

Analyzing Rib Stability and Support Using A Coal Pillar Rib Rating

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ABSTRACT

Researchers from the National Institute for Occupational Safety and Health (NIOSH) are developing a methodology for assessing the stability of coal pillar ribs. The developed methodology is a hybrid numerical-empirical technique that provides ground control engineers with more insight into primary rib support in underground coal mines. The Coal Pillar Rib Rating (CPRR), Primary Rib Support Density (PRSD), and overburden depth are the key elements in the developed rib assessment methodology. The CPRR was developed based on numerical models of different rib compositions. The Unsupported Rib Factor of Safety (RibFOS) for development loading of mining is defined using the CPRR and overburden depth. A database of 118 coal pillar rib cases was collected by NIOSH from active underground coal mines in the United States, MSHA rib fatality reports, and published mining reports in Australia. It was found that all ribs in the longwall mines database are supported. A RibFOS threshold of 1.5 could be used to delineate the boundary between supported and unsupported ribs in room-and-pillar mines. Relationships between the applied PRSD and calculated RibFOS for rib cases were developed. Currently, additional research is underway with the goal of investigating the effects of rock brows on rib stability and support density.

INTRODUCTION

Coal ribs, or sidewalls, are the exposed members (coal and/or rock) of pillars in underground coal mines. Coal ribs are usually found as alternating units of coal and rock beds interfaced with bedding planes as shown in Figure 1. Coal seam usually refers to different coal units as well as any rock partings that may be present. Figure 1 shows a typical coal seam composed of two coal units and a rock parting. The coal unit can be composed of a single lithotype coal band (see “Coal unit-1” in Figure 1) or multiple coal bands of the same or different lithotypes separated by in-seam bedding planes (see “Coal unit-2” seam in Figure 1).

Over the past decade, rib falls resulted in 16 fatalities, representing over 50% of the ground-fall fatalities in U.S. underground

coal mines. Statistical analyses on the fatality cases resulting from underground coal pillar rib falls from 2010 to 2019 shows that more than 70% of the accidents occurred during the development loading (MSHA, 2019). More recently, the falls of rib or face led to all three of the ground-fall-related fatalities in 2018 and 2019. Efforts to improve the stability of underground mine ribs have continued for decades. The early research on rib stability was conducted with a focus on improving roof control through better pillar stability rather than improving rib stability. Rib stability and design of rib support were analyzed by many researchers (Bauer and Dolinar 1999; Colwell 2004; Mark et al. 2009; Pappas and Mark 2012; Jones et al. 2014; Zhang et al. 2017; Mohamed et al. 2019, 2020a; Rashed et al. 2020). Given the ongoing rib-support-related research, it is unfortunate that there has been a continual trend in the occurrence of rib-related fatalities in underground coal mines.

Three types of coal ribs are observed in underground coal mines: (1) solid coal ribs with or without thin rock partings, (2) coal ribs with in-seam rock partings (greater than 6 in), and (3) coal ribs with a brow. Mohamed et al. (2020b) developed a methodology to analyze the stability and support of solid coal ribs (Type 1). In this paper, the developed methodology is extended to include coal ribs with in-seam rock partings (Type 2). Coal ribs with brows (Type 3) are still being studied.

Mining depth has always played a very important role in assessing rib stability and is one of the major topics concerning the design of rib support systems. In a 2010 publication by Gauna and Mark, they completed an analysis of rib fatalities that occurred between 1996 and 2010. One of their most prominent and influential findings was the identification of a relationship among fatalities, depth, and mining height [Gauna and Mark, 2010]. In this research, rib stability can be assessed by defining the load applied on the rib and the integrity of the rib. Overburden depth is a significant factor affecting the induced stresses in coal pillar ribs. Therefore, overburden depth is a good indicator of the load applied on coal pillar ribs during development loading. Other sources of rib loading such as

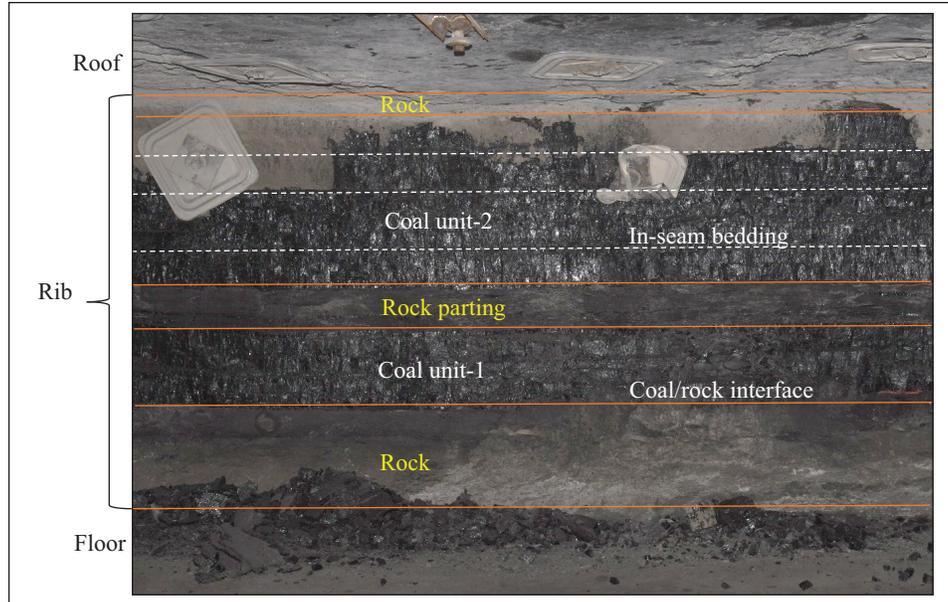


Figure 1. Typical coal rib composition in underground coal mines

multiple-seam interaction loads and high horizontal stresses are not considered in the calculations of rib loading. Mohamed et al. (2020b) developed the CPRR to quantify the integrity of solid coal ribs (Type 1) using the strength parameters of coal ribs. This paper extends the applicability of CPRR to include coal pillar ribs with in-seam rock partings (Type 2). The strength of the rock parting is included in the updated CPRR. Similar to the study of Type 1 coal ribs, a systematic numerical modeling approach has been employed to determine the CPRR for Type 2 coal ribs with varying rock partings of different thicknesses and strengths (Xue and Mohamed, 2021). Expanding the applicability of the CPRR for coal pillar ribs with brows (Type 3) is still being studied.

