. Therefore, a relatively soft pillar/roof interface was assumed. The Coulomb friction model was assumed for the Seam A/roof rock interface, and the friction angle and the cohesion of the interface were 10° and 100 kPa, respectively. The normal and shear stiffness of the interface between pillar and roof were assumed to be 1.00 and 0.50 MPa/m, respectively.

Recently, National Institute for Occupational Safety and Health (NIOSH) researchers Mohamed et al. developed a coal material



(a) Short pillar (b) Slender pillar (c) Benched pillar

Fig. 3. Pillar layouts.

Table 1
Input parameters for coal material.

	Coal seam	A	B
Elastic property	Modulus (GPa)	2.760	4.550
	Poisson's ratio	0.250	
Strength parameter	σ_{ci} (MPa)	21.000	35.000
	m	3.510*	
	s	0.065*	
	a = constant	0.500	
	$\sigma_{cr=3.085} \times (D, mm)^{-1.241}$ (MPa)	1.380*	
	$\sigma_{c=}\sigma_{ci} \times s^a$ (MPa)	5.350*	8.920*
Degradation parameter	$n_{d=0.144} \times \ln(D, mm) - 0.568$	0.327*	
	$\Upsilon^p_{crit=0.1} \times (D, mm)^{-0.44}$	0.154*	
Ubiquitous joint friction angle (°)		25.000**	
Fracture plastic shear strain		0.030**	
Fracture plastic tension strain		0.003**	

* Means the strength parameters for coal-mass size (D) of 500 mm.
** Refers to calibrated parameters.

Table 2
Input parameters for stone material.

Rock strata		Roof/floor	Shale	Fireclay
Elastic property	Modulus (MPa)	20.000	10.000	8.000
	Poisson's ratio		0.250	
Strength parameter	σ_{ci} (MPa)	Elastic	48.000	43.000
	m		6.859	2.341
	s		0.189	
	a		0.500	
	σ_{cr} (MPa)		2.600	
	$\sigma_c = \sigma_{ci} \times s^a$ (MPa)		20.870	18.700
Degradation parameter	n_d		0.200	
	Υ^p_{crit}		0.123	
Ubiquitous joint friction angle, degree			25.000	
Fracture plastic shear strain			0.020	
Fracture plastic tension strain			0.002	

model [3,4]. In this model, the peak strength of the coal is evaluated by the generalized Hoek–Brown failure criterion. The residual stiffness and strength are evaluated by the Fang and Harrison local degradation model [5]. The dilation of the coal material is defined by the Alejano and Alonso peak-dilation model [6].

Mohamed, Tulu, and Murphy 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 [4]. 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 the strain softening, ubiquitous joint model available in FLAC3D. The coal material model has been calibrated to field cases and fully implemented in the FLAC3D program as a user-defined constitutive model.

Input parameters used for Seam A and Seam B in this paper are summarized in Table 1. In Table 1, σ_{ci} is the intact unconfined compressive strength of the coal, and m, s, and a are the scaled peak strength parameters of the coal as used in the Hoek–Brown failure criterion. The σ_{ci} is estimated from the coal brightness profiles of the respective seams with Seam A having a bright and dull banded composition, and Seam B being predominantly dull coal. σ_c is the peak, and σ_{cr} is the residual of the field-scale unconfined compressive strength. n_d 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 [3,4]. Υ^p_{crit} is the scaled critical plastic shear strain. Coal material

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