ALPHA FOUNDATION FOR THE IMPROVEMENT OF MINE SAFETY AND HEALTH

Final Technical Report

Project Title: Reducing Rib Hazards in Underground Coal Mines by Improvement of the Coal Pillar Rib Rating (CPRR) System

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1.0. Executive Summary

Despite more than a decade of efforts to evaluate and understand rib performance in underground coal mines, rib-related fatalities in these mines continue to be prevalent. The average fatality rate from rib falls in the U.S. remained steady at around 1.5 per year between 2009 and 2021. Researchers from National Institute for Occupational Safety and Health (NIOSH) have started to develop a new engineering-based rib classification method known as Coal Pillar Rib Rating (CPRR) system. CPRR is a technique to measure the integrity of coal ribs and utilizes empirical field observations and numerical parametric studies to estimate the stability of solid coal ribs. In its original form, the CPRR covers only a narrow range of coal rib conditions and has not been adapted or widely used by the mining industry. The primary focus of this project is to improve the applicability of the CPRR system to a diverse range of coal rib compositions, including rock partings, in-seam beddings, and strong-weak interfaces, with the ultimate goal of minimizing rib failure hazards in underground coal mines. We accomplished this objective through a series of steps which included conducting eight additional coal rib surveys at underground coal mines across the United States, updating the coal-mass constitutive model to be compatible with distinct element-based solvers such as 3DEC, expanding the CPRR system through DEM-based numerical simulations, and developing user-friendly calculation tables and charts for mine operators to determine the CPRR and the rib factor of safety (RibFOS).

The CPRR system has been notably updated with the help of our findings and the collaborative effort between NIOSH and Missouri S&T researchers. The updated CPRR system is now more versatile and can be applied to a broader array of geologic and geotechnical conditions. Additionally, the project has produced easy-to-use calculation charts and tables that enable mine professionals to determine the CPRR at their site without requiring advanced numerical simulations. Moreover, the practical CPRR and RibFOS calculation methodology and methods developed through this research are readily available to the coal mining industry. The developed charts and tables provide a quick and quantitative assessment of the stability of coal pillar ribs, taking into account various parameters such as rib unit thickness, rib unit strength, homogeneity of coal beds, bedding conditions within the coal unit, coal/rock interface strength, and face cleat orientation relative to the entry direction. NIOSH researchers have evaluated and incorporated the outcomes of this project into their rib support design project and Design of Rib Support (DORS) software.

Based on the insights obtained through the project's extensive coal mine surveys, we have collaborated with NIOSH researchers to develop a comprehensive "rib data collection procedure and safety protocol." As part of this collaboration, the existing data collection sheet for CPRR studies has undergone significant enhancements, making it more practical and user-friendly. The updated data collection sheet has been expanded to two pages, aiming to enhance the efficiency and speed of estimating CPRR and RibFOS by mine professionals. To ensure its effectiveness, our team gathered feedback from mine professionals through in-person interviews, identifying and removing sections that were considered unnecessary or overly complex.

In addition, in the initial phase of this study, a comprehensive literature was conducted to assess the effectiveness and weaknesses of existing rib stability systems. Subsequently, in-person interviews were carried out with mining professionals to systematically evaluate their perspectives on the rib rating system and the factors they consider influential in rib behavior based on their field experience. These interviews revealed that mine professionals have a positive outlook on the CPRR system and expressed their willingness to utilize it in their operations.

This study also covers a preliminary analysis aimed at determining the maximum capacity of the primary rib support system. This analysis is crucial in establishing a threshold value that distinguishes the boundary between primary and secondary rib support requirements. The main finding from this analysis, which holds significance for future research, is that RibFOS values below 0.70 would not be stable with primary support.

During the course of this project, we have produced three conference papers, two journal articles, and two academic conference presentations, which constitute a noteworthy contribution to the field of mining health and safety, with a particular emphasis on rib control. These outputs have the potential to make significant improvements to industry practices. Our aim is to utilize the developed system to improve the safety of underground coal mining in the United States, with the ultimate objective of eliminating injuries and fatalities associated with this industry.

2.0 Problem Statement and Objective

The majority of coal mine stability research over the past 30 years has been largely focused on the development of a systematic methodology for coal mine roof support. As a result, there has been a considerable drop in the number of fatalities caused by roof falls in coal mines; however, the majority of fatalities in recent years have been caused by rib and face instabilities. To address this critical area of coal mine support engineering, researchers in key coal-producing countries have been working to develop engineering-based coal rib control methods. However, regardless of ongoing/completed rib-control studies, the prevalence of rib-related fatalities in underground coal mines continues such that the average fatality rate from rib falls in the U.S. remained steady at around 1.5 per year between 2009 and 2021 (MSHA, 2021).

To decrease the rib-related fatalities in underground coal mines and aid mine professionals in rib control, developing a coal rib-specific rating system idea was proposed by Mohamed et al. (2016). Rock mass classification systems are the basic component of empirical mine design and are commonly used to assess the rock mass conditions for support design and stability assessment. Practically all rock mass classification systems are developed based on case histories not pertinent to coal-pillar rib performance, and their direct use for coal-ribs could result in unrealistic outcomes. The coal pillar rib rating (CPRR) was developed at the National Institute of Safety and Health (NIOSH) in response to the lack of a rock mass classification system that considers the unique characteristics found in coal-mass such as cleat density and their orientation, and heterogeneous nature of coal pillar ribs. The CPRR uses empirical data from 22 coal seams in the United States and synthetic data from numerical parametric studies of 201 pure coal ribs (a total of 1,206 Finite Difference Method (FDM) based models using FLAC3D) to quantify the integrity of coal pillar ribs and to aid mine operators in the early selection of coal pillar rib supports. The numerical simulations utilized the Coal-Mass constitutive model, developed by NIOSH researchers (Mohamed et al., 2018), to realistically simulate the loading, deformation, and failure of coal pillar ribs. The face cleat system in the coal-mass model was simulated with anisotropic material properties in the coal material matrix using the ubiquitous joint model available in FLAC3D.

The CPRR uses readily available geologic and engineering data as inputs for a one-page calculation to estimate the structural integrity of coal pillar ribs and determine support requirements for the mining area in question. The inputs include the depth of cover, rib homogeneity, bedding conditions, face cleat orientation with respect to entry direction, and strength of the coal units. The original version of the CPRR covers a limited range of coal rib conditions and has not been widely adapted or used in the mining industry.

The overarching goal of this project was to improve the Coal Pillar Rib Rating (CPRR) system, with the ultimate goal of minimizing the rib failure hazards in underground coal mines. The specific objectives of this project, as outlined in the proposal, included:

1. Conducting coal rib and rib support surveys across the United States in collaboration with our industry partners at Peabody Energy and Arch Coal Resources to expand the CPRR empirical data set beyond the original 22 surveyed coal seams.

2. Adapting the coal-mass constitutive model from its original form used in FLAC3D to make it compatible with 3DEC, a distinct element-based solver that can incorporate discrete discontinuities.
3. Expanding the CPRR calculation with the field survey and 3DEC simulation outcomes taken into account complex geologic settings as plastic roof and floor conditions, thick in-seam rock/coal partings and strong rock/coal brows.
4. Developing a user-friendly CPRR and RIBFOS calculation sheet and methodology

The anticipated outcome of this research is the widespread adaption of the CPRR by coal mining industry across the United States. The enhanced CPRR system will enable mine operators to identify potential hazards in coal pillar ribs in advance, enabling them to proactively mitigate risks through appropriate rib supports.

3.0. Research Approach

The CPRR is a newly developed rating system, and detailed evaluations and improvements are needed to facilitate the widespread adaption and use of this system by the U.S. coal mining industry. This research project is in response to the Alpha Foundation Request for Proposal: *Minimizing Rib Failure Hazard, Subtopic 1: Assessment of Rib Stability Rating Systems*.

To achieve outlined objectives of this effort, the project was divided into six key research tasks designed to analyze and eliminate the barriers in implementing the existing coal rib rating systems, as well as to make improvements that facilitate the use of the CPRR system by the coal mining industry.

Task-1 involved conducting a comprehensive literature review of the currently accepted rib classification and rating systems. In Task-2, the effectiveness and weaknesses of the identified rib rating systems were analyzed. Task-3 examined the potential levels and barriers to implementing the rib rating system by industry. Task-4 involved conducting a field survey of coal ribs, adapting a coal mass constitutive model for distinct element-based numerical analysis, and validating this constitutive model. Parametric studies to produce required inputs for developing the CPRR calculation sheet were the scope of Task-5. Finally, the last task focused on developing the CPRR calculation sheet, which mine operators can use to quantitatively assess rib conditions in the field.

The following sections outline the specific research tasks, their backgrounds, methods, and analyses implemented to accomplish the specific objectives mentioned in the problem statement and objective section.

3.1. Specific Objective 1: Expanding the CPRR Empirical Data Set

3.1.1. Task #1: Review of Existing Rib Stability Rating Systems

Rock mass classification and rating systems are used extensively in rock engineering. However, most of the classification and rating systems found in the literature are inadequate for coal mass classification, as they fail to incorporate significant parameters specific to coal mass, such as cleat density/orientation and heterogeneity. Furthermore, these systems are mainly based on case histories that are rarely relevant to coal mass. As the coal, roof, and floor units vary considerably in their constitution and behavior, different classification systems have been developed to address each constituent. Molinda and Mark (1994) developed the Coal Mine Roof Rating (CMRR) System to use in coal mine roof support selection and design for U.S. coal seams. In addition to roof rating systems, floor, and entry rating systems have been proposed by different researchers recently (Mo et al., 2020; Van Dyke, et al., 2021). The majority of the efforts on coal rib stability have focused on proposing classification/rating systems for rib support design. Table 3.1 presents examples of rib rating/classification systems found in the literature. While most of the presented studies focused solely on visually determining the amount of rib sloughing, some researchers suggest using site-specific parameters, similar to other well-known classification systems. As a result, rib classification system studies are divided into two groups— categorical (C) and empirical (E)—to distinguish a rib rating system by placing ribs in one or more categories based on visual estimates (categorical) or the combination of field measurements (empirical).

Table 3.1 Rib classification systems

Classification/Rating system	Country	Reference	Class*
Rib damage rating	U.S.	Heasley & Chekan, 1998	C
Pillar deterioration index (PDI)	U.S.	Karabin & Evanto, 1999	C
Coal mine classification rating (CMCR)	UK	Whittles, 2000	E
Rib classification system	UK	Bigby & Cassie, 2003	C
The Rib support rating (RIBSUP)	AU	Colwell & Mark, 2005	E
Rib rating	U.S.	Lawson et al., 2012	C
Rib deformation rating (RDR) Rib rating index (RRI)	AU, NW, UK, NZ	Golder Assoc. (Stone, 2016) Stone, 2016	E
Coal pillar rib rating (CPRR)	U.S.	Mohamed et al., 2021a, 2021b	E

*C: Categorical and E: Empirical.

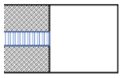
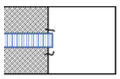
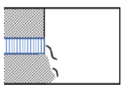
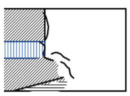
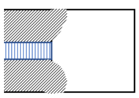
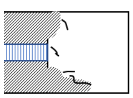
Categorical classification systems

Heasley and Chekan (1998) simulated the stresses of two U.S. coal mines by using a boundary-element code, LaModel (Heasley & Salamon, 1996). They compared model outputs and actual stress mapping results. The authors proposed a rib damage rating for stress mapping ranging from 0 to 5. If the rib is still intact with no sloughed coal and original rock dust in place, the rib is ranked at 0. On the other extreme, a rank of 5 is assigned when the rib is composed of completely broken coal at the angle of repose.

Karabin and Evanto (1999) also performed model simulations to resolve complex ground control problems in underground coal mines. They established deterioration indices for roof, floor, and pillar to describe actual ground conditions and validated their models. The pillar deterioration index (PDI) describes eight different deterioration conditions on a scale from 0 to 5 (from best to most severe). In addition, the 0–5 scale for rib classification was also used by Lawson et al. (2012).

In the literature, risk-assessment-based rib classification systems have also been proposed. In these types of studies, the general risk assessment of the mine is estimated by assigning values between 1-6 to parameters such as geological structure, rib condition, roadway dimension, groundwater condition, and stress changes (Bigby & Cassie, 2003). In the study conducted by Bigby and Cassie, visual descriptions were used for three different U.K. coal mines, and based on these descriptions, six different rib conditions were defined. The rib rating methods used for general purposes have similar ranking approaches. The general comparison of these ratings is presented in Table 3.2.

Table 3.2 Rib classification criteria

Bigby and Cassie (2003)			Heasley and Chekan (1998)	Karabin and Evanto (1999)
	Good	1 - No spalling	0 - Rib still intact with no sloughed coal	0 -Virtually no sloughing
		2 - Minor visible deformation	1 - Very slight pillar sloughage, and some broken coal at base of the rib	1 - Corner sloughing
	Fair	3 - Visible rib movement, upper rib intact and spalling in lower rib	2 - Slight pillar sloughage; broken coal covers one-third of rib	2 - Light perimeter sloughing 2.5 - Onset of pillar stability concerns
		4 - Moderate rib movement, decoupling	3 - Significant pillar sloughage; broken coal is piled halfway up rib	3 - Significant perimeter sloughing 3.5 - Supplemental support required
	Poor	5 - Rib bulging, significant spalling, and failed rib bolts	4 - Severe pillar sloughage; broken coal is piled almost to roof	4 - Severe perimeter sloughing
		6 - Gross rib failure and deterioration	5 - Rib is composed of completely broken coal at the angle of repose; pillar may be failed	5 - Complete pillar failure

<u>Empirical rib classification systems</u>

This section provides a detailed discussion of four different rating systems, presented in chronological order.

- *<u>Coal mine classification rating (CMCR)</u>*

The Coal Mine Classification Rating (CMCR) system was proposed by Whittles (2000). Although many classification systems for coal mining exist in the literature, in the CMCR system, parameters have different weights for rib, roof, and floor conditions. Similar to the RMR system, CMCR uses a linear scale between 0 and 100. The researcher aimed to achieve better acceptance in the U.K. mining industry by developing the CMCR rating directly correlated with RMR.

Fundamentally, the CMCR rating consists of six main and one adjustment parameters. These parameters and calculation algorithms are presented in Figure 3.1. Each parameter can be easily determined from the associated table or graph. The parameters include the coal UCS, moisture content, groundwater condition, as well as information on the geologic characteristics of the coal, such as the presence of bedding planes and the fissility (the ability of a rock to split along flat weakness planes) of coal. This rating system contains several sub-parameters that can reflect the current field conditions. For example, multiple different graphs/tables are proposed by Whittles (2000) to determine each parameter given in Figure 3.1.