Uniaxial compressive strength of rib units (coal and rock) and condition of bedding planes are primary inputs for the CPRR calculations. Therefore, a concise review of these inputs is given here. The uniaxial compressive strength (UCS) of the units composing coal ribs can be determined directly from the compression tests or indirectly from the Schmidt Hammer Test or the Point Load Test (Rashed et al., 2018). The coal brightness profile can be used as an alternative procedure to estimate the UCS of coal bands (Rusnak, 2018). The relative strength of the bedding (strong or weak) in coal ribs can be quantitatively determined using indirect testing methods. Molinda and Mark (1994) proposed a simple method to determine the bedding plane shear strength by using a 9-cm mason chisel and a hammer to split a hand sample of the coal rib. Weaker, less cohesive surfaces require fewer chisel blows to split. The bedding plane is classified as “weak” bedding if the hand sample is split along the bedding plane by three (3) or less blows with the mason chisel and a hammer. The condition of coal/rock interfaces and in-seam beddings could be either strong or weak.

To assess the structural stability of coal ribs (Type 1 and Type 2) in the development loading, a regression model was developed for correlating the RibFOS with CPRR and the overburden depth (H) as in Equation 1:

$$RibFOS = 19.76 * \frac{CPRR}{H, ft} \quad (1)$$

The calculated RibFOS does not consider the potential rib fall hazard. For example, the rib instability associated with the fall of large pieces of rib unit at the top of the rib is more hazardous than the instability of a friable rib unit at the top of the rib. Equation (1) can give insight about the potential of rib brow formation but it cannot assess the stability of formed brow. The authors are aware of the need to consider rib hazard assessment in the evaluation of rib stability and the stability of formed brows, and these topics will be studied in the future.

UPDATED COAL PILLAR RIB RATING (CPRR)

The CPRR can be calculated using numerical models (Mohamed et al., 2020b; Xue and Mohamed, 2021). Calculating the CPRR using the numerical model approach is time-consuming and requires expertise in numerical modeling, making it unfavorable in practical application. A more practical alternative is to develop a system of regression equations obtained from numerical modeling studies of a wide range of geological and geometrical parameters of coal pillar ribs. In this study, the CPRR of 201 solid coal pillar ribs of different compositions were calculated using numerical modeling [Mohamed et al., 2020b]. Similarly, the CPRR of 287 coal pillars with rock partings of different compositions were calculated using numerical modeling [Xue and Mohamed, 2021]. A set of regression equations were developed to correlate the CPRRs of Type 1 and Type 2 coal ribs calculated by the numerical models and their geological and geometrical parameters.

The calculation of CPRR from the regression equations is conducted in three steps as depicted in the simple flowchart shown in Figure 2. In the first step, the basic (unadjusted) Coal Unit Rating (CUR) is calculated for each of the coal units in the rib. The basic CUR quantifies the inherent quality of a coal unit by rating the variation of UCS within the coal unit (homogeneity) and the condition

of in-seam beddings. In the second step, the calculated CUR is adjusted for the strength of adjacent rock partings, the condition of coal/rock interfaces, coal unit thickness, and dominant cleat angle. In the third step, the CPRR is calculated as the minimum of all adjusted coal unit ratings within the coal pillar. A user-friendly standalone application was developed to ease the calculations of the CPRR, but it is recommended for the users to be familiar with the calculation steps given below.

Step 1—Calculation of the Basic Coal Unit Rating, CUR_{Basic}

The basic rating for each coal unit (i) in the rib is calculated using Equation 2. The basic rating of a coal unit is composed of two components: homogeneity rating ($\beta(i)_h$) and in-seam bedding rating ($\beta(i)_{(in-seam-bedding)}$).

$$CUR_{Basic}(i) = \beta(i)_h + \beta(i)_{in-seam-bedding} \quad (2)$$

where i is the ID of a coal unit, which is composed of “k” bands.

Figure 2. Flowchart showing the procedure for calculating CPRR

The homogeneity rating, ($\beta(i)_h$), of each coal unit is calculated as follows:

$$\beta(i)_h = 3.72 \times \frac{\sigma_c(i)}{\sigma_{BC}} \times \left(4 - \frac{1}{r(i)}\right) \quad (3)$$

$\sigma_c(i)$ is the weighted average UCS of the coal unit, calculated as follows:

$$\sigma_c(i) = \frac{\sum_{b=1}^k \sigma_c(b) \times t(b)}{\sum_{b=1}^k t(b)} \quad (4)$$

where $\sigma_c(b)$ and $t(b)$ are the UCS and thickness of coal band (b), respectively. The UCS of coal band range is between 1,250 psi and 5,000 psi [Mohamed et al., 2020b].

σ_{BC} is the UCS of bright coal lithotype, which is 1,250 psi.

$r(i)$ is the homogeneity index of coal unit. It is calculated as follows:

$$r(i) = \begin{cases} 1, & \text{if } k = 1; \\ \min_{j=1:k-1} \left[\frac{\min(\sigma_j, \sigma_{j+1})}{\max(\sigma_j, \sigma_{j+1})} \right], & \text{otherwise} \end{cases} \quad (5)$$

where σ_{j+1} are the UCSs of coal bands j , and $j+1$, respectively. The rib homogeneity index ranges between 0.25 and 1.0.

The in-seam bedding rating, $\beta(i)_{(in-seam-bedding)}$, of a coal unit is calculated as follows:

$$\begin{aligned} \beta(i)_{in-seam-bedding} &= 11.94 \times \left[\frac{\sigma_c(i)}{\sigma_{BC}} \right] - 1.85 \\ &\text{for coal unit with no in-seam bedding} \\ &= 11.45 \times \left[\frac{\sigma_c(i)}{\sigma_{BC}} \right] - 3.85 \\ &\text{for coal unit with strong in-seam bedding} \\ &= 5.44 \times \left[\frac{\sigma_c(i)}{\sigma_{BC}} \right] - 1.85 \\ &\text{for coal unit with weak in-seam bedding} \end{aligned} \quad (6)$$

Step 2—Adjusting the Calculated Basic Rib Rating for Coal Unit

The calculated basic rating of each coal unit (i) is adjusted for three (3) parameters, as follows:

1. Adjustment for the adjacent rock parting and the condition of the coal/rock interface, $\alpha(i)_{parting}$. The calculated $CUR_{Basic}(i)$ is adjusted for the strength of adjacent rock units and condition of bedding between the coal unit (i) and adjacent rock units, as follows:

$$\begin{aligned} \alpha(i)_{parting} t &= \left[0.0459 \times \left\{ \frac{\sigma_{parting}(l)}{\sigma_{BC}} \right\} - 0.256 \right] \times CUR_{Basic}(i) \\ &\text{for strong coal/rock interface} \\ &= \left[0.0510 \times \left\{ \frac{\sigma_{parting}(l)}{\sigma_{BC}} \right\} - 0.3471 \right] \times CUR_{Basic}(i) \end{aligned} \quad (7)$$

for weak coal/rock interface

where $\sigma_{parting}(l)$ is the uniaxial UCS of rock units (partings) adjacent to the coal unit (i). The strength of rock parting ranges between 2,500 psi and 6,500 psi [Xue and Mohamed, 2021].

2. Adjustment for the thickness of coal units. Field observations of coal pillar ribs show that as the rib development height increases, rib sloughing is more likely to occur. The effect of rib height on the stability of coal pillar rib is explained as an end-constraint provided by surrounding strata. Minimal rib constraint could be expected for thick ribs and/or for ribs with weak beddings. Therefore, please note that there is no adjustment for the thickness for coal pillar ribs with weak coal/rock and/or in-unit beddings. The thickness adjustment for a coal unit is complicated because it depends on mutually interacting parameters (thickness of coal unit, the homogeneity of the coal unit, and the basic rating of the coal unit). The thickness adjustment $\alpha(i)_t$ for a coal unit is calculated as follows:

- i. For homogenous coal units, thickness adjustment is applicable for coal units of thickness less than a critical value, $t_c(i)$.

$$\begin{aligned} t_c(i) &= 4.0 - 0.00022 \times [CUR_{Basic}(i)]^2 \\ &\quad - 0.0005 \times CUR_{Basic}(i) \end{aligned} \quad (8)$$

$$\alpha(i)_t = c_1 + c_2 \times t(i) \quad (9)$$

where $t(i)$ is the thickness of coal unit (i) in ft. Thickness adjustment of a homogenous coal unit is applicable for a coal unit thickness between 1.5 ft and 4 ft [Xue and Mohamed, 2021].

c_1 and c_2 are constants and calculated for $CUR_{Basic}(i) < 50$, as follows:

$$\begin{aligned} c_1 &= CUR_{Basic}(i) \\ &\quad \times [0.014 \times CUR_{Basic}(i) + 0.6583] \end{aligned} \quad (10)$$

$$\begin{aligned} c_2 &= CUR_{Basic}(i) \\ &\quad \times [-0.0045 \times CUR_{Basic}(i) - 0.1440] \end{aligned} \quad (11)$$

and for $CUR_{Basic}(i) \geq 50$ c_1 and c_2 are calculated as follows:

$$c_1 = -1.2805 \times CUR_{Basic}(i) + 135.3 \quad (12)$$

$$c_2 = 0.2927 \times CUR_{Basic}(i) - 33.927 \quad (13)$$

- ii. For nonhomogeneous coal units, thickness adjustment is calculated as follows:

$$\alpha(i) = c_1 + c_2 \times t(i) + c_3 \times CUR_{Basic}(i) + c_4 \times t(i) \times CUR_{Basic}(i) + c_5 \times [CUR_{Basic}(i)]^2 \quad (14)$$

The regression constants of Equation 14 are listed in Table 1. Thickness adjustment of nonhomogeneous coal units is applicable for a coal unit thickness between 2.0 ft and 11.0 ft [Xue and Mohamed, 2021].

3. Adjustment for the dominant cleat angle, $\alpha(i)_{cleat}$. Cleat adjustment in coal units is only applicable for cleat angles equal to or greater than 20° with respect to entry direction. The adjustment for cleat angle is calculated as follows [Mohamed et al., 2020b]:

$$\alpha(i)_{cleat} = 2.25 \times \left[\frac{\sigma_c(i)}{\sigma_{BC}} - 1 \right] \quad (15)$$

The rating of each coal unit, $CUR(i)$, in the rib is calculated by adding the basic unit rating to the unit adjustments (Equation 16).

$$CUR(i) = CUR_{Basic}(i) + \pm(i)_{parting} + \pm(i)_t + \pm(i)_{cleat} \quad (16)$$

Step 3—Calculation of Coal Pillar Rib Rating (CPRR)

The coal unit of minimum rating dictates the integrity of the rib. Therefore, the CPRR of the coal rib is defined as the minimum rating of all coal units in the coal pillar.

$$CPRR = \min_{i=1:n} [CUR(i)] \quad (17)$$

where n is the number of coal units in the coal pillar rib.

The calculated CPRR using Equations 2 to 17 ranges between 1 and 100. A CPRR of 1 designates the weakest coal rib, while a CPRR of 100 designates the strongest rib. Figure 3 shows the CPRR for solid ribs and ribs with in-seam partings calculated by numerical models and calculated by the regression Equations 2 to 17. Fewer significant figures could be used in the regression constants for calculating coal unit ratings and adjustments, but our goal was to make the CPRR calculated by regression equations as close as possible to those calculated by numerical models. Figure 3 shows that the regression equations are a good approximation for calculating the CPRR of coal pillar ribs.

In this paper, a platform for calculating CPRR is presented, but more work is planned to be conducted to study the sensitivity of the key input parameters on the calculated CPRR, such as; the intact strength of coal units, the intact strength of rock units, and the condition of in-seam bedding and coal/rock interface. Also, more

Table 1. Regression constants of Equation 14

	c_1	t	c_3	c_4	c_5
$CUR_{Basic}(i) < 50$	0.4788	-0.1284	0.5914	-0.03715	-0.0001419
$CUR_{Basic}(i) > 50$	59.5	-3.676	-0.592	0.0360	0.0003869

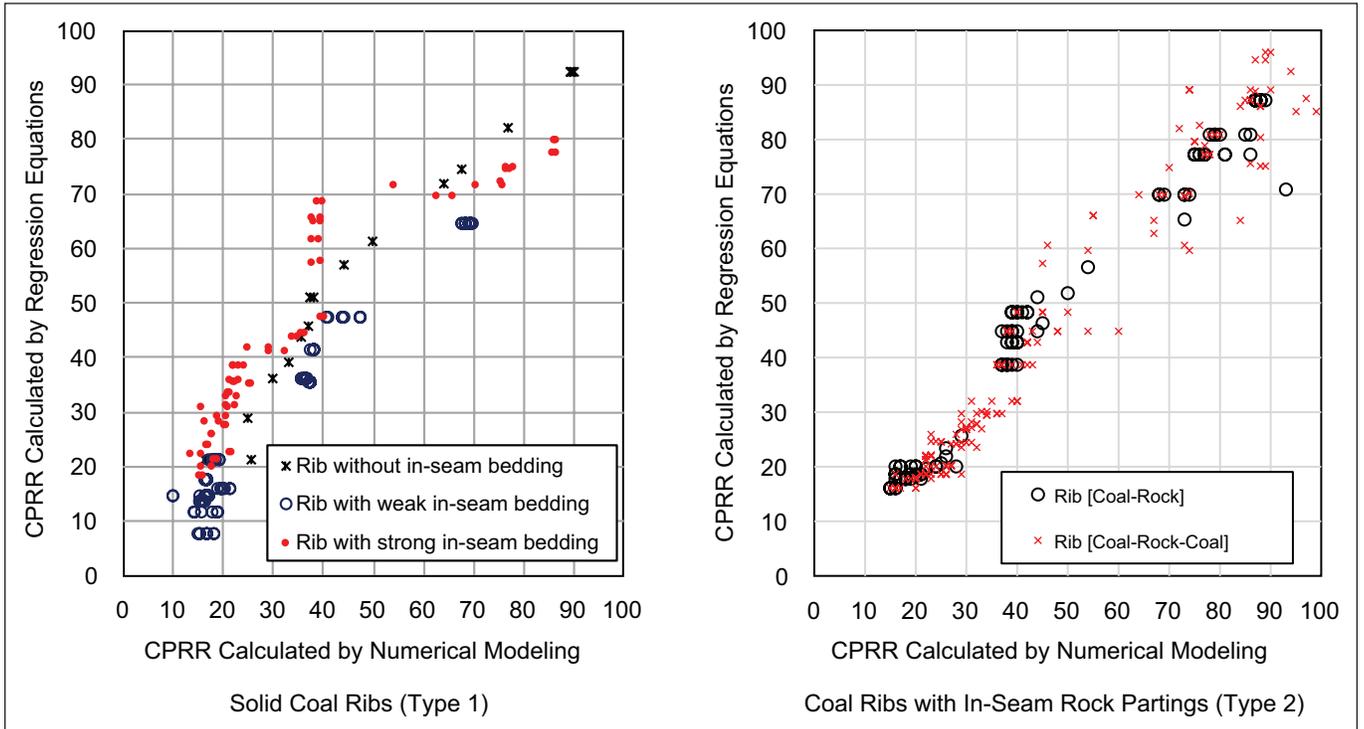


Figure 3. CPRR calculated by regression equations in comparison with CPRR calculated by numerical modeling

Table 2. Coal pillar rib properties and rib bolt parameters obtained from the U.S. coal mines

Rib parameter	Room-and-pillar mines			Longwall mines		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
Depth, ft	1,011	175	2,000	1,581	700	2,275
Coal strength, psi	2,847	1,250	5,000	1,903	1,250	3,633
Mining height, ft	7.19	4.1	12.5	8.20	5.90	11.10
Bolt length, ft	5	3	6	5	3	6
Bolt spacing, ft	5	4	8	5	3	12
Number of bolts per vertical rib bolt row	1	1	3	1	1	2
Yield capacity of rebar, lbf	22,523	15,229	33,134	20,183	13,500	26,507
Anchorage capacity of mechanical bolt, lbf	8,487	5,114	15,737	11,413	7,194	18,000

Table 3. Coal pillar rib properties and rib bolt parameters reported from longwall coal mines in Australia

Rib parameter	Mean	Minimum	Maximum
Depth, ft	840	508	1,640
Coal strength, psi	1,575	870	3,625
Mining height, ft	9.54	8.20	11.15
Bolt length, ft	5	4	6
Bolt spacing, ft	4	3	7
Number of bolts per vertical rib bolt row	2	1	3
Yield capacity of rebar, lbf	50,806	11,240	76,435
Shear strength of point anchor, lbf	7,868	7,868	7,868

work is planned to be conducted to establish how to implement the data collection protocol proposed by the authors (Mohamed, et al., 2020b).

Rib Support Methodology

In any underground coal mine, two important questions are usually raised regarding the rib support in the roof control plan: (1) what is the criterion for deciding if rib support is required or not? and (2) if it is required, what is the rib support density to control rib sloughing? The answers to these questions can be determined empirically by conducting observations of rib conditions for coal mines of different rib compositions and overburden depths. A RibFOS threshold to delineate supported rib cases can be established empirically by classifying the collected data into supported and unsupported cases. The amount of rib support required can be determined by correlating the applied rib support densities in these mines and the calculated RibFOS from Equation 1.

A database has been created from the surveyed coal pillar ribs in underground coal mines. The sources of the rib database are rib data collected by the authors from active underground coal mines in the Eastern United States, MSHA rib fatality reports across the U.S., and reported rib data in Australian coal mines [Colwell, 2004].

Rib Support Criterion

For the period from 2012 to 2019, coal pillar ribs were surveyed for the development loading in 14 room-and-pillar and 8 longwall coal

mines in the U.S. The survey includes 67 rib cases in room-and-pillar mines and 38 rib cases in longwall mines. Table 2 summarizes the recorded rib parameters in the surveyed coal mines. About 43% of the surveyed coal pillar ribs in room-and-pillar mines are not supported.

Coal rib data was reported for 7 longwall coal mines in Australia [Colwell, 2004]. The data of 39 surveyed ribs was reported for the Australian database. Table 3 summarizes the reported rib parameters in Australian longwall coal mines.

The U.S. and Australia coal rib database shows that all coal pillar ribs in longwall mines are supported. Therefore, the decision for rib support is applicable only for room-and-pillar mines. Surveyed coal pillar ribs in room-and-pillar mines show that there are 38 supported rib cases and 29 unsupported rib cases. RibFOS were calculated (using Equation 1) for all coal pillar rib cases (supported and unsupported) in room-and-pillar mines. The classification matrix for coal rib cases in room-and-pillar mines at a RibFOS of 1.0 is shown in Table 4. For a RibFOS equal to 1.0, all supported ribs—38 cases—are correctly classified, while 4 cases out of 29 unsupported rib cases are falsely classified as supported. Therefore, rib support is required during development in room-and-pillar mines if coal pillar ribs have a RibFOS below 1.0. As mentioned earlier, rib hazard assessment was not part of the RibFOS calculation (Equation 1), but rib-fall hazard is already considered when selecting rib support. Therefore, the collected data of rib support practices indirectly includes a degree of rib hazard assessment.

A RibFOS threshold (1.0) for supporting coal ribs was tested against rib data collected from coal pillars at sites with rib-related fatalities (MSHA, 2019). For the period between 2009 and 2019, 12 fatalities were reported in room-and-pillar mines and 1 fatality occurred in longwall mines. In room-and-pillar mines, 9 of the 12 fatalities occurred during the development loading stage and 3 occurred during pillar retreat. The fatality in the longwall mine occurred during longwall retreat. Table 5 summarizes the key parameters of coal pillar ribs at fatality sites. All the fatality cases, except Enlow fork, have either undermining or overmining seams. The interburden thickness ranges between 43 ft and 200 ft. MSHA fatality reports identified multiple-seam interaction as a cause of rib instabilities for #23 mine and 4 West Mine where the interburden thicknesses are 45 ft and 78 ft, respectively.

RibFOS and CPRR were calculated for the fatality case studies using regression equations 1 to 17. The calculated RibFOS for #23 mine and 4 West Mine are 1.09 and 1.21 which it could be even lower if the loading effect of multiple-seam interaction was considered. The RibFOS model (Equation 1) is graphically represented as contour lines in the CPRR-Overburden depth space (Figure 4). Rib data from room-and-pillar mines and fatality cases are projected on the RibFOS model (Figure 4). About half of the fatality cases were predicted using a RibFOS threshold of 1.0. Figure 4 shows that all fatality cases, except the #1 Mine, can be avoided using a RibFOS threshold of 1.5. Considering that the UCS of Elkhorn No. 3 seam in the #1 Mine is 3,436 psi [King and Frantz, 1980], the CPRR at the pillar corner in #1 Mine is calculated as 40 even with the assumption of weak coal/rock interfaces in the coal pillar ribs.

Table 4. Classification matrix of rib cases at development stage

Actual Rib Control Cases	Predicted Based on a RibFOS Threshold of 1		Error
	Supported	Unsupported	
Supported	38	0	0
Unsupported	4	25	14%

Table 5. Coal pillar rib parameters for the fatality case studies

ID	Mine name	Mining method	Mining stage	Depth, ft	Rib height, ft	Support	PRSD, ton/ft ²	S _c , psi
1	Mine #2	R&P	DEV	700	9.3	No	0	2,857
2	Clover Fork #1	R&P	RET	1,762	15	Yes	0.13	3,045 - 5,075
3	Eagle #1 Mine	R&P	DEV	300	8.75	Yes	0.11	1,678
4	P-1 Mine	R&P	DEV	720	6.8	No	0	2,000 - 2,500
5	Kingston #2	R&P	DEV	1,100	5.66	No	0	2,125
6	#23 mine	R&P	DEV	600	8.5	No	0	3,842
7	Huff Creek No.1	R&P	RET	1,640	6.5	No	0	5,000
8	Deep Mine 41	R&P	RET	700	7.5	Corners	n/a	2,278
9	4 West Mine	R&P	DEV	700	7	No	0	3,963
10	Sentinel	R&P	DEV	700	7	Corners	0	3,000
11	CVB NO.1	R&P	DEV	900	9.75	No	0	4,225 - 5,000
12	#1 Mine	R&P	DEV	410	10	No	0	3,436
13	Enlow Fork	LW	RET	1,040	8.5	Yes	0.59	2,500

R&P = Room and Pillar, LW = Longwall, DEV = Development loading, RET = Pillar (Panel) retreat loading

With a shallow overburden depth of 410 ft at the fatality site, the calculated RibFOS for #1 Mine is 1.92, indicating a stable rib. The mechanism of failure in the #1 Mine was not defined as a standard rib fall (Figure 5a), but rather as a localized corner failure because the ribs of the pillar at the fatality site were intact as shown in Figure 5b.

Rib Support Density

Rib support requirements for development loading can be calculated empirically by establishing a relationship between the RibFOS and the applied rib support density. The PRSD in ton/ft² is calculated using Equation 18.

$$PRSD = \frac{\tau_{rb} \times N}{S \times h} \quad (18)$$

where

- τ_{rb} is the anchorage capacity of rib bolt in short ton,
- N is the number of bolts per vertical rib bolt row,
- S is the bolt spacing between vertical rows in ft, and
- h is the mining height in ft.

The anchorage capacity of mechanical rib bolts is determined by the pull-out test (Mohamed et al., 2020c). The anchorage capacity of fully grouted rib bolts is calculated as the product of the short encapsulation bolt capacity times the bolt length. The limited number of pull-out tests conducted by the authors for different encapsulation lengths of grouted rib bolts showed that the anchorage capacity of fully grouted rib bolts is usually limited by the shear capacity of the rebar (Rashed et al., 2020). The shear capacity of the rebar is assumed to be 65% of the yield load of the rebar. Table 2 summarizes rib bolt parameters used in the surveyed room-and-pillar and longwall mines in the U.S. Table 3 lists the bolt parameters reported from longwall mines in Australia. For the mines in Australia, Colwell (2004) found that the square root of shear capacity of the rib bolt is a more appropriate indicator of the bolt's performance in terms of improving rib behavior. The reason for this discrepancy in the shear capacity determination between the U.S. and Australia mines could be that the latter uses higher-strength and larger-diameter rebars (see Tables 2 and 3).

Rib control plans in room-and-pillar mines differ from that in longwall mines. The difference in rib control is not so much about the expected load and abutment pressures during the mining as it is more about operational practices. Longwall mines are typically required to perform rib support during section development before the large stage loader is in place in the belt entry and the large longwall power center is in place on the haulage. It becomes operationally difficult to rib bolt safely or efficiently once those items are in place, so longwall mines become proactive and support the ribs during continuous miner development.

Rib support densities in room-and-pillar and longwall coal mines are treated separately. Figure 6 shows the relationship between RibFOS and PRSD for surveyed coal pillar ribs in 14 room-and-pillar mines and 12 coal pillar ribs associated with fatality accidents in room-and-pillar mines. The maximum limit of the horizontal axis in Figure 6 was set to 2 for better visualization of the plotted data, but 15 unsupported sites that have a RibFOS greater than 2.0 are not shown in Figure 6. A preliminary rib support curve is proposed in Equation 19 for room-and-pillar mines. The proposed rib support curve was defined by three criteria: (1) rib support is not required in coal pillars of RibFOS greater than 1.5, (2) the applied PRSDs for most of the surveyed sites are greater than the design curve, and (3) the PRSDs for most of the fatality sites are smaller than the design curve.

$$\text{Room and pillar PRSD, in ton/ft}^2 = \frac{3.5}{1 + e^{(3.5 \times (\text{RibFOS} - 0.01))}} \quad (19)$$

Figure 6 shows that the preliminary rib support curve satisfied the predefined conditions, except for the coal pillar rib at the fatality site of #1 Mine.

Figure 7 shows the relationship between RibFOS and PRSD for coal pillar ribs in 8 longwall mines in the United States, 7 longwall coal mines in Australia, and a fatality site at the Enlow Fork mine. A preliminary rib support curve is proposed (Equation 20) for longwall mines. The proposed rib support curve was defined by three criteria: (1) the ribs of longwall pillars have a minimum PRSD of 0.1 ton/ft², (2) the applied PRSDs for most of the surveyed sites are greater than the rib support curve, and (3) the PRSDs for most of the fatality sites are smaller than the design criterion.

$$\text{Longwall PRSD, in ton/ft}^2 = \frac{6.0}{1 + e^{(5.0 \times (\text{RibFOS} + 0.03))}} + 0.1 \quad (20)$$

Figure 7 shows that the proposed rib support curve satisfied the predefined conditions, except for the coal pillar rib of the Enlow Fork fatality. The fatality at the Enlow Fork mine occurred in the headgate entry at the longwall face during longwall retreat. The applied rib support density of 0.59 ton/ft² was adequate during the

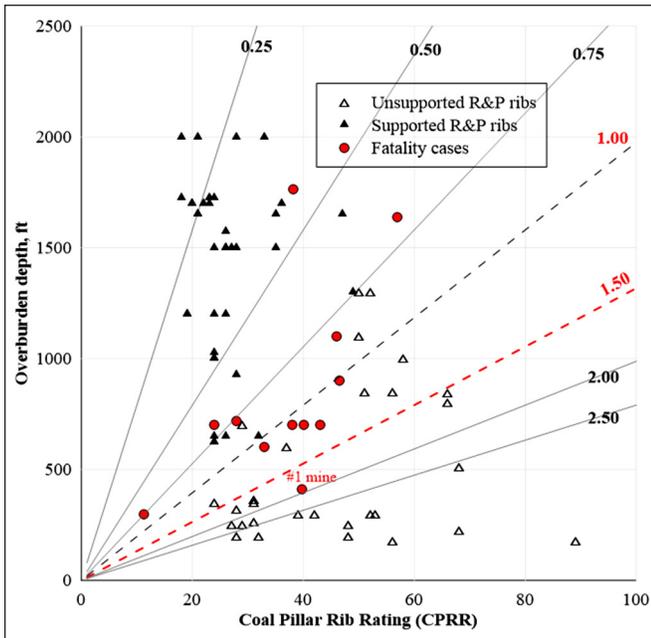
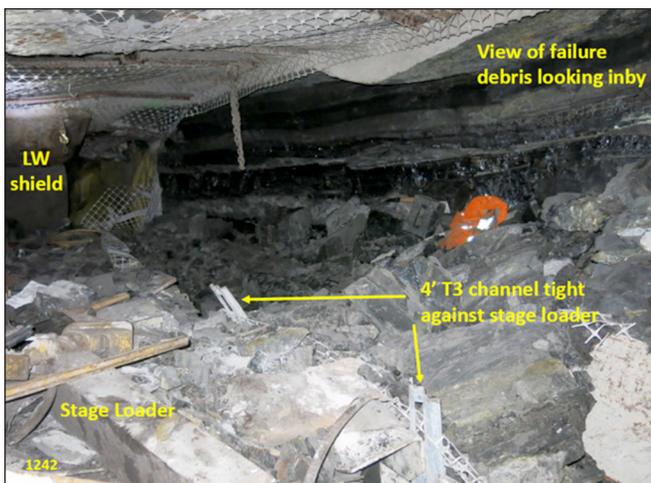
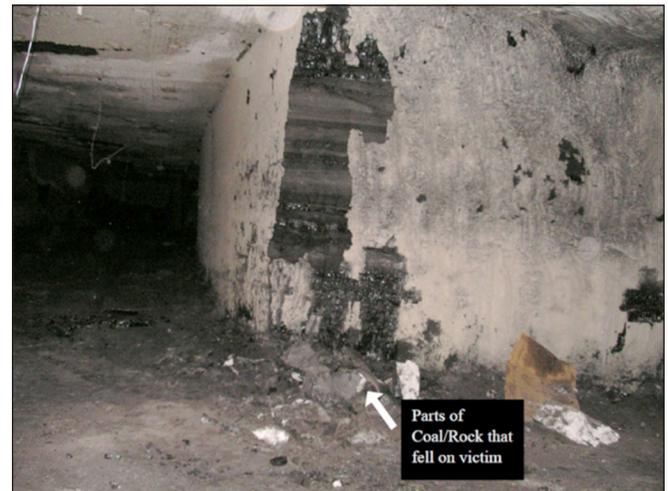


Figure 4. Classification of coal ribs (supported versus unsupported) based on CPRR and overburden depth



(a) Enlow Fork mine, PA



(b) Elkhorn No. 3 coal seam, #1 Mine, Kentucky

Figure 5. Rib fatality sites at Enlow Fork mine and Elkhorn No. 3 (MSHA, 2019)

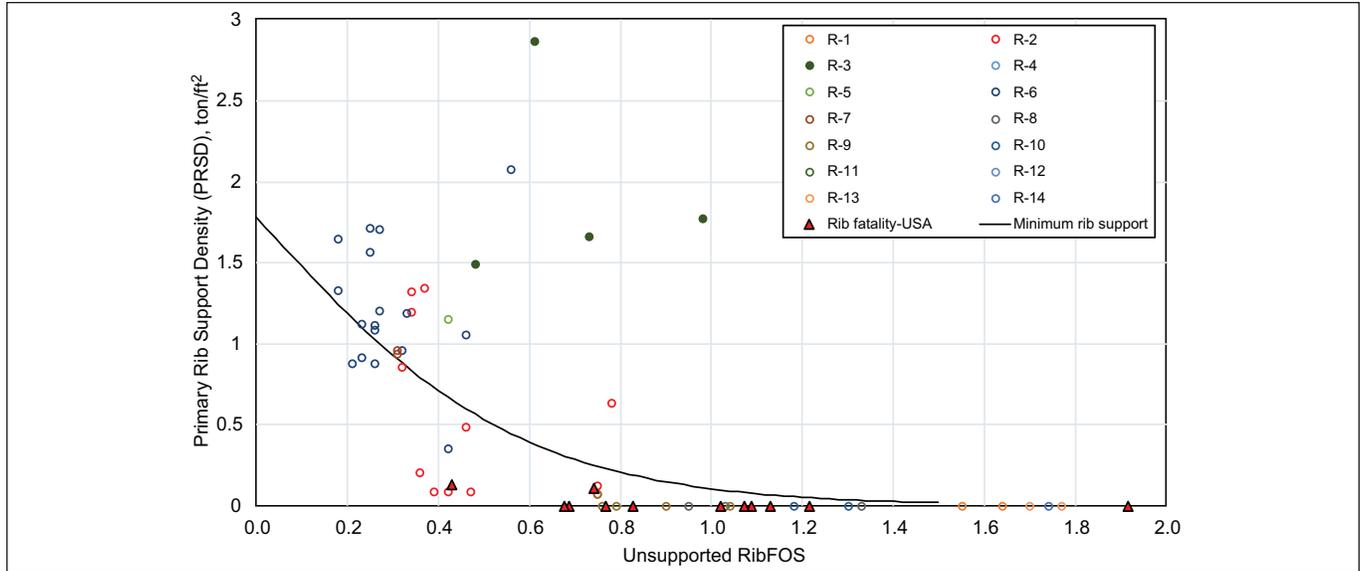


Figure 6. Calculated PRSD versus RibFOS of surveyed ribs in room-and-pillar mines showing the preliminary rib support curve

development stage, but it was not enough to control rib deformation caused by the headgate abutment load.

Rib hazard is indirectly considered in determining the PRSD curves because the rib support densities in the collected rib data, in Figures 6 and 7, contain a degree of rib hazard assessment.

DESIGN OF RIB SUPPORT (DORS)— STANDALONE APPLICATION

Despite the preceding simple steps for calculating CPRR, RibFOS, and PRSD, the calculation steps could be tedious when performing a hand calculation. Therefore, a user-friendly standalone application is being developed to ease the calculations of rib support. The name of the application is Design of Rib Support or simply DORS. The DORS application was developed and compiled as a standalone application using MATLAB, and it is built for the Windows operating systems.

Formations of rib brow are frequently found in coal mines. The current version of DORS does not provide an output for the potential of rib brow formation and its stability. Planned future improvements to DORS include outputs for rib bolt length, the potential for rib brow formation, and rib brow stability.

Figure 8 shows a snapshot of the DORS application. DORS is a single window application that consists of two sections—input and output. In the input section, the user will need to input the following information:

- Site name
- Rib composition:
 - number of rib members
 - type (rock or coal)
 - thickness in feet
 - strength in psi and
 - bedding condition (weak or strong).
- Overburden depth in feet
- Dominant cleat angle, with respect to entry direction, in degrees

- Study location (pillar side or pillar corner)
- Mining method (room-and-pillar or longwall).

After pressing the Calculate button, the output section will be displayed. The output section consists of the following:

- Graphical representation of strength variation of rib composition and location of weak beddings (see red dashed line in rib lithology, Figure 8). This plot helps the user to verify the rib composition input.
- A plot of RibFOS versus a wide range of overburden depths (Equation 1) showing the RibFOS at the study site (solid green circle in Figure 8). This plot shows how the RibFOS could change for a given rib composition as the overburden depth changes. Rib support may not be required for room-and-pillar mines if the RibFOS is greater than 1.5. Therefore, this plot can assist in determining the overburden depth at which rib support may not be required.
- Rib support chart composed of: (1) scatter plot of PRSD versus RibFOS of actual cases and reported fatality cases, and (2) the rib support density rib support curve showing the calculated PRSD at the study site. The application has two design charts: one for room-and-pillar mines (Figure 6) and the other for longwall mines (Figure 7).
- A report of key parameters at the study site:
 - Development rib height,
 - Calculated CPRR,
 - Calculated RibFOS,
 - Rib support decision, required or not required, and
 - Primary rib support density.
- The user can save the report of the study site, including the input parameters and rib design parameters. A snapshot of the study site can be saved or printed.

SUMMARY AND CONCLUSION

Rib falls are a major workplace hazard impacting the safety and health of mineworkers in underground coal mines. Researchers from NIOSH are currently developing an engineering-based rib

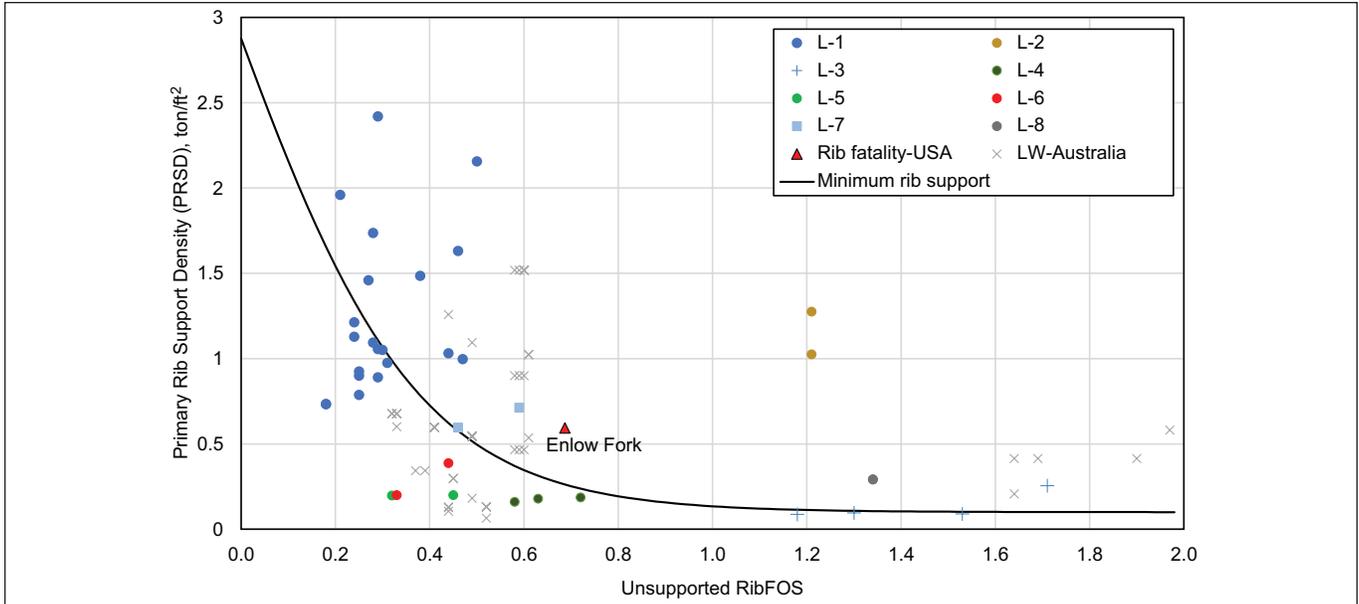


Figure 7. Calculated PRSD versus the RibFOS of surveyed ribs in longwall mines showing preliminary rib support curve

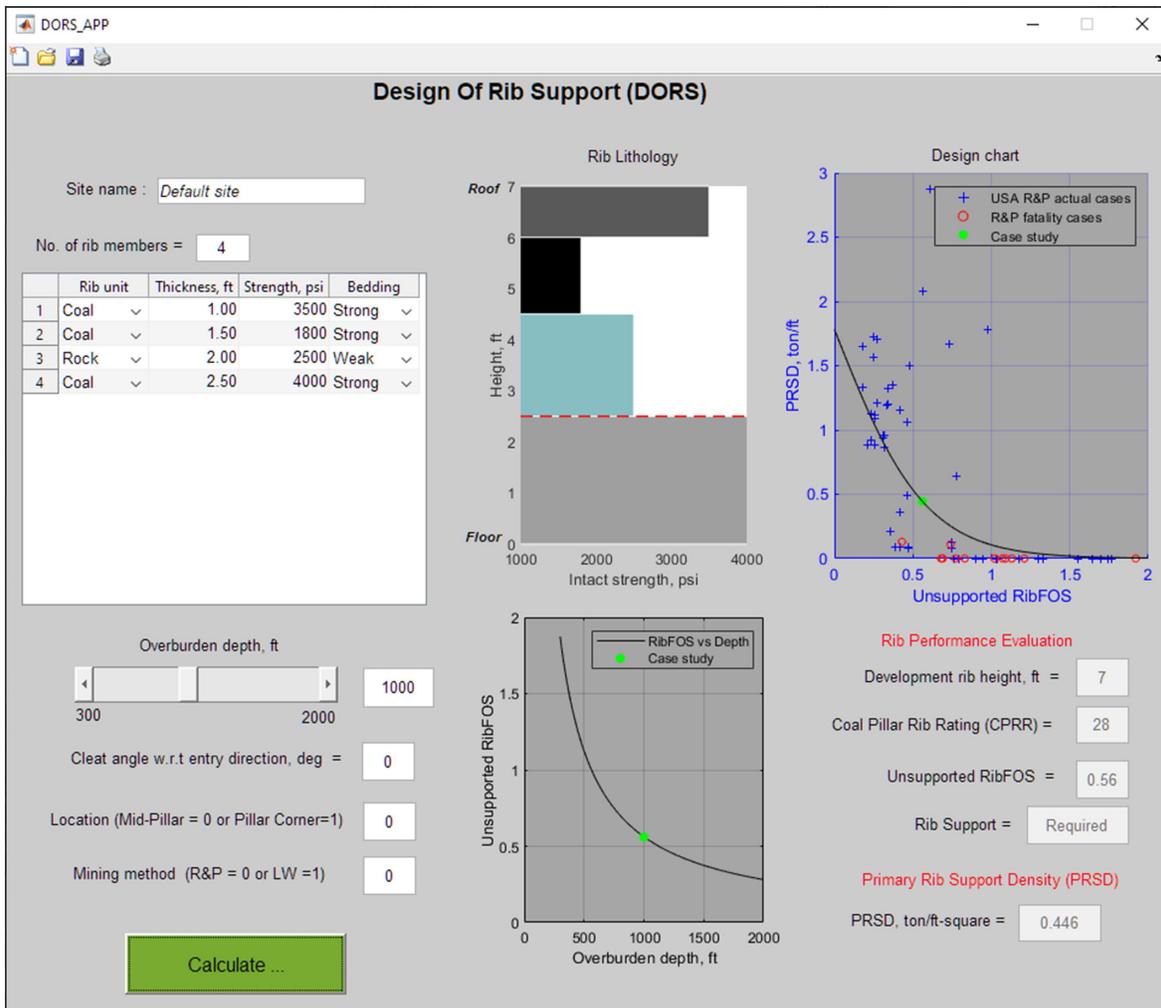


Figure 8. A snapshot of the DORS Standalone application

stability analysis and primary support design for the development mining stage. The update of this ongoing research is summarized in the following:

- The CPRR of solid coal ribs was updated to include the effect of rock partings on rib integrity. The strength of the rock partings and the coal/rock interface conditions are included in the calculation of updated CPRR. The updated CPRR extends the potential applicability of the CPRR in underground coal mines.
- The current rib control practice in longwall coal mines showed that all the surveyed coal pillar ribs are supported. About 43% of the surveyed coal pillar ribs in room-and-pillar mines were not supported. A RibFOS threshold of 1.5 was defined to delineate the boundary between supported and unsupported ribs in room-and-pillar mines.
- Rib support curves to calculate the PRSD are developed for room-and-pillar and longwall mines.
- Simple steps for calculating CPRR, RibFOS, and PRSD are presented. A user-friendly standalone application (DORS) is being developed to ease the calculations of rib support. The DORS application will be a “tool in the toolbox” for mine engineers and operators. DORS should be used in conjunction with site-specific understanding of the mine rib circumstances and how the mining process affects the stability of the coal ribs. Prudent and accepted operational practices are to be observed whenever undertaking the procedure to support the coal mine ribs.
- The DORS program represents the first program of its kind for the analysis of coal rib support in the U.S. that is useful to mine engineers or operators with the impact of reducing mine worker injuries and fatalities. Future versions of DORS will include a calculation for rib bolt length, potential for rib brow formation, and rib brow stability. This future research will extend the potential for usage of the CPRR to most coal ribs.
- The DORS program and the applicability of the CPRR are valid for the range of the studied coal pillar ribs, which are currently being tested through various stakeholders for more study cases of coal pillar ribs.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention.

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