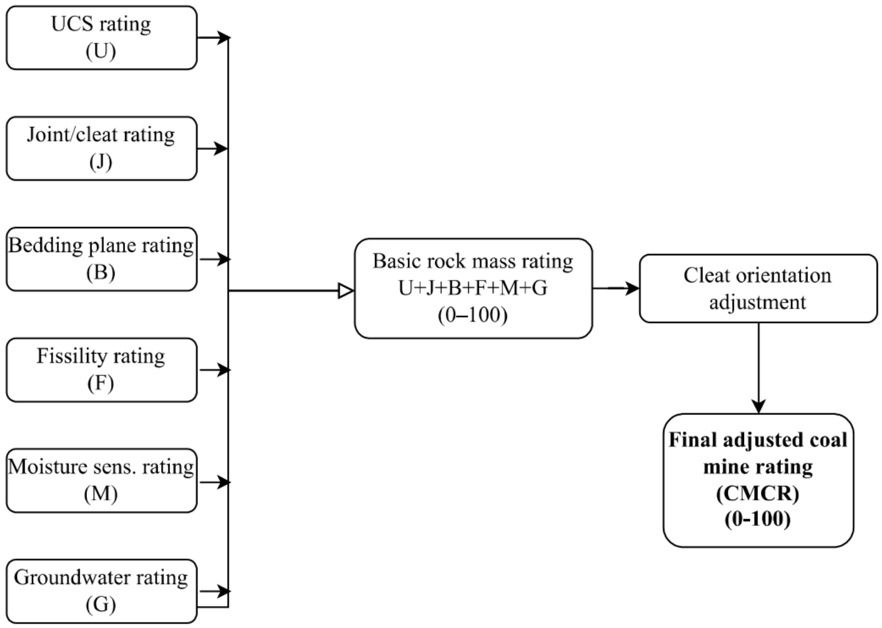


Figure 3.1 CMCR Calculation Algorithm (Whittles, 2000).

The cleat orientation adjustment factor presented in this research was also considered in the studies conducted by different researchers (Figure 3.2). The cleat adjustment rating provides an adjustment of +/− 10 points depending on two parameters: cleat orientation with respect to entry direction and joint roughness coefficient (Barton et al., 1974). As pointed out in the Cleats section of this study, smooth-planar cleat surfaces oriented parallel to the roadway represent the most unfavorable condition for the cleat sets.

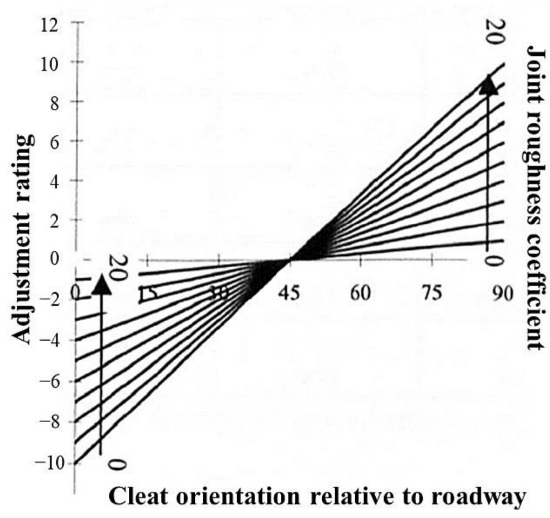


Figure 3.2 Adjustment rating for cleat orientation with respect to entry direction (Whittles, 2000).

Whittles (2000) also presented the percentage significance values of all parameters used in the classification system, considering the five different rib deformation mechanisms defined in his study. According to Whittles, if rib spalling is the primary deformation mechanism, the most significant parameter for spalling is the UCS value. On the other hand, the cleat rating parameter is crucial for the deformation mechanisms of cleat dilation and yield zone development. The importance of UCS and cleat rating is also emphasized in this study. It is noteworthy that the cleat orientation adjustment factor is not included in this important rating study. Table 3.3 presents the critical ratings (in percent) of required parameters for the calculation of CMCR.

Table 3.3 Importance ratings of CMCR parameters (Whittles, 2000).

<table>
<tr><th>Parameters (%)</th><th colspan="2">Sidewall spalling</th><th colspan="2">Sidewall cleat dilation</th><th colspan="2">Shear along joint planes</th><th colspan="2">Wedge/block failure in pillar sides</th><th colspan="2">Yield zone development</th></tr>
<tr><td>UCS</td><td colspan="2">45</td><td colspan="2">10</td><td colspan="2">10</td><td colspan="2">10</td><td colspan="2">20</td></tr>
<tr><td>No cleat sets</td><td>4</td><td rowspan="4">13</td><td>15</td><td rowspan="4">40</td><td>10</td><td rowspan="4">30</td><td>11</td><td rowspan="4">30</td><td>10</td><td rowspan="4">30</td></tr>
<tr><td>Cleat spacing</td><td>3</td><td>15</td><td>10</td><td>12</td><td>11</td></tr>
<tr><td>Cleat profile</td><td>3</td><td>5</td><td>5</td><td>4</td><td>5</td></tr>
<tr><td>Cleat dominance</td><td>3</td><td>5</td><td>5</td><td>3</td><td>4</td></tr>
<tr><td>Bedding spacing</td><td>6</td><td rowspan="2">12</td><td>12.5</td><td rowspan="2">25</td><td>15</td><td rowspan="2">30</td><td>15</td><td rowspan="2">30</td><td>10</td><td rowspan="2">20</td></tr>
<tr><td>Bedding strength</td><td>6</td><td>12.5</td><td>15</td><td>15</td><td>10</td></tr>
<tr><td>Fissility</td><td colspan="2">15</td><td colspan="2">15</td><td colspan="2">15</td><td colspan="2">15</td><td colspan="2">15</td></tr>
<tr><td>Water flow</td><td>10</td><td rowspan="2">15</td><td>7.5</td><td rowspan="2">10</td><td>8</td><td rowspan="2">13</td><td>10</td><td rowspan="2">15</td><td>8</td><td rowspan="2">15</td></tr>
<tr><td>Moist. sensitivity</td><td>5</td><td>2.5</td><td>5</td><td>5</td><td>8</td></tr>
</table>

- *The rib support rating (RIBSUP) & analysis and design of rib support (ADRS)*

Colwell (2005) has conducted research to provide a rib support design methodology for the Australian coal industry. To propose the Analysis and Design of Rib Support (ADRS) methodology, 204 case histories were collected from Australian coal mines. According to our literature review, this study is the first systematic study to develop a rib support design technique for underground coal mines worldwide. The Rib Support Rating (RIBSUP) methodology constitutes an essential part of this research to estimate the support density of the supported ribs. Risk assessment analyses have also been performed, as this project's scope is to classify all case histories for five different risk levels.

RIBSUP is developed for coal ribs, and it has three components: RBOLT – bolting capacity per square meter of rib, FPLATE – relative effectiveness/confinement offered by the face plate, and CF – confinement offered by a liner. These measures can be calculated by the following equations:

$$\mathrm{RBOLT} = \frac{L \times N \times \sqrt{S_{\mathrm{h}}}}{S \times h}\ , \qquad \mathrm{FPLATE} = \sqrt{\frac{A_{\mathrm{FP}}}{A_{\mathrm{SP}}}}, \qquad \mathrm{CF} = 1 + \left(3 \times \frac{A_{\mathrm{L}}}{100}\right), \qquad (1)$$

where L is the length of the rib bolt-dowel (m); N is the average number of rib bolts-dowels per vertical row; S_h is the shear strength of the rib (kN); S is the spacing between vertical rows of bolts-dowels (m); h is the development height; A_{FP} is the area of face plate; A_{SP} is the area of the standard plate; and A_L is the covered surface area with the liner (%). A_{SP} was taken as 0.084 m^2 and 0.165 m^2 for Australian and U.S. coal mines, respectively. The RIBSUP rating can be calculated by multiplying RBOLT and CF (where a liner is used) or RBOLT and FPLATE (where a face plate is used). The ADRS system gives relatively significant weight to the use of liner.

With the logistic regression analysis performed within the scope of the research, the four parameters that affect the rib performance the most were determined. Accordingly, it is presented that the average pillar stress (σ_P) has a 35% effect on rib performance, followed by the RIBSUP value with 29%. Development height (h) and Hardgrove Grindability Index (HGI) also impact rib performance (25% and 10%, respectively). Colwell and Mark (2005) reported a discriminant equation for the direct estimation of the RIBSUP value using the above-mentioned three significant parameters. It should be noted that Colwell and Mark's findings are associated with maingate/tailgate loading conditions. Further details of the analyses associated with the other loading conditions can be found in Colwell (2005). If a mining professional is planning to design ribs with a moderate-low level of risk, the following equation is recommended with an 85% success rate:

$$\text{RIBSUP} = 41\,h + 2.58\,\sigma_{\text{p}} + 0.47\,\text{HGI} - 169 \qquad (2)$$

Various support systems have been suggested to keep the pillar rib at moderate to moderate-low risk levels at the end of this extensive study. Mining professionals can estimate the suggested support system using the average pillar stresses on the rib and the RIBSUP values as summarized in Table 3.4.

Table 3.4 Recommended support levels for various RIBSUP and σ_P values (Colwell & Mark, 2005).

Moderate risk		Moderate-low risk		Suggested rib support level
RIBSUP	σ_p (MPa)	RIBSUP	σ_p (MPa)	
>2.5	>11	>5	>8	Rib support should be installed.
>6	>13	>11	>10	Steel bolts & plates are preferred to cuttable support.
>40	>23	>6	>13	Steel bolts & plates should be utilized.
>10	>15	>11	>10	Some form of liner (i.e., straps or mesh) is preferred.
>20	–	–	>13	Some form of liner (preferably mesh with a CF ≥ 2.5) should be utilized.
>50	>23	>20	>20	Mesh (preferably steel with a CF ≥ 2.5) should be utilized.

- *Rib deformation rating (RDR) and rib rating index (RRI)*

Rib Deformation Rating (RDR) is an empirical classification parameter proposed by Golder Associates (Stone, 2016) and utilized to estimate primary rib reinforcement density. The estimation based on the collected database consists of case histories from over 40 coal mines in Australia, New Zealand, the U.K., and Norway (Stone, 2016). According to the projects carried out by Golder Associates, roadway height and depth of cover are significant factors influencing rib behavior, so the proposed RDR value is a combination of these parameters. Using the RDR value, the primary reinforcement density index (PRDI) is estimated with the graph presented in Fig. 15. PRDI (in MN/m) consists of the axial capacity of the roof bolt, the number of bolts per row and row spacing, length of the installed bolt, and roadway width. In this system, generally, an RDR rating of less than 500 represents a good rib condition, a rating between 500 and 1000 RDR is associated with moderate conditions, a rating between 1000 and 2000 RDR indicates moderate to poor rib conditions, and a rating greater than 2000 RDR reports poor to very poor rib conditions. An important point regarding the upper and lower limit intervals in Fig. 15 should be noted—the angle between cleat orientation and roadway direction being 20° is interpreted as critical. When this orientation difference is above 20°, the design value lies between the upper design and regression lines. On the contrary, if the difference is below 20°, the value approaches the lower design line. According to this interpretation, it has been observed that additional ranking points can be added in future classification systems in cases where the angle between the cleat orientation and the roadway direction exceeds 20°.

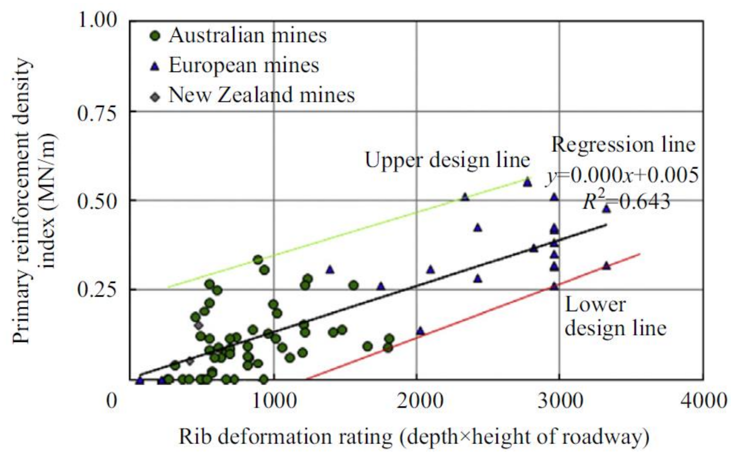


Figure 3.3 Golder's primary rib support database (Stone, 2016).

RDR is a highly general value, and when it intersects with three different design lines presented in Figure 3.3, a wide range of PRDI values can be estimated. Therefore, using the upper design line value is considered suitable for practical use in estimating the maximum preliminary reinforcement density. This study also presents a general trend between a calculated RDR value and bolt length. This general trend is shown in Figure 3.4 just to provide an idea of it on a global scale.

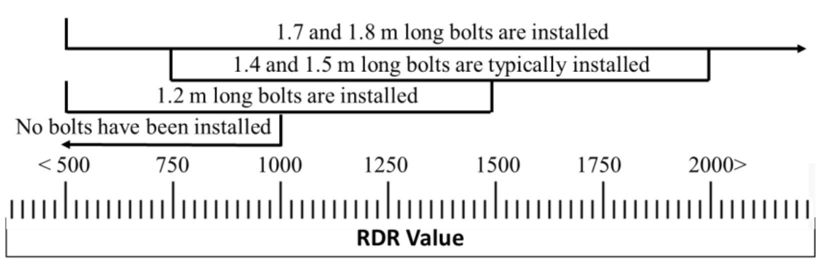


Figure 3.4 General trend between RDR and bolt length (Stone, 2016).

Stone (2016) updated the RDR to take into account the critical coal strength parameter by proposing a Rib Rating Index (RRI). An in situ coal strength parameter was added by performing back analysis for all existing cases in the current database. The proposed RRI can be calculated as follows:

$$\mathrm{RRI} = \frac{H \times R_{\mathrm{h}}}{S}, \tag{3}$$

where H is the depth of cover in meters, R_h is the roadway height in meters, and S is the average in situ coal strength in MPa (determined using a Sonic-derived UCS from site-specific geophysical data). The database has been updated only for Australian collieries, taking the form presented in Figure 3.5. As it can be seen, although the regression coefficient value remains steady, the upper and lower design lines get closer to each other.

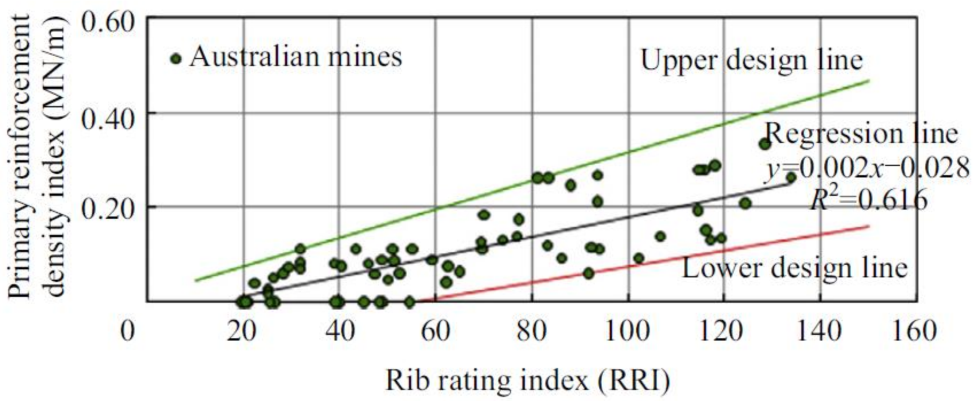


Figure 3.5 Updated database (RRI versus PRDI) (Stone, 2016)

- *Coal pillar rib rating (CPRR) system*

Researchers at NIOSH conducted a comprehensive mining project to propose a design methodology for rib control in coal mines. A new engineering-based rib classification method, the Coal Pillar Rib Rating (CPRR) system, is currently being developed. Similar to the widely used rock mass rating systems, CPRR uses a linear scale between 1 and 100. CPRR 1 designates the weakest pillar rib, and 100 designates the strongest pillar rib. A hybrid numerical-empirical approach is being used for the proposed rating system. The empirical data gathered from 22 underground coal mines in the U.S. and over 1500 numerically generated data are the basis of the CPRR system. The CPRR was developed using underground site observations, calibrated and validated rib models, and the findings presented in published papers pertaining to geology and underground coal rib performance. Through the examination of current rib support practices and techniques in U.S. coal mines, three distinct rib categories were identified: (1) solid coal ribs with no partings or parting thickness less than 5 cm, (2) coal ribs with greater than 15 cm in-seam partings, and (3) coal ribs with a roof brow (Figure 3.6). Among these rib categories, the original form of CPRR is only applicable to solid coal ribs without partings and with thin partings (< 5 cm) (Mohamed et al., 2019).

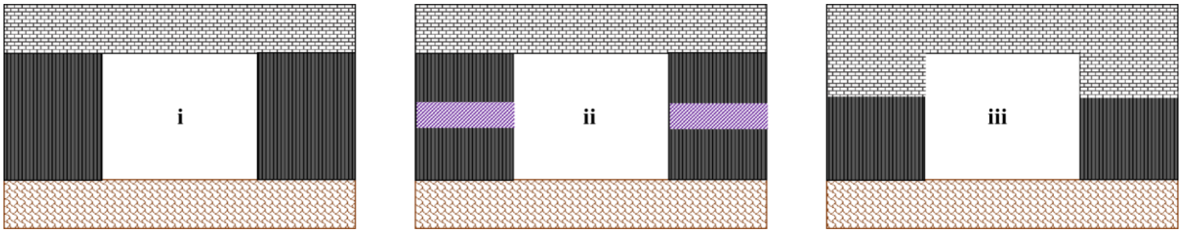


Figure 3.6 Main rib categories, after Mohamed et al. (2019).

In the rib data collection procedure, various parameters potentially affecting rib performance were recorded. These parameters are entry dimensions and orientation, overburden depth, spalling block size, spalling-sloughing type, coal brightness, groundwater condition, coal unit thicknesses, face and butt cleat properties (spacing, persistence, orientation, condition), current support practice, and rib deterioration index. It is worth noting that such a detailed parameter collection has not been done in any previous rib study. Moreover, it is observed that the prepared table for the determination of the rib deterioration index is consistent with the previous studies as stated in the general rib classification systems section.

A parametric study was carried out for the numerical model part of the study by analyzing the collected field data. A continuum-mechanics-based coal mass constitutive model, developed by Mohamed et al. (2018), was used in the numerical modeling part of the study. FLAC3D was used to simulate 201 different rib conditions for solid coal pillar ribs and 287 coal pillars with rock partings of different compositions (Mohamed et al., 2021a, 2021b). As a result of the parametric studies, a one-page practical user-oriented CPRR calculation sheet was developed.

According to the developed methodology, CPRR has five parameters (measurable in the field): rib homogeneity strength, bedding condition, rock parting condition, face cleat orientation with respect to entry direction, and coal unit thickness. Mohamed et al. (2021b) updated the developed CPRR to be used for the first rib category and are working to extend the potential for usage of the CPRR for most coal ribs in collaboration with researchers at Missouri S&T.

The calculation methodology of the CPRR is summarized in Table 3.5. Each parameter presented in this table is calculated using different equation(s). Further information can be found in Mohamed et al. (2021b).

After the CPRR is determined, the factor of safety of the pillar rib (RibFOS) and the performance categories of solid ribs can be estimated by Eq. (4). Also, four different performance categories are presented depending on RibFOS values. The RibFOS values of 0.9, 1.5, and 4.5 are the boundaries of these categories.

$$\mathrm{RibFOS} = 6.02 \times \frac{\mathrm{CPRR}}{\text{overburden depth (m)}} \tag{4}$$

In the final part of this paper, an empirical relationship between the RibFOS and the applied rib support density is presented based on surveyed cases. The support density is proposed in the primary rib support density index (PRSD) from Eq. (5):

$$\mathrm{PRSD} = \frac{\tau_{\mathrm{rb}} \times N}{S \times h}, \tag{5}$$

where τ_{rb} is the anchor capacity of rib bolts (t); N is the average number of rib bolts-dowels per vertical row; S is the spacing between vertical rows of bolts-dowels (m); h is the development height. The PRSD formula overlaps with the RBOLT formula offered by Colwell and Mark (2005). Mohamed et al. (2021a) preferred using pull-out test results to bolt shear strength values.

Table 3.5 CPRR calculation steps (Mohamed et al., 2021b).

(i) Measure the rib height and thickness of each coal and parting unit	
(ii) Find the UCS of each coal and parting unit	
(iii) Calculate the weighted average UCS *(use i and ii)*	
(iv) Measure the angle between face cleat orientation and roadway direction	
(v) Mark the bedding condition	
(vi) Calculate rib homogeneity index (r) (min $\left[\frac{\sigma_k}{\sigma_{k-1}}, \frac{\sigma_k}{\sigma_{k+1}}\right]$ σ_k: minimum UCS of rib unit)	
Parameter 1: *The rib homogeneity rating*	**$\beta(i)_h$**
Use (iii) and (vi)	
Parameter 2: *Bedding condition rating*	**$\beta(i)_{\text{in-seam-bedding}}$**
Use (iii) and (v)	
$\boxed{\beta(\mathrm{i})_{\mathrm{h}} + \beta(\mathrm{i})_{\text{in-seam-bedding}} = CURBASIC}$	
Parameter 3: *Adjustment for the adjacent rock parting and the condition of the coal/rock interface*	**$\alpha(i)_{parting}$**
Use (ii) and CURBASIC	
Parameter 4: *Adjustment for the thickness of coal units*	**$\alpha(i)_t$**
Use (i) and CURBASIC	
Parameter 5: *Face cleat orientation adjustment*	**$\alpha(i)_{cleat}$**
***Applicable when iv* ≥ 20°**	
Use (iii)	
$CURBASIC + \alpha(\mathrm{i})_{\mathrm{parting}} + \alpha(\mathrm{i})_{\mathrm{t}} + \alpha_{\mathrm{cleat}} = CUR(\mathrm{i})$	
$\boxed{\mathbf{CPRR} = \min_{\mathbf{i=1:n}}[\mathbf{CUR(i)}]}$	

Users can also reach the suggested PRSD value by estimating the RibFOS using the CPRR value. Since the rib support practices are different for room and pillar, and longwall mines in the U.S., Mohamed et al. (2021b) proposed separate equations for each mining method. Estimated PRSD values can be calculated by Eq. (6). If CPRR users already know the current PRSD values, they will be able to estimate the RibFOS values from the proposed graphs.

$$\text{Room and Pillar PRSD}\left(\frac{\mathrm{t}}{\mathrm{m}^2}\right) = \frac{37.66}{1 + e^{(3.5\times(\mathrm{RibFOS}-0.01))}}$$

$$\text{Longwall PRSD}\left(\frac{\mathrm{t}}{\mathrm{m}^2}\right) = \frac{64.56}{1 + e^{(5\times(\mathrm{RibFOS}+0.03))}} + 0.1 \tag{6}$$

In order to provide users with practical calculations for CPRR, RibFOS, and PRSD, a MATLAB-based application called Design of Rib Support, or simply DORS, is proposed. It is noteworthy to mention that all the proposed equations for the CPRR system were updated according to the finding of this project.

3.1.2. Task #2: Determine the Effectiveness and Weakness of the Existing Rib Stability Rating Systems

- *Overall Assessment*

CMCR

When the CMCR rating system is examined categorically, it is observed that the parameters are determined in a very detailed manner by considering the entire rock and coal mass rating literature. Although there is the impression that the CMCR rating value can be found with 6 + 1 parameters, upon detailed examination, it is observed that mining professionals need 14 parameters to assign the ranking value. For simplicity and ease of application, it is essential that a few parameters to be used to estimate the overall rib ratings. The CMCR may have been used in U.K. coal mines after it was published in a doctoral dissertation. However, there is no evidence of its practical application in any published literature.

Another critical point is that the proposed rating systems must be supported with case histories to gain the trust of mining professionals. Unfortunately, the rib rating part of the CMCR classification system has not been updated since its development. Updates were made by adding case histories and numerical model results (Whittles et al., 2007). This research, which is thought to be highly effective in its use, is included in this review, as it has potential in rib classification and is considered functional for further studies.

RIBSUP and ADRS

The RIBSUP rating and ADRS tool were based on more than 200 case histories from Australian collieries, dealing with both mains and gateroad development. Although the design recommendations presented are specific to the Australian coal industry, the data collection and analysis parts are applicable to other countries coal mining operations. Indeed, the RIBSUP rating system is also used to analyze the current rib support practices in U.S. coal mines. An attempt has been made to correlate RIBSUP value with significant design parameters for U.S. coal mines, such as mining depth and spall volume, but an apparent relationship could not be observed (Mohamed et al., 2016a, 2016b).

Colwell (2005) also developed a computer-based design tool called ADRS for Australian collieries. This research project is thought to be used very effectively for coal mines across the Australian continent. Two factors stand out that make this study functional: (1) the estimation of RIBSUB values can be done using only three parameters (h, σ_P, and HGI), and (2) preliminary support design recommendations can be obtained practically. It is notable that the proposed ADRS system is not a prescriptive technique; however, it is an assisting tool for mining professionals to assess their rib support requirements in the context of the risk assessment process.

To our knowledge, Colwell (2005) is the first in the literature to suggest using the Hardgrove Grindability Index (HGI) to determine rib classification/rating. HGI measures the ease of size reduction of coal, which represents a composite physicomechanical property. HGI can also be correlated with UCS, Schmidt hardness, and point load index values (Mark & Barton, 1996; Tiryaki et al., 2001). However, it is thought that it would be more appropriate to correlate the coal strength (UCS) instead of using the HGI value in predicting rib behavior. Although such a correlation may have been made considering the unique nature of Australian coal seams, HGI cannot be correlated with support requirements in U.S. coals (Mark and Barton, 1996; Jones et al., 2014). Moreover, as opposed to common knowledge in ground control, the effect of cleat presence is not considered a significant parameter for the rib support estimation based on the result of statistical analyses carried out by Colwell (2005).

RDR and RRI

The empirical classification system presented is based on 40 different case histories. If more detailed information about case histories were used while creating the database, it is thought that more precise estimates could be made. For example, since effective parameters for rib behavior such as cleat density, cleat mechanical properties, condition-type of bedding in the coal seam, and cleat direction with respect to roadway were not taken into account for the estimation, this rating system can generally be able to make a rough estimation.

CPRR

It is evident that the developed rating system is the most detailed study done for pillar ribs so far. During the database construction phase, various data from over 20 coal mines were collected in accordance with the developed procedures. The detailed data collection procedures ensured the reliability of the collected data and their comparability with each other. The CPRR system has been developed using the collected data and the synthetic data generated from numerical parametric studies. However, the majority of the data used in CPRR are synthetic data. It is clear that expanding empirical datasets can enhance the accuracy of the CPRR system. The number of empirical cases in well-known rock classification systems is expressed in hundreds. Thus, it is thought that adding more case histories and verifying the recommended CPRR values with new cases is essential to use the CPRR technique more widely. Also, additional data sets significantly enhance the proposed rib support design line.

The data collected in the field for the CPRR database are very analogous to the previous studies. The rib deterioration index table has also been used in previous studies (Karabin & Evanto, 1999; Heasley & Chekan, 1998; Mo et al., 2020). In addition, the cleat orientation adjustment factor has been used very similarly by other researchers (Whittles, 2000). Besides, giving the rib category to which the CPRR is valid also shows the study's sensitivity.

The original form of CPRR only applies to solid coal ribs without partings and thin partings (less than 5 cm thick). However, most US coal mines have thick rock partings and multiple coal units with weak interfaces. Improvements are needed to facilitate the widespread adaption and use of this system by the U.S. coal mining industry.

Since the impact of mining height on rib stability has not been observed in their numerical models, which contradicts the field observations, the mining height has not been included in the rating system. This is one of the main limitations of the CPRR system.

The stress-driven failure mechanism is simulated in the parametric studies performed while developing the CPRR. However, kinematic failure, which is another common failure mechanism, and the situations where these two mechanisms cause failure together could not be solved by numerical modeling due to the continuum-mechanics-based nature of the code.

In addition, researchers agreed that continuum mechanics-based models of rock support structures do not capture the complete complex interaction between support and the rock material (Esterhuizen, 2012; Tulu et al., 2016; Bahrani and Hadjigeorgiou, 2018; Sunkpal and Sherizadeh, 2021). This is due to the fact that continuum-based numerical models are incapable of capturing large-scale deformation, as well as the detachment/separation and rotation of rock components. Therefore, their numerical modeling approach is not suitable for assessing the efficacy of rib support but rather useful for estimating the stability of unsupported coal ribs.

The main objective of this project is to address the above-mentioned limitations by expanding the field data set, incorporating the influence of mining height, and conducting parametric studies using discontinuum mechanics-based models. The ultimate goal of this project is to promote the widespread use of the enhanced CPRR by coal mining engineers across the US, as the research team believes that the updated version of CPRR holds significant potential for achieving this goal. The improvements in the CPRR system are presented in the following sections of this report.

- *Comparison of the available rib classification/rating systems*

This section analyzes the main similarities and differences between studies that can be considered categorical and empirical rib classification/rating systems. Studies classified as categorical classification systems only include visually analyzed rib conditions and typically assign a point value for rib condition. Another common characteristic of categorical rib classification study cases is that the obtained rib classification rating value is only used to specify the current rib state quantitatively. Although the determined rib rating value has been evaluated as a risk factor in some studies, generally, these values cannot be used for purposes such as primary support estimation or rib factor-of-safety evaluation. It is observed that the studies made for this categorical classification form a basis for subsequent empirical studies. It is noteworthy that the concept of the "rib deterioration index" utilized in recent studies was developed by considering these initial studies.

Four rib rating studies that can be evaluated as empirical methods are analyzed by considering their strengths and weaknesses. In these studies, the concepts considered critical, such as parameters used for the rib rating estimation, practicality of use, and preparation methodology, are also compared.

First of all, the considered parameters for developing the rating systems and the parameters required for the calculation are presented in Table 3.6. According to Table 3.6 table, many parameters are considered for the development of CMCR and CPRR as compared with other systems. Overburden depth, rib height, and strength-stress parameters, known to be significant, are considered in almost all classification systems. On the other hand, fissility, moisture, and Hardgrove Grindability Index parameters are considered and then used in only one system.

Table 3.6 Considered and required parameters for rib rating/classifications.

	CMCR (U.K.)	RIBSUP-ADRS (A.U.)	RDR- RRI	CPRR (U.S.)
Overburden Depth	–	C	C, R	C, R
Rib Height	–	C, R	C, R	C, R
Strength-Stress	C, R*	C, R	C, R	C, R
In situ	–	C, R	C, R	C
UCS	C, R	–	–	C, R
Cleat / Joint	C, R	C	–	C, R
Orientation	C, R	C		C, R
Spacing	C, R	–		C
Persistence	C	–		C
Condition	C, R	C		C
Bedding Plane	C, R	–	–	C, R
Type	C, R			C, R
Condition	C, R			C, R
Groundwater	C, R	–	–	C
Mining Direction	C, R	C	–	C, R
Roof & Floor Conditions	–	–	–	C
Support Density	–	C, R	C, R	C, R
Fissility-Moisture	C, R	–	–	–
Hardgrove Grindability Index	–	R	–	–

C: Considered; R: Required for calculation

Suppose the classification systems are evaluated only by considering them in terms of used/required parameters. In these cases, CMCR and CPRR systems come to the forefront. It must be noted that the cleat and bedding plane parameters are critical and should be used in rating calculations. When the practicality concept is considered, the RDR-RRI system is thought to be the most effective system. CPRR calculation is also practical as well compared with the other systems. Although the number of case histories used in the RDR-RRI system is much more than those in the other systems, the variety of data is limited. For example, parameters such as rib condition, cleat, or bedding information were not included. Therefore, in the estimations to be made with this system, the actual field conditions may not be represented precisely, and a broad range of rating values may be obtained. On the other hand, CMCR, the system requiring the largest number of parameters in the calculation, is based on only three case histories. While generating the database, it is recommended to use the field data based on as many reliable, representative parameters and larger sample sizes as possible. If feasible, increase the data of the rating system by performing parametric studies with numerical approaches.

As a result of the evaluation made among empirical classification systems, strong (green) and less strong (yellow) features of each system were determined, as shown in Table 3.7. It should be noted that this assessment is only our opinion and highlights the strengths and weaknesses, not to praise or disparage a researcher's work but to critique the research.

Table 3.7 Strong and less strong features of rib rating/classification systems.

	CMCR (UK)	RIBSUP-ADRS (AU)	RDR- RRI	CPRR (U.S.)
Number of cases (Sample size)				*
Considered-Collected Param.				
Required Param. for calculation				
Practicality				
Applicability to specific conditions				

* Collected data and the synthetic data generated from validated numerical studies

None of the classification systems examined above, or even the systems that are likely to be developed in the future, can make successful estimations if the field data is (1) not sufficient to reflect the mine site, (2) poorly collected/biased, and (3) not collected in accordance with procedures/standards.

3.1.3. Task #3: Examine the Level and Barriers to Implementation of the Rib Rating Systems by Industry

The eventual widespread use of the improved CPRR by coal mining engineers throughout the United States is one of the major expected outcomes of this project. As the intended end users of CPRR will be mine professionals, their prejudices, general thoughts, and practices regarding coal rib control should be analyzed in detail. The main purpose of this task is to conduct a systematic evaluation of the views of mine professionals for using the rib rating system and the parameters that they believe impact the rib behavior based on their field experience. It was decided that the questionnaire technique was the most effective method of making this assessment. In the preliminary interviews with mine managers and engineers, we realized none had detailed information about the CPRR or any other rib rating system. For this reason, a detailed 5-page document describing the CPRR system has been prepared. Afterward, a questionnaire consisting of nearly 100 questions, and this document was sent to mine professionals. This method was not attractive to mine professionals, and we received only a few completed questionnaires. Received comments and results indicate that the mine professionals did not read the 5-page document, filled out the questionnaire, and submitted it without reading it.

Therefore, the project team decided it would be more appropriate to implement this questionnaire by asking the mining personnel during the mine surveys via in-person meetings. As this project's scope, we have visited seven coal mines to expand the empirical dataset. During these site visits, we conducted in-person meetings with 3-4 mine professionals for each mine. We had a chance to share detailed information about the CPRR system and the data collection procedure. After these meetings, we implemented a significantly shortened questionnaire to ensure that the results would reflect their opinions and expertise. Since the questionnaire should follow a straightforward pattern that makes it feasible for the respondent to fill it out within a few minutes and should quantitatively provide information, we decided to prepare the questionnaire using a Likert scale (Likert, 1932). This rating scale method is extensively utilized in survey research and the social sciences. The main purpose of using this scale is to quantitatively compare various mine experts' preferences, opinions, and attitudes. Our questionnaire consists of two parts based on statements with multiple-choice answers. The prepared questionnaire was applied to 22 mine professionals from 7 different underground coal mines, with a maximum of 4 respondents in each mine. The individuals who participated in the survey held senior positions as either geotechnical engineers, mine engineers, or mine managers.

The first part of the questionnaire focuses on understanding the potential of mine professionals to utilize a rib rating system and the approaches they apply for rib control in light of their experience. The second part is intended to analyze/verify the impact of a wide range of parameters when deciding their pillar rib support type/density. The questionnaire results for the first part are presented in Figure 3.7. In the available literature, some researchers emphasize the impact of roof and floor conditions on rib stability. Klemetti (2020) stated that it is critical to study the entire roof/floor/rib and strata system holistically, as we proposed in this project, rather than just the ribs in a "black box." The first question is intended to verify the necessity of one of our subtasks to include the effect of different roof/floor strata conditions on the CPRR system. Similar to our literature findings, over 90% of respondents observed the impact of roof/ floor strata on the stability of their ribs, which emphasizes the necessity of including these conditions in the CPRR system. Similar to our literature findings, most of the mine professionals are using their local practices and experiences for rib control instead of conducting numerical models. All respondents believe that experiences of other US coal mines may be useful for their rib control study. This information emphasizes the importance of expanding empirical datasets for enhancing the CPRR. In addition, during the interviews after the questionnaire, most of the mine professionals recommended that the number of empirical data sets from US coal mines included and to be included in the CPRR system should be increased. The general trend among mine professionals is that they are confident with their rib control strategy, and over 60% are not encountering any unpredictable rib instability problems in their current operations. However, they believe it is necessary to quantify the current state of their ribs. In addition, for the preliminary rib support designs, classifying coal ribs based on their stabilities may be helpful. The results of the questionnaire once again emphasized the importance of CPRR or any other rib rating systems, indicating their potential for use among mining professionals. All respondents expressed a positive attitude towards using a rating system that allows them to quantify rib stability and estimate primary rib support density in a more practical manner for their mines.

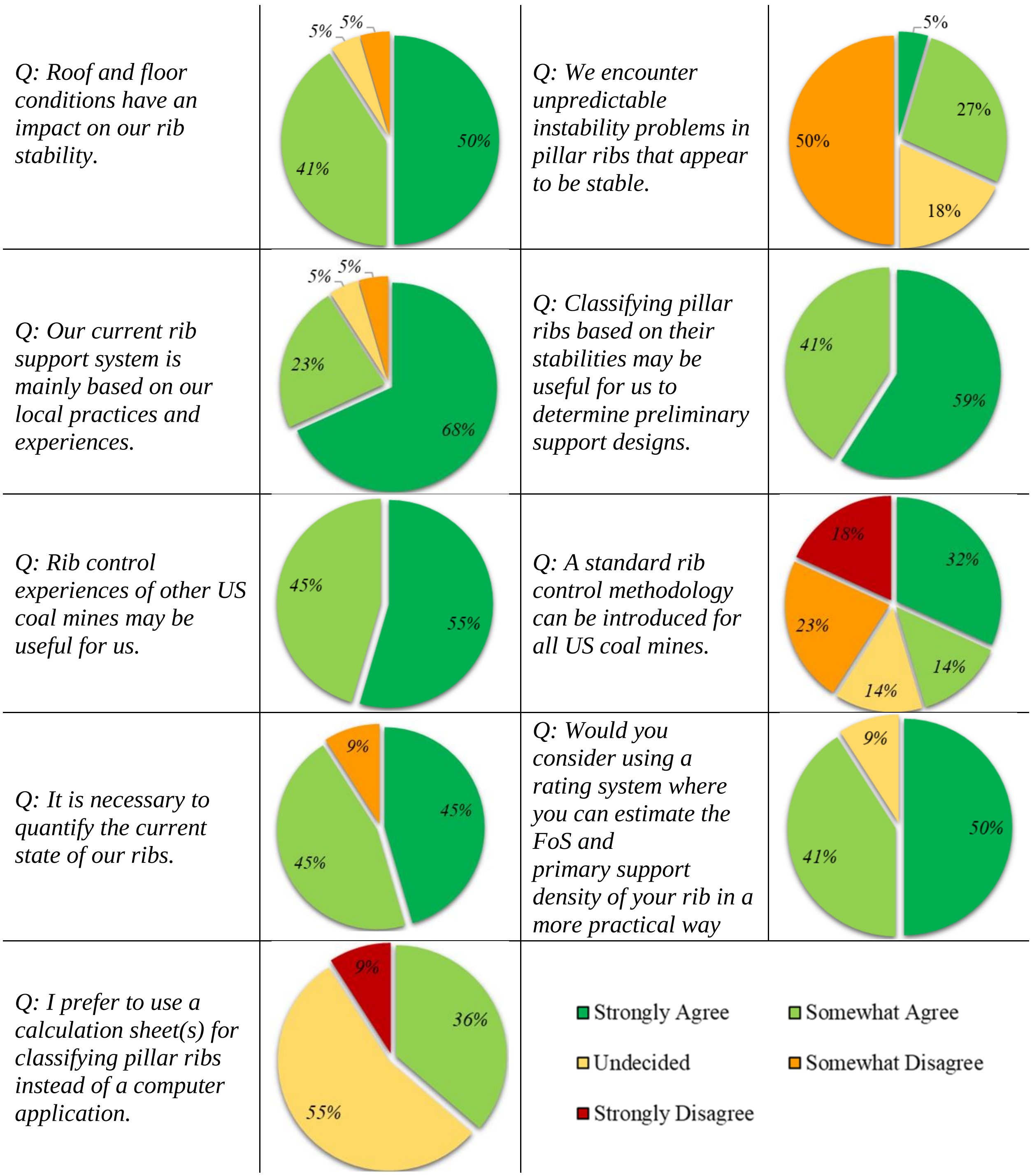


Figure 3.7 Questionnaire results (Part A)

Another interesting result that can be drawn from this part of the questionnaire is that mine professionals do not have a consensus on introducing a standard rib control methodology and guidelines for US coal mines as in some states of Australia. More than 40% of respondents are against that kind of guideline. During the interviews, three senior mine engineers expressed their lack of confidence in implementing a standard rib control methodology. They believe that each US coal seam has unique characteristics, and mechanical responses vary considerably from one site to another, so proposing such methodology and guidelines will not be valid in US coal mines. On the other hand, 45% of the mine professionals think introducing a standard rib control methodology will benefit the US coal mining industry.

This project's final task was to develop an easy-to-use calculation sheet for mine operators to determine the CPRR at the mine site. As stated in the literature review section, NIOSH researchers are developing a standalone computer application using this project's outcomes and empirical datasets. Since the developed CPRR calculation charts and software end users will be mine professionals, we asked about their preference tendencies. More than 50% of potential CPRR system users have no preference and can use both charts and software. On the other hand, almost 10 % of them strongly prefer computer applications for the CPRR system calculation, and 36 % might prefer charts rather than software.

The second part of the questionnaire is intended to analyze/verify the impact of a wide range of parameters when deciding their pillar rib support type/density. In the literature review, the parameters affecting rib performance were examined individually. As a result, nine parameters to be measured/used in the data collection and analysis part were determined. Approving the necessary input parameters for the improved CPRR system by mine professionals is important for the long-term acceptance of the system as they are the end users. For this reason, the effects of these nine parameters on determining pillar rib support density were asked to mine professionals to get an expert opinion. We requested respondents to rank their opinions for the impact of each parameter ranging from "very strong" to "no" to get quantitative results. The questionnaire results for the second part are presented in Figure 3.8.

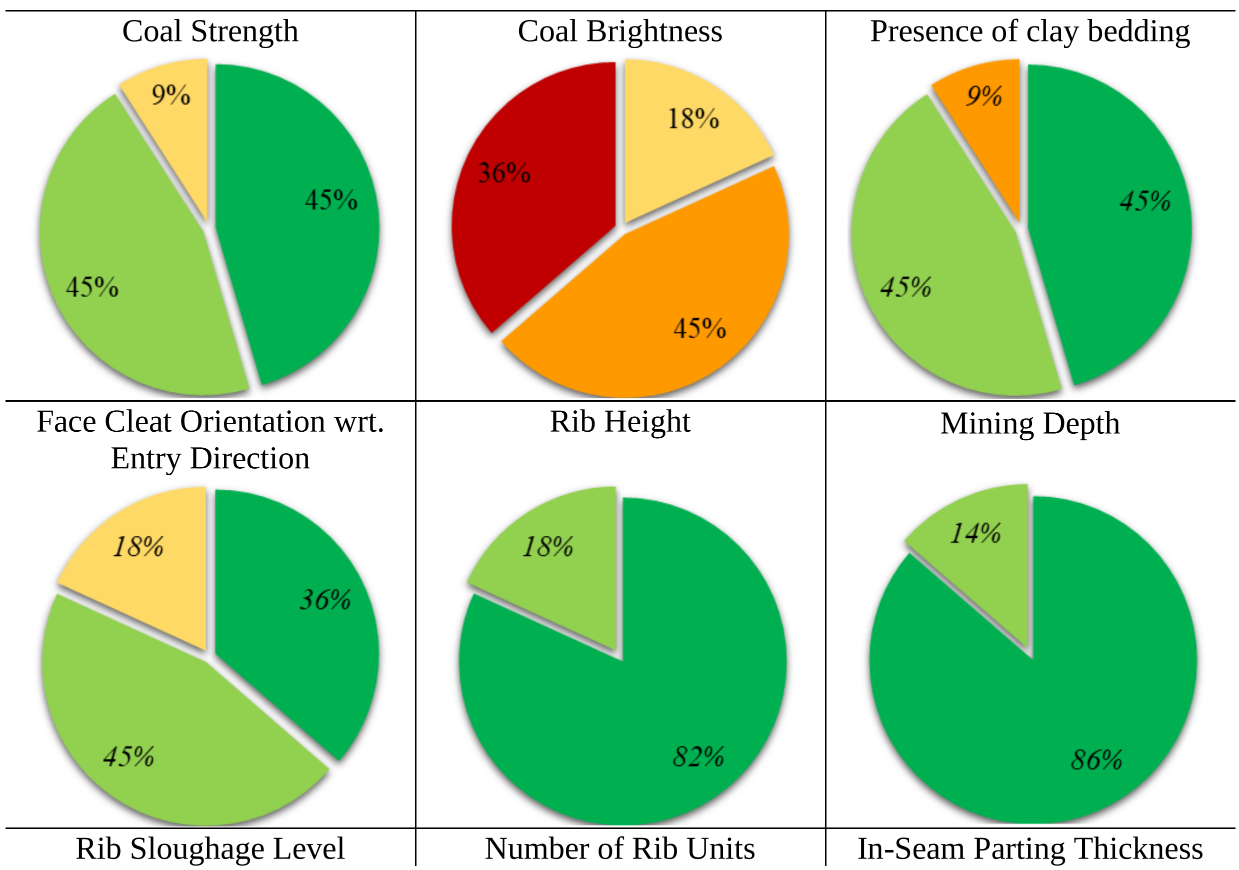
Strength is a mechanical property often used as an input in most analytical and numerical studies on coal rib stability, including every classification system. It has been known to be an essential parameter for coal pillar design for over a hundred years (Daniels & Moore, 1907). While some studies argue that UCS may not be essential for coal pillar design, there is no doubt that it is crucial for coal rib design (Mark & Barton, 1996; Heritage, 2018; Mohamed et al., 2021a). The respondents' answers are consistent with the literature: 90% of respondents agree with the strong impact of coal strength on rib performance. 10% of the mine professionals dealing with their moisture-sensitive clay bedding in their rib control noted that the coal strength moderately impacts their rib management strategy. It is noteworthy to mention that the indirect coal strength estimation methods, including the Schmidt hammer rebound test, are also discussed with mine professionals, and they evaluated the use of the mushroom head hammer as practical and applicable.

The relative strength of the various coal units within a rib profile can be quickly and alternatively determined using the coal brightness profile (Rusnak, 2017). These profiles were included in the CPRR data collection sheet (Khaled et al. 2021a). During the in-person interviews, these practical profiles were shown to mining professionals, and their opinions on an alternative strength determination method in the CPRR system were measured quantitatively. More than 80 % of the mine professionals selected either weak or no impact choice in the questionnaire. They mostly prefer other practical strength estimation methods, the Schimidt hammer, over brightness profiles.

The presence of the clay bedding in the coal rib may serve as another weakness plane and thus is considered one of the reasons for kinematic failures. It is known that clay beddings in the coal seam cause stress anomalies within the coal. The interaction between strong and weak partings leads to unfavorable stress concentrations within the coal rib and impacts rib performance. Over 90% of the mine professionals agree with this argument.

Entry directions in coal mines are primarily designed based on production planning and the orientation of the major principal stress. The direction of the advance can impact the stability of the rib in terms of cleat orientation. The mine professionals agree with this argument. Although cleat orientation is not a main parameter for their panel/advanced orientation selection, all respondents agree that it has a moderate or more impact on their rib stability.

Q: Please rate the influence of the given parameters when deciding your pillar rib support type/density?



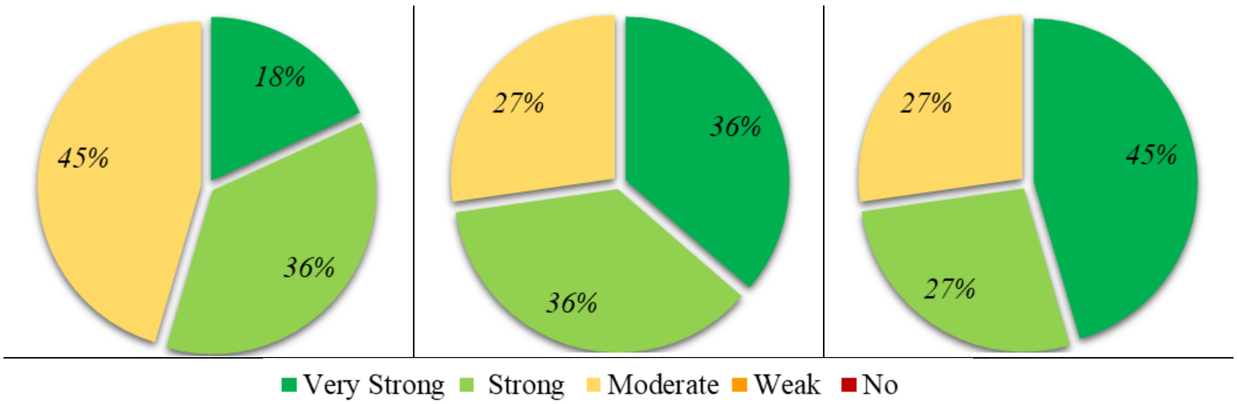


Figure 3.8 Questionnaire results (Part B)

Overburden depth and rib height are identified as the two major principal factors affecting rib stability: 76% of the fatal rib failure accidents in the U.S. in the last 20 years occurred in underground mines with overburden depths of 210 m or deeper (Gauna & Mark, 2011; MSHA, 2020). Since the impact of mining height on rib stability has not been observed in numerical models conducted for the initial CPRR system development work, we decided to ask about the impact level of the mining height on their rib management strategies. As expected, all mine professionals have confirmed the strong impacts of these two parameters.

Rib sloughage level is also a common rib classification criterion to define the category of the rib and the deterioration index. This level is also noted in our data collection sheet to make a qualitative description of the current condition of the rib. Mine professionals also emphasize that this measure gives qualitative signs about the condition of their rib. Moreover, the impact of rock parting thickness and the number of rib units are also confirmed by the mine professionals. They all agree that these parameters have at least a moderate impact on their rib stability.

During the in-person interviews with the mine professionals, they informed us that as the CPRR system is still developing and improving, they are not interested in attending a workshop to train their personnel. Therefore, our team has decided to arrange these workshops after the completion of our new project, "*Improvement of Rib Support Design Utilizing Recent Advancements of the Coal Pillar Rib Rating (CPRR) System*," supported by the Alpha Foundation.

3.1.4. Task #4.1: Expanding the CPRR data set

In this subtask, the research team expanded the CPRR dataset by surveying 20 additional coal ribs. The initial synthetic data used for developing the CPRR system was generated using continuum mechanics-based models by NIOSH researchers, as mentioned in Sections 3.1.1 and 3.1.2.

The lithologic strength of rib units is an important controlling parameter for rib performance. The unconfined compressive strength is one of the key input parameters in the CPRR system for assessing coal rib stability. The uniaxial compressive strength (UCS) of these units should be estimated either directly from the laboratory test or indirectly from the Schmitt hammer test. During our field surveys, a low-energy Schmidt hammer with a large area plunger (mushroom head) was used to estimate UCS, with reasonable results. Each coal and rock lithologic unit was tested at least 20 times and averaged for the rebound number obtained on the Schmidt hammer test for each lithologic unit, excluding the lowest and highest set of numbers. Estimating the UCS values is a straightforward process using empirical relationships that link the Schmidt hammer rebound number with the strength of the intact rock. Several empirical equations have been developed in the literature by conducting Schmidt hammer tests on various rock types. However, for this study, the equations proposed by Rashed et al. (2018), which are tailored to US coal mines, were deemed suitable.

The collected data from the rib survey is crucial for future stages of the project, and hence, a mere estimate of the lithological units' UCS may not be sufficient. During our site visits, we collected more than 30 coal and rock lump samples from different rib units to conduct rock mechanics laboratory tests. Our research team conducted *110* valid uniaxial compressive tests (UCT) covering the uniaxial failure response of the samples with a constant axial displacement rate to the sample using the MTS 816 Rock Test System loading frame (Figure 3.9). Test samples were prepared according to ISRM specifications for specimen dimensions and surface flatness with equipment in our rock mechanics laboratories. The rate of loading was kept constant at 0.005 in/min for all specimens so that the failure occurred within the five to ten-minute period. The tests were run until specimens reached their residual strength. The data acquisition unit continuously recorded the load, displacement, and test time at a rate of 8 Hz. The summary of conducted test results is given in Table 3.8. Details of all rock mechanics test results are presented in Appendix A.

Figure 3.9 A view of the test system and a tested specimen.

Table 3.8 Summary of rock mechanics test results

Site No.	Unit	Number of Tests	Perpendicular*		Parallel	
			UCS (MPa)	Tangent Modulus (GPa)	UCS (MPa)	Tangent Modulus (Gpa)
1	Coal/1	8	15.05 ± 4.96	1.18 ± 0.23	6.30 ± 1.49	0.79 ±0.11
1	Coal/2	8	14.86 ± 2.59	1.04 ± 0.06	12.62 ± 6.02	0.92 ± 0.55
2	Coal	9	16.53 ± 4.09	1.13 ± 0.13	10.87 ± 4.76	1.47 ± 0.44
3	Shale	6	40.35 ± 5.93	3.73 ± 0.12	24.90 ± 2.74	3.69 ± 0.12
3	Coal/1	4	10.13 ± 3.41	1.04 ± 0.13	3.86 ± 0.30	0.48 ± 0.14
3	Coal/2	9	18.60 ± 3.71	1.50 ± 0.42	18.60 ± 1.58	1.75 ± 0.16
3	Coal/3	7	19.25 ± 4.91	1.84 ± 0.64	10.69 ± 3.89	1.18 ± 0.20
4	Coal/1	8	21.59 ± 5.39	1.84 ± 0.24	16.52 ± 5.31	1.43 ± 0.58
4	Coal/2	6	15.46 ± 2.97	1.36 ± 0.95	13.31 ± 1.18	2.34 ± 0.27
5	Shale	6	21.17 ± 3.17	4.40 ± 0.66	21.17 ± 3.17	4.40 ± 0.66
5	Coal/1	11	5.35 ± 2.98	0.63 ± 0.40	5.35 ± 2.98	0.63 ± 0.40
5	Coal/2	11	7.82 ± 5.99	1.12 ± 0.94	7.82 ± 5.99	1.12 ± 0.94
6	Coal/1	6	8.78 ± 4.45	1.51 ± 0.64	8.78 ± 4.45	1.51 ± 0.64
6	Coal/2	10	9.27 ± 3.99	1.26 ± 0.46	9.27 ± 3.99	1.26 ± 0.46

*Perpendicular loading direction with respect to the bedding planes

By completing this Subtask, we achieved the proposed specific aim #1. The improved CPRR empirical data set now covers 30 coal mines, including collected rib data from 20 more coal ribs. It is noteworthy that our team plans to arrange additional site visits for our other ongoing project, "Improvement of Rib Support Design Utilizing Recent Advancements of the Coal Pillar Rib Rating (CPRR) System," supported by the Alpha Foundation and will conduct more rib surveys during these site visits to expand the database further.

3.2. Specific Objective 2: Adapting the Coal-Mass Constitutive Model

This section describes two sub-tasks undertaken to improve the CPRR system in a methodical manner. The research team adapted and verified the Coal-mass constitutive model for distinct element-based solvers to enable a more accurate simulation of the complex response of the coal rib, which involves discrete discontinuities, face cleats, and in-seam beddings. It is important to note that the calibration of the adapted constitutive model is the scope of Task 5 and is presented in Section 3.3.

3.2.1. Subtask 4.2: Adaption of Coal-Mass Constitutive Model for Use in Distinct Element Solvers

The Coal-mass constitutive model used in the development of the initial CPRR system by NIOSH researchers was established for FLAC3D Version 5 & 6 (Mohamed 2018). In this sub-task, our research team adapted the Coal-mass constitutive model from its original form to a constitutive model that is compatible with 3DEC, a distinct element-based solver. This adaptation enabled us to simulate the kinematic and stress-driven failures simultaneously, resulting in a more accurate simulation of the conditions present in underground coal mines.

Our team has updated the Coal-Mass constitutive model, initially developed by NIOSH researchers for FLAC3D-V6, to make it compatible with FLAC3D-V7. We shared the new version of the constitutive model with NIOSH researchers for their review. Some new functionalities, such as the automated rib factor-of-safety (FOS) calculation, have been added to the constitutive model. The updated constitutive model was faster and more efficient for conducting parametric studies. Developed constitutive model and updated models were shared with the NIOSH research team, contributing to the CPRR development from the early stages of our research. The FLAC3D-V7 and 3DEC-V7 constitutive models are compatible with each other. After our team ensured that the constitutive model was functioning properly in FLAC3D-V7, the validation task was started in 3DEC-V7.

3.2.2. Subtask 4.3: Validation of Adapted Constitutive Model

During the validation stage of the adapted Coal-mass constitutive model, pillar scale uniaxial compressive strength (UCS) and triaxial compressive strength (TCS) tests simulations were performed similarly to validation tests conducted by NIOSH researchers. Afterward, an additional series of validation simulations were performed to estimate the RibFOS for solid coal ribs using 3DEC. The results of these analyses were compared to those conducted using the FLAC3D version of the Coal-mass constitutive model—the following two subsections present pillar scale and rib-scale model validation results. As the main objective of this part was to validate the adapted constitutive model, the ubiquitous joint method is used to simulate the effect of jointing on the coal in 3DEC models only for this validation purpose.

- *Pillar-scale UCS and TCS model validation*

UCS and TCS test simulations were carried out for three different coal types (dull, banded-bright, and bright), with consistent model geometries and mesh sizes compared to the NIOSH validation study. In this stage of validation, no explicit discontinuities were introduced in 3DEC models. Since 3DEC uses a finite difference method in the absence of explicit joints (similar to FLAC3D), the results of this solver are expected to be near-identical to the ones from FLAC3D. A geometry that represents mine pillars of 2-meter height and 6-meter width, with a 50 cm grid size, was used in these models. The coal mass properties used in this validation part are presented in Table 3.9.

Table 3.9 Coal mass properties used in the validation part

Coal Type	Bright Coal	Banded-Bright Coal	Dull Coal
Intact UCS (Mpa)	8.58	19.7	35.0
Bulk modulus (Mpa)	552.0	1701.3	2344.7
Shear modulus (Mpa)	331.2	1020.8	1406.8
Coal Mass Scale (CMS)	20	20	20
Fracture plastic shear strain	0.06	0.055	0.055
Fracture plastic tensile strain	0.0033	0.003	0.009

For the UCS simulation, a constant velocity was applied from the top of the pillar. In TCS tests ($\sigma_2=\sigma_3$), 1 MPa confinement stress was applied initially, and a constant velocity was applied. Firstly, FLAC3D-v6 and v7 results were compared, then, after obtaining identical results, the model validation was performed in 3DEC v7. As presented in Figure 3.10, the linear elastic and post-peak brittle behavior of the coal pillar is simulated properly with a updated constitutive model for all three coal types under a uniaxial stress state. A slight difference (~10%) is observed in the residual stress part as a result of differences in meshing schemes used in FLAC3D and 3DEC. The elastic response and the post-peak strength behavior are also simulated correctly according to TCS test simulation results, presented in Figure 3.11. As a result of the coal pillar validation study, near-identical coal responses were obtained, and this step was successfully completed.

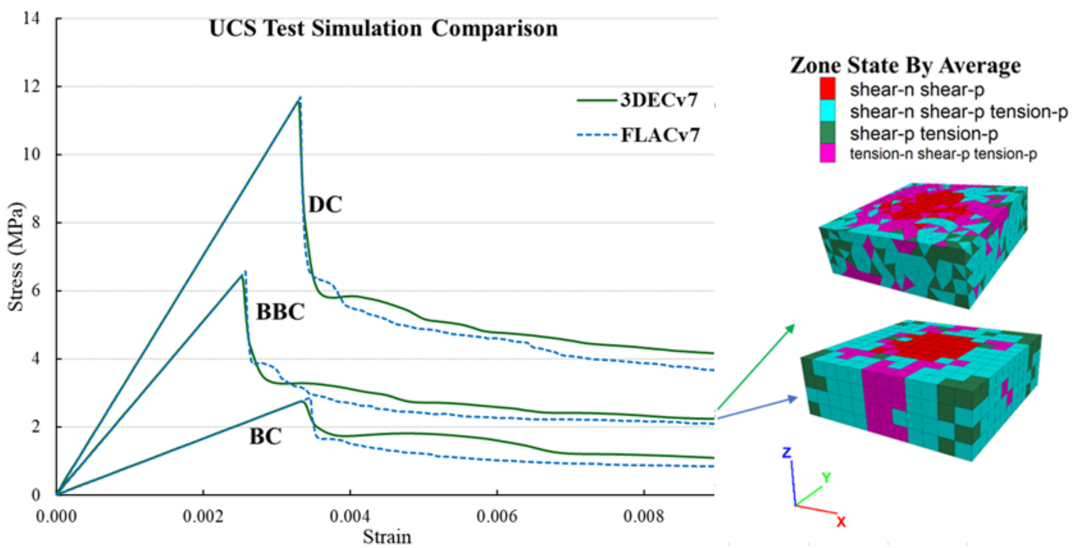


Figure 3.10 FLAC3D vs. 3DEC pillar scale UCS model comparison

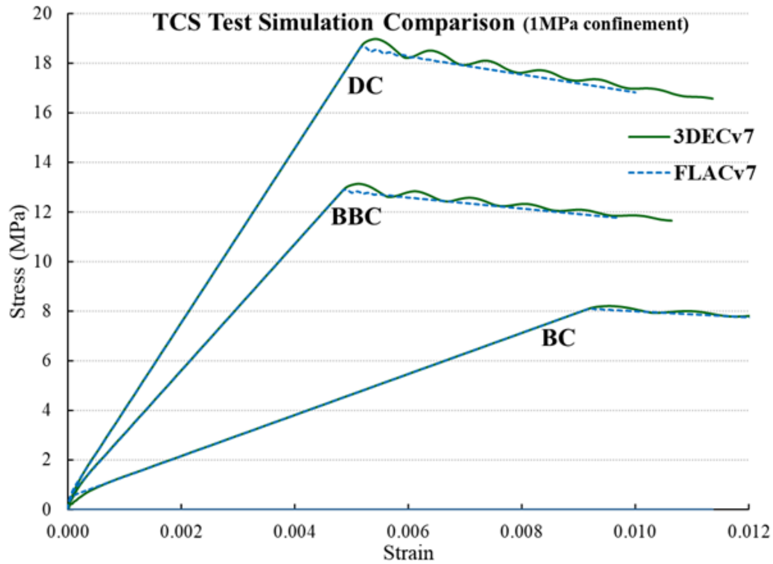


Figure 3.11 FLAC3D vs. 3DEC pillar scale TCS model comparison

- <u>*Solid coal rib scale model validation*</u>

In the second part of the validation, the FLAC3D coal rib models, developed by NIOSH researchers, were adapted to 3DEC versions. Consistent model geometry, boundary conditions, in-situ stress conditions, material properties, and thicknesses of the overlying/underlying strata were used in 3DEC models. Since FLAC is a continuum mechanics-based solver, the effect of jointing on the coal was simulated with the ubiquitous joint method. As the main objective of this sub-task is to validate the updated constitutive model, the ubiquitous joints are also used in 3DEC models only for this validation purpose. The solid coal rib models were validated with various overburden depths, mining heights, and coal types. A total of 15 base models were solved in 3DEC using the updated Coal-mass constitutive model. The results from the 3DEC models were compared to those from the models solved using the original form of the Coal-mass constitutive model in FLAC3D-v7. The FOS function added to the Coal-mass constitutive model using C++ language was used in both codes. Stresses and displacements of initial equilibrium (geostatic) and development stages were compared, and almost identical results were obtained.

A representative model comparison for unstable rib (rib displacement, yielded zone, and stresses) is presented in Figure 3.12. The presented model has a 180 m depth with 3.3 m of mining height. The maximum extent of the yielded zones (Figure 3.12a), rib displacements (Figure 3.12b), and stresses (Figure 3.12c-d) obtained in 3DEC models (for the same mechanical step number) are similar to those obtained in FLAC3D-v7.

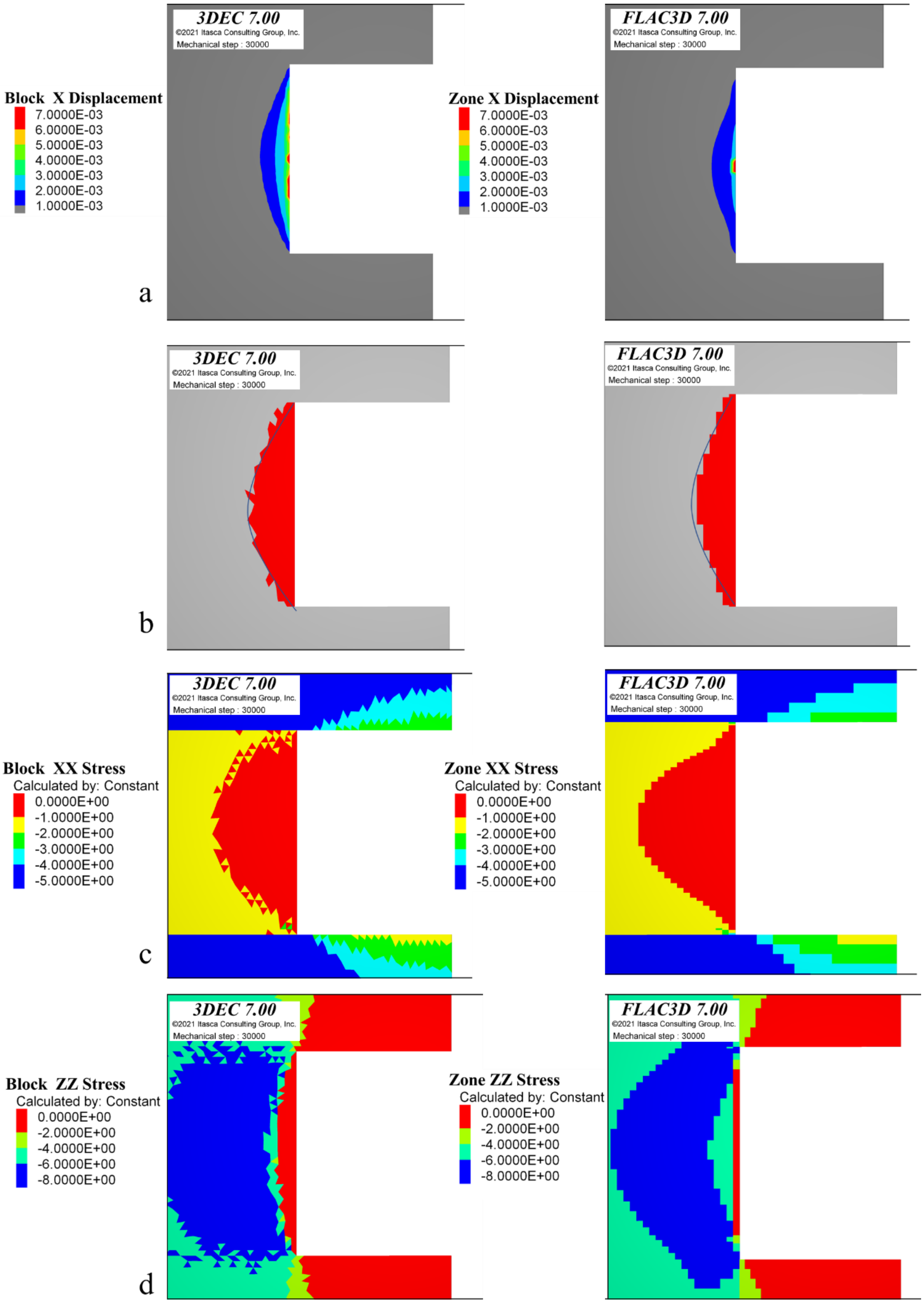


Figure 3.12 Rib displacement (a), yielded zone (b), and stresses (c, d) comparisons of unstable coal ribs using 3DEC (left) and FLAC3D (right).

The validation study was completed by comparing the FOS values obtained from the 3DEC models with the values obtained using FLAC3D-v7. The FOS results for 15 base models are presented in Table 3.10. According to the second part of the validation study, the targeted FOS ranges were achieved, and this Subtask is completed.

Table 3.10 Rib validation results for 15 base models (Rib Factor-of-Safety comparison)

Dull Coal					
Model Number	1	2	3	4	5
Depth (m)	90	180	180	180	315
Rib Height (m)	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	>5	>5	4.99	3.37	2.05
FOS (3DEC)	>5	4.42	3.88	3.49	2.25
Bright Coal					
Model Number	6	7	8	9	10
Depth (m)	3.3	1.5	2.1	3.3	3.3
Rib Height (m)	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	1.01	0.89	0.56	0.56	0.44
FOS (3DEC)	1.02	0.78	0.55	0.55	0.55
Banded-Bright Coal					
Model Number	11	12	13	14	15
Depth (m)	3.3	1.5	2.1	3.3	3.3
Rib Height (m)	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	2.67	2.52	1.51	1.36	0.89
FOS (3DEC)	2.33	2.25	1.71	1.4	0.94

3.3. Specific Objective 3: Expanding the CPRR Calculation Through DEM-Based Numerical Simulations

3.3.1. Task #5: Parametric Studies to Produce Required Inputs for Developing CPRR Calculation Sheet

Task-5 involves the calibration of base models and parametric studies to produce the required input for further improvement of the CPRR system. It is well established that coal entry stability is a complex problem where rib, roof, and floor conditions are interrelated from the ground control design perspective. To this end, a comprehensive rib stability study was conducted using 3DEC modeling, considering several parameters such as overburden depth, rib height, the strength of rib units, number and thickness of rib units, bedding condition, and roof and floor conditions (Table 3.11). These parameters were chosen based on those used in recent coal rib studies by NIOSH researchers to be consistent with our research (Mohamed et al., 2021a; Xue and Mohamed, 2021).

Table 3.11 Studied parameters and their ranges.

Parameter	Range
Overburden depth	300 to 1,050 ft
Rib height	5 to 11 ft
Coal UCS	Bright coal (BC) 1250 psi Banded bright coal (BBC) 2857 psi Dull Coal (DC) 5075 psi
Rock parting UCS	2625 psi 5570 psi
Number of rib units	1 to 10
Rib unit thicknesses	1 to 11 ft
Bedding conditions	Soft-clay bedding (weak) Clay-free bedding (strong)
Roof conditions	CMRR 30, 50, and 70
Floor conditions	Weak and strong

- *Calibration of Base Models*

The Coal-mass constitutive model was originally developed as a user-defined constitutive model (UDM) for the simulation of the coal mass response using FLAC3D, a continuum mechanics-based solver. The Coal-mass constitutive model employs the implicit ubiquitous joints to simulate the weakening mechanism of face cleats based on the smeared crack concept. In addition, the critical plastic shear and tensile strain values were used as two significant parameters in this model to determine the rib stability in the numerical models simulated using FLAC3D. Our preliminary analyses showed that the implemented ubiquitous joints in this constitutive model have a very slight effect on the behavior of the Coal-mass model until the induced plastic shear or tensile strain values reach pre-defined critical plastic strain limits. Once the implicit joint set reaches the critical strain values, joint strength parameters are altered to their pre-set values, and these elements are marked as fractured. The fractured elements with altered parameters, which initially manifest in the rib-line, exhibit varying strain responses and continue to strain as the model steps further, ultimately changing the condition of the rib from stable to unstable. The critical plastic strain parameters used in the Coal-mass model for three major coal types were obtained through calibration of the Coal-mass model against field observations and measured stresses and deformations in coal ribs (Mohamed et al., 2018). The ubiquitous joint concept utilized in the Coal-mass constitutive model is a strength anisotropy model that ignores the modeled material's stiffness anisotropy. Moreover, since this model only implicitly models the joints, it cannot properly simulate the bending/buckling behavior of individual layers of the jointed material, as the layers cannot detach from each other. The models with the ubiquitous joint may also yield incorrect and extensive localized deformations. These limitations may lead to misrepresenting the deformation and yielding response of the rock mass. This is a significant drawback of this approach, rendering it unsuitable for studying rib failure mechanisms. Additionally, implementing or designing effective support systems using this modeling approach is not feasible.

To overcome the aforementioned limitations associated with the implicit simulation of the coal mass cleat system using the ubiquitous joint concept in FLAC3D, we decided to employ 3DEC, a hybrid continuum-discontinuum-based solver. 3DEC can simulate the behavior of the rock mass more realistically with explicit representation of the discontinuities within the rock mass.

During the calibration phase of our updated model, the explicit face cleat set was introduced to the model, and the implicit joints were deactivated. This implementation aims to simulate the more realistic mobilized zones through the coal rib by explicitly modeling the detachment of coal blocks along face cleat planes. The mechanical and strength parameters of the explicitly introduced face cleats were calibrated to achieve results comparable to the FOS values obtained from the FLAC3D models calibrated to field observations.

Researchers agree that coal cleat spacing can vary greatly depending on coal type and lithological conditions, in the ranges of 0.2 and 30 cm (Ting, 1977; Hucka, 1991; Ayers and Kaiser, 1994). According to our preliminary model runs in 3DEC, modeling the tightly spaced face cleats were computationally inefficient; thus, a face cleat spacing between 10 and 30 cm was utilized. Since the face cleat spacing has a significant role in the rib behavior, the optimum spacing was determined as a result of the calibration methodology, and a final value of 25 cm was found to be appropriate and utilized in subsequent models.

Tetrahedral elements were utilized, and three different grid sizes were employed in the vicinity of the opening to increase the accuracy of the results. The model, gridded block, and boundary conditions are illustrated in Figure 3.13. The symmetry axes and the left boundaries of the model were fixed in the x-direction, and a fixed boundary condition was applied to the bottom horizontal boundary to prevent movements and rotations along with this direction. A stress boundary condition was applied at the top of the model to achieve the desired simulated depth. According to field observations, the average fractured zone depth along the rib is typically in the range of 0.5-2.0 m (Seedsman, 2021). Therefore, only the first 4 m of the coal pillar at its rib side will be modeled using face cleat sets to allow explicit fracture formation and separation.

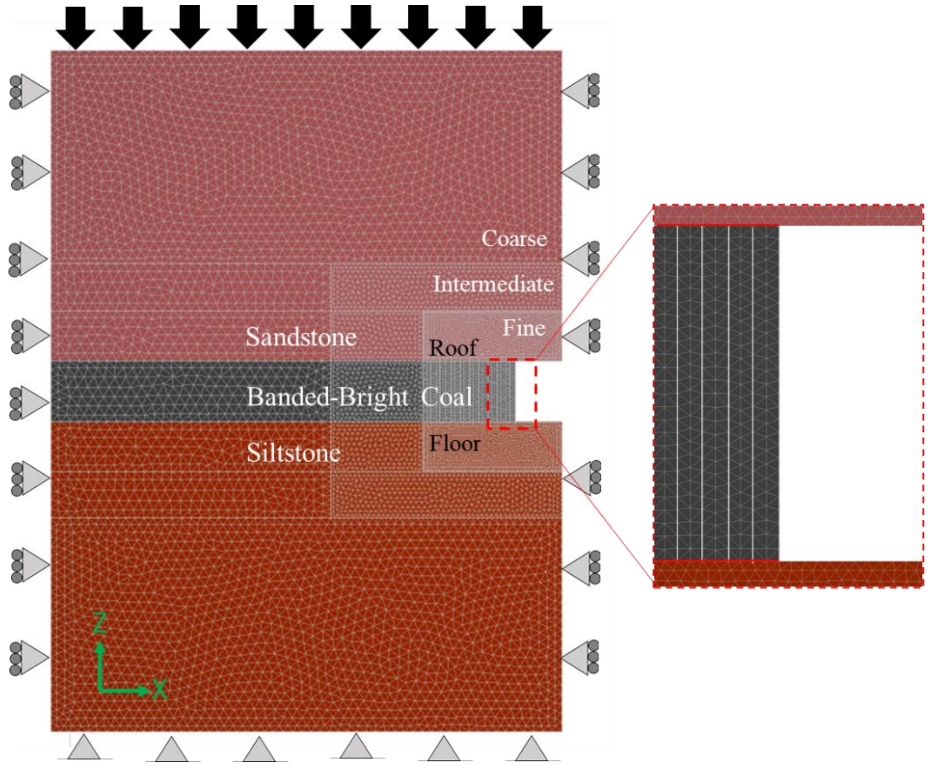


Figure 3.13 Model boundary conditions and geometry configuration. The zoomed-in view shows the face cleats and roof-floor contacts.

The gateroad is assumed to be parallel to the maximum horizontal stress in the model and the face cleats are also assigned in the same orientation, considering the worst case. The in-situ stresses in the coal pillar and rock layers were initialized with different approaches. Equations proposed by Lui et al. (2016) were used for coal seam in-situ stress initialization (Eq. 7-9). The in-situ stresses in the rock layers used the recommendations of Esterhuizen 2017 (unpublished) in Mohamed et al.'s (2019) study (Eq 7, 10, 11).

$$\sigma_v = \gamma \times Z \tag{7}$$

$$\sigma_{Hc} = 1.174 + 0.024 \times Z_c \tag{8}$$

$$\sigma_{hc} = 0.018 \times Z_c - 1.475 \tag{9}$$

$$\sigma_{Hr} = 0.313 + 0.027 \times Z_r + 0.000278 \times E_r \tag{10}$$

$$\sigma_{hr} = 0.65 \times \sigma_{Hr} \tag{11}$$

where σ_v is the maximum vertical stress for both coal seam and rock layers, γ is the specific weight of the geologic units in MN/m3, $\sigma_{Hc}$and σ_{hc} are the maximum and minimum horizontal stresses, and Z_c and Z_r are the depth of coal seam and depth of rock layers, respectively in meters.

σ_{Hr} and σ_{hr} are the maximum and minimum horizontal stresses of the rock layers, respectively, E_r is the Young's modulus of rock layers in MPa. All stress units are given in MPa.

Equivalent models were compared to reveal the coal rib response difference between models with ubiquitous joints and explicit joints. Figure 3.14 presents the computed displacements of the unstable rib case. The explicitly modeled cleated coal rib (Figure 3.14-a) has a more representative mobilized zone and deformation response compared to cleats modeled with ubiquitous joints (Figure 3.14-b). The ubiquitous joint model produces excessively localized large deformations on the rib side, and the predicted depth of the mobilized zone was limited in this case. Note that the depth of the mobilized zone has significant importance in estimating the required rib bolt lengths. As a result, it is anticipated that one of the valuable outcomes of the rib models with explicit joints (3DEC) will be the development of more realistic models that can be used to estimate the required primary rib support, which will be of great benefit in field applications.

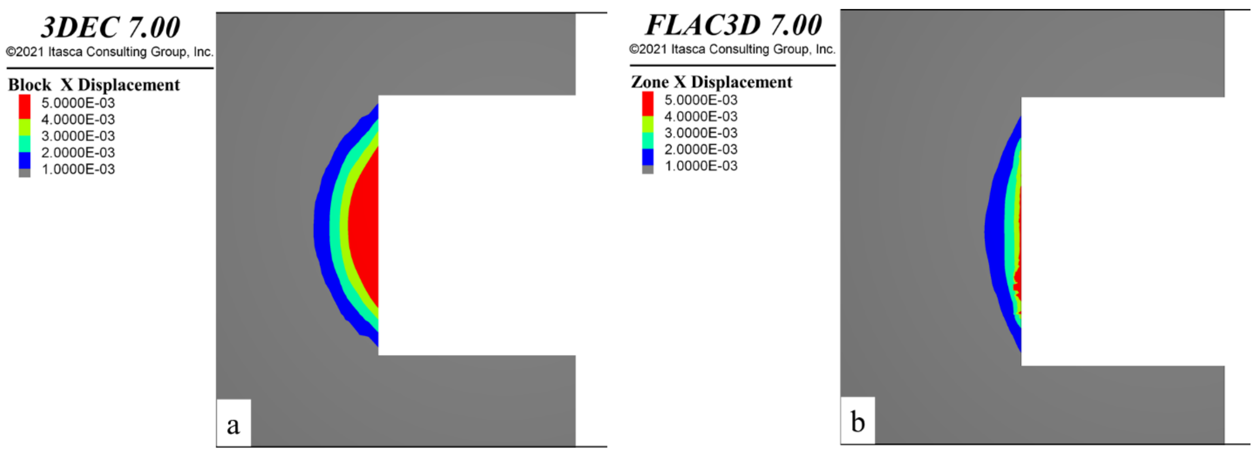


Figure 3.14 Unstable rib models with face cleats (explicit joints (a) ubiquitous joints (b)).

The Coal-mass model uses the Coal Mass Scale (CMS) parameter, which ranges from 1 to 100, for the FOS determination. A CMS value of 1 represents the intact coal, and the upper limit represents the weakest coal material. Similar to the Mohr-Coulomb strength reduction method, the coal mass strength is reduced by increasing the CMS, and the RibFOS is defined as the maximum CMS required to prevent rib failure. In our updated and calibrated models, RibFOS is calculated by applying the strength reduction factor (SRF) on CMS and face cleat strength properties (cohesion and tensile strength). In this way, the consistency between the cleat and coal matrix properties was achieved in accordance with the literature.

According to Mohamed et al. (2019), the coal mass scale (CMS) is a parameter used to introduce the size dependency of coal material. For RibFOS calculations, the strength of the coal material is reduced by increasing the CMS of the coal mass model. The peak and residual strengths of the coal mass constitutive model are a function of CMS value, as shown in the following set of equations:

$$m = 2455 \times [\alpha + \beta \times CMS]^{-0.683} \tag{12}$$

$$s = 267 \times [\alpha + \beta \times CMS]^{-1.359} \tag{13}$$

$$\sigma_{cr} = 3085 \times [\alpha + \beta \times CMS]^{-1.241} \tag{14}$$

$$n_d = 0.144 \times ln(\alpha + \beta \times CMS) - 0.568 \tag{15}$$

where, m and s are the Hoek Brown peak strength parameters, σ_{cr} is the residual UCS, n_d is a degradation parameter (Fang and Harrison, 2002), and α and β are regression coefficients. These coefficients were obtained by evaluating laboratory test results and in-situ small coal pillars (Mohamed et al.,2019).

In contrast to SRF values, which are used as denominators to degrade the material properties of the model, the CMS is used as a multiplier, creating a linear relationship between the CMS and the RibFOS. In the coal mass constitutive model, a CMS value of 20 represents the critical equilibrium condition of the coal rib (RibFOS:1). The calculated RibFOS lies between the range of 0.05 and 5.00. For RibFOS equal to 0.05, CMS=1 is used to find the peak and residual strengths of the coal mass. Conversely, a RibFOS of 5.00 equates to a CMS value of 100.

The following is a brief sample calculation to demonstrate the relationship between CMS and RibFOS:

Firstly, a bracket will be defined for the RibFOS calculation. Let us assume [0.50-2.50].

The initially applied SRF value is (0.5+2.5)/2= 1.5. Since the default CMS value in the model is 20, the current CMS for this trial will be 20×1.5= 30. For this trial, the face cleat cohesion and tensile strength parameters are reduced by 1.5 times.

If the model is stable based on the "5 mm of deformation at a depth of 25 cm within the rib" criterion, the second trial will be done for SRF of ((1.5+2.5)/2) = 2. In this trial, the CMS will be set to 20 × SRF = 40, and the face cleat parameters will be reduced by the SRF of 2.

This trial will be repeated until the resolution difference between the current and previous RibFOS trials is less than or equal to 0.01.

For the base rib model calibration, twenty-four different models with various coal types, overburden depths, and mining heights were selected after consulting with the NIOSH researchers. During the calibration phase, over 1000 models were examined one by one, and deformation-based stability criteria were established by considering realistic observed rib deformation limits in the field. In the approach developed by the project team, in order for the rib to be considered unstable, the depth of the mobilized zone must exceed 25 cm from the pillar face. In addition, the elements that reach 1 cm deformation through the excavation were considered as mobilized. In brief, if over 1 cm of deformation occurs at a depth of 25 cm within the rib, this rib is classified as unstable. The proposed instability criterion was discussed with the NIOSH CPRR research team and is considered representative of the current strain-based criteria used in FLAC models. Representative examples of stable (a) and unstable (b) rib models are presented in Figure 3.15. Red zones indicate the mobilized areas based on the proposed criteria. The mobilized block volume presented in Figure 3.15-b is unstable and of sufficient volume to cause a fatal injury.

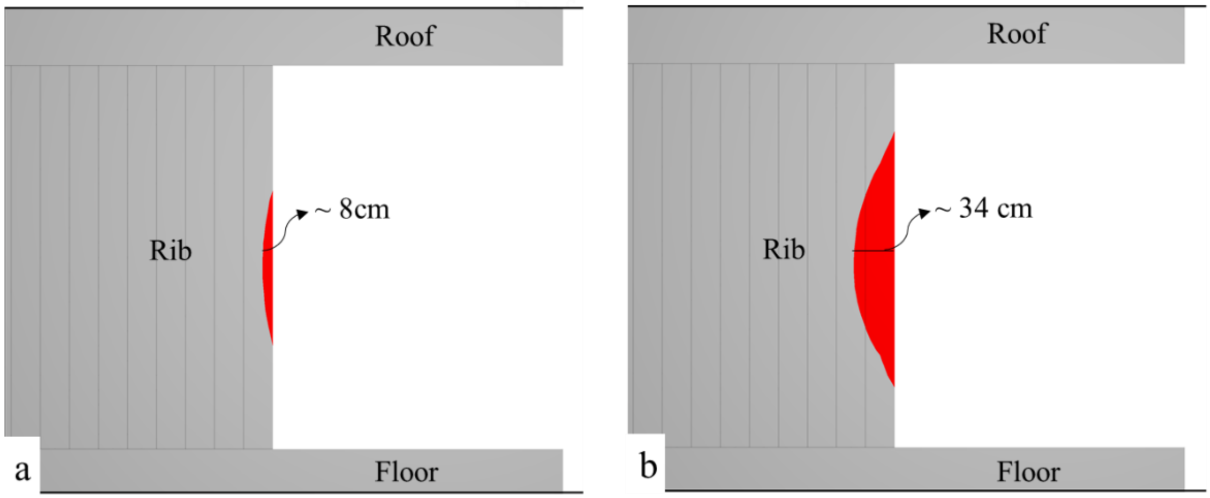


Figure 3.15 Representative examples of stable (a) and unstable (b) rib conditions based on the proposed criterion.

Since the built-in FOS function in 3DEC was not compatible with the proposed stability criteria, a new FOS code (Python script) with the ability to detect current rib deformations and evaluate the stability of the rib was written by our research group. The developed FOS code has the same iteration principles as the built-in FOS function and can save all iterated models for monitoring rib responses in each FOS trial.

Sub-task 5.1 was completed by calibrating face cleat properties for three coal types to get similar FOS values from 3DEC runs. Table 3.12 presents the calibrated face cleat contact stiffness and strength properties.

Table 3.12 Calibrated face cleat properties.

Coal Type	Dull Coal	Bright Coal	Banded-Bright Coal	Roof & Floor Contacts
Shear Stiffness (Gpa/m)	100	100	100	78
Normal Stiffness (Gpa/m)	40	40	40	2.6
Peak Friction angle (°)	24	10	12	25
Residual Friction angle (°)	18	8	9	14
Peak Cohesion (MPa)	0.80	0.15	0.17	0.40
Residual Cohesion (MPa)	0.30	0.05	0.06	0.20
Peak Tensile Strength (MPa)	0.10	0.03	0.04	0.01
Residual Tensile Strength (MPa)	0.06	0.01	0.01	0

To verify that the presented face cleat parameters and models were calibrated, 24 base model runs were conducted, and the FOS results were compared with ones obtained from FLAC3D-v7. The calibration results were also discussed with the NIOSH CPRR research team and concluded to be sufficient for the completion of this sub-task. Calibrated models' FOS results and comparisons are presented in Table 3.13.

Table 3.13 Calibrated base models (Rib Factor-of-Safety comparison)

Dull Coal								
Model Number	1	2	3	4	5	6	7	8
Depth (m)	90	180	180	180	245	245	245	315
Rib Height (m)	3.3	1.5	2.1	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	>5	>5	4.99	3.37	>5	3.85	2.55	2.05
FOS (3DEC)	>5	>5	4.87	3.42	>5	3.41	2.11	1.51
Bright Coal								
Model Number	9	10	11	12	13	14	15	16
Depth (m)	90	180	180	180	245	245	245	315
Rib Height (m)	3.3	1.5	2.1	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	1.01	0.89	0.56	0.56	0.60	0.43	0.31	0.14
FOS (3DEC)	1.11	0.80	0.55	0.39	0.40	0.25	0.19	0.10
Banded-Bright Coal								
Model Number	17	18	19	20	21	22	23	24
Depth (m)	90	180	180	180	245	245	245	315
Rib Height (m)	3.3	1.5	2.1	3.3	1.5	2.1	3.3	3.3
FOS (FLAC3D)	2.67	2.52	1.51	1.36	1.94	1.12	1.14	0.89
FOS (3DEC)	4.05	4.47	2.62	1.29	2.61	1.59	0.94	0.57

The FOS results obtained at the end of the calibration were generally within the targeted ranges. Although a completely different FOS detection methodology from FLAC models had to be followed, the project group and NIOSH researchers agreed that all results were consistent with each other.

- *Parametric Studies – Excavation Dimensions*

The effects of mining height and overburden/ depth of cover parameters are considered in the original CPRR calculations. In the analyses made during the calibration and validation phases, it has been observed that the effect of mining height plays a more dominant role in the rib stability in the 3DEC models compared to the FLAC3D models. The impact of mining height and depth of cover on rib stability are also examined in parametric studies and will be discussed in the following sections of this report. In this section, base models are developed to study the effect of excavation width, which was not considered in the original CPRR calculation. Based on our bi-weekly meetings with NIOSH researchers and literature review, most of the coal mines in the U.S. utilize entry widths between 4.5 and 6 m. It was predicted that the 1.5 m change in entry width might not significantly affect the general rib stability under solid coal and elastic roof conditions. 24 base models were tested to validate this assumption (Table 3.14). As a result of the models; it was observed that the 1.5 m change in the excavation width for solid coal rib did not have a significant effect on the RibFOS results, as expected.

Table 3.14 The effect of excavation width on RibFOS

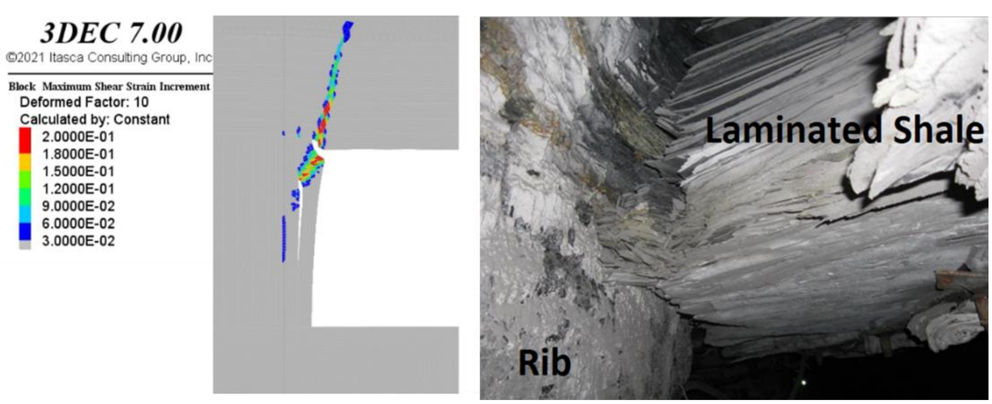
Model Number	Coal Type	Depth (m)	Rib Height (m)	FOS (4.5 m)	FOS (6 m)
1	Dull Coal	90	3.3	>5	>5
2		180	1.5	>5	>5
3		180	2.1	4.87	4.87
4		180	3.3	3.42	3.06
5		245	1.5	>5	>5
6		245	2.1	3.41	3.34
7		245	3.3	2.12	2.08
8		315	3.3	1.51	1.37
9	Bright Coal	90	3.3	1.11	1.11
10		180	1.5	0.80	0.76
11		180	2.1	0.55	0.55
12		180	3.3	0.39	0.36
13		245	1.5	0.40	0.33
14		245	2.1	0.25	0.25
15		245	3.3	0.19	0.18
16		315	3.3	0.10	0.08
17	Banded-Bright Coal	90	3.3	4.05	3.58
18		180	1.5	4.47	4.05
19		180	2.1	2.62	2.24
20		180	3.3	1.29	1.24
21		245	1.5	2.61	2.24
22		245	2.1	1.59	1.59
23		245	3.3	0.94	0.81
24		315	3.3	0.57	0.46

In light of these results and meetings with the NIOSH CPRR team, we decided to exclude mining width parameters in our parametric studies. Similar to the previous models conducted by NIOSH, a mining width of 4.5 m is used in subsequent modeling efforts. It should be noted that the presented results do not imply that the entry width has no impact on rib stability. Instead, the results should be interpreted as the expected effect could not be observed between the entry widths of 4.5 and 6 m.

- *Parametric Studies – Plastic Roof and Floor Conditions*

So far, efforts have been made for CPRR development based on the assumption that roof and floor conditions are strong and not impacting rib response. However, it is critical to study the entire roof/floor/rib and strata system holistically, rather than just the ribs or the roof. Therefore, in addition to the strong roof strata condition (CMRR>= 70), our team has decided to examine two different roof strata conditions based on Coal Mine Roof Rating (CMRR) approach as weak (CMRR 30) and moderate (CMRR 50). We decided to follow this approach by discussing our idea with Dr. G.S. Esterhuizen, an expert on coal mine roof failures. The combined impact of various roof and weak floor conditions on rib stability were analyzed, as stated within the scope of this sub-task. In addition to the solid coal ribs, the plastic roof and floor analyses were conducted with ribs having softbands, multiple coal units, thick rock partings, and thick rock partings with softband conditions.

In this sub-task, the available constitutive models and bedding-lamination representations (explicit/implicit or both) to simulate the interactions between roof and rib more realistically were evaluated. Based on our preliminary results, it was found that more than three elements are required for each bedding layer to capture the realistic lamination and separation response of the explicitly modeled roof strata. Simulating the roof shale having 10 cm or less lamination thickness requires 2 cm or smaller element size, which is impractical and almost impossible considering the current computational technology. Therefore, we decided to use combined explicit and implicit representations for roof lamination. A new constitutive model, developed by the PI of the project (Dr. Taghi Sherizadeh), was used to simulate the combined bedding-lamination representations. The Anisotropic Strain Softening Rock Mass (ANSSRM) constitutive model applies the strength anisotropy of laminated rocks and simultaneously integrates the elastic stiffness anisotropy. The ANSSRM constitutive model successfully simulates cutter roof fractures, a compressional failure that begins on the rib-roof intersection and propagates upward into the roof at angles greater than 60 degrees from the horizontal (Figure 3.16). The constitutive model used at this stage of the project is intended to be used in future projects which focus on the analysis of coal mine roof stability.



(a) **(b)**

Figure 3.16 Cutter roof in laminated shale (a) 3DEC using ANSSRM constitutive model, (b) Herrin No. 6 seam (Molinda and Mark, 2010)

The CMRR parameters of simulated roof strata are presented in Table 3.15. The roof was supported with fully grouted rockbolts of 1.8 m long. The immediate roof (unit 1) was simulated for 1.5 m thick laminated shale, and the rest of the roof above the bolting horizon was simulated with rock strata stronger than the bolted interval. Joints and rock matrices are modeled with a 90% reduction in cohesion and tensile strength after 0.5% strain (softening) is exceeded. To simulate weak floor conditions, a low stiffness value (3 Gpa), 15 MPa rock matrix strength, and 5-cm spaced weak clay beddings with 0.5 MPa cohesion and 20° friction angle were selected.

Table 3.15 CMRR properties for modeling weak and moderate cases

Parameters	Moderate roof		Weak Roof	
	Unit 1	**Unit 2**	**Unit 1**	**Unit 2**
Strength index	Craters	Craters	Craters	Craters
Joint Cohesion	Moderate-weak	-	Weak-slickensided	Weak-slickensided
Joint Roughness	Planar	-	Planar	Planar
Spacing	8-24”	-	2.5-8” & 8-24”	2.5-8”
Intact Rock Cohesion	-	Strong-moderate	-	-
Cohesion Adj.	20	51	13 & 13	13
Spacing Adj.	20	-	13 & 20	13
Multiple Discont. Adj.	-	-	4	-
Strength Adjustment	10	10	10	10
Total Rating	50	61	32	36
Adjusted CMRR	50		30	

More than 500 model runs have been completed for five different scenarios in this task. Rib deformations for the solid Dull Coal (DC) buried at 315 m depth and having an 3.3 m mining height case are presented in Figure 3.17. For the scenario given in Figure 3.17-a, in which the roof and floor are strong (roof CMRR>=70), the unsupported RibFOS is calculated as 3.46, whereas the unsupported RibFOS decreases dramatically for the weak roof (CMRR~30) and floor conditions to 1.77 and 1.94, respectively (Figure 3.17-b and 2-c). The buckling and horizontal rib dilation are appropriately simulated in these models, and the significance of the roof and floor conditions are revealed.

Five scenarios studied to integrate the effect of the roof and floor condition on RibFOS were evaluated separately. Since the effect of roof and floor conditions has not been examined in the studies conducted for CPRR, the results of these models are presented by comparing them with RibFOS estimated in the strong roof and floor conditions. Notably, models conducted for this subtask include the following coal rib compositions: single solid coal, ribs with soft and/or strong beddings, and with/without rock partings.

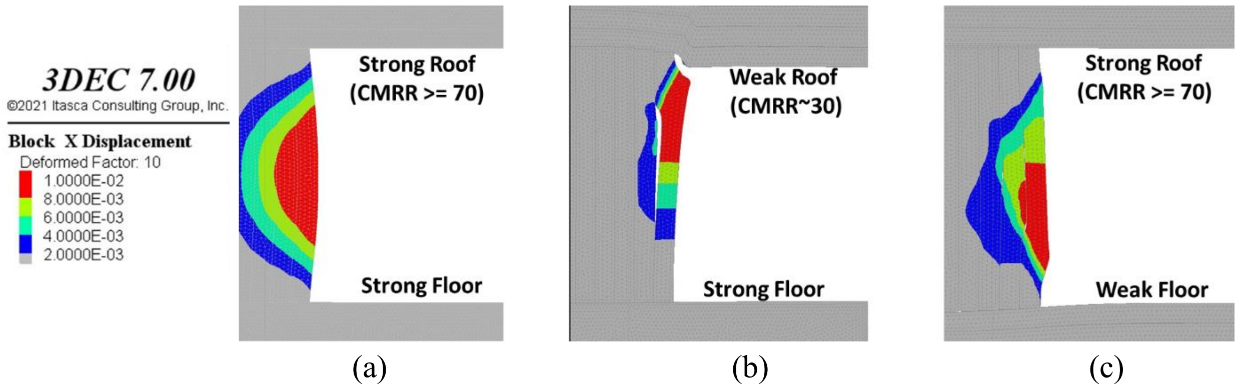


Figure 3.17 Representative rib deformation plots for three scenarios

The CPRR is a technique to measure the integrity of coal ribs; therefore, this value is independent of the roof or floor conditions. Instead, these conditions substantially impact the coal rib stability (RibFOS). So the equations to be proposed as a scope of this part should update the base RibFOS according to roof-floor conditions. Figure 3.18 presents plastic roof and floor model results and a comparison with a strong roof and floor case.

According to Figure 3.18, we can conclude that the impact of the moderate roof condition (CMRR=50) on rib stability is relatively small, and the RibFOS value decreases by approximately 20%. On the other hand, this effect has been found to be highly critical in poor roof conditions. Another conclusion that can be drawn is that the rib stability is reduced by approximately 50% regardless of whether the roof, floor, or both are highly incompetent, when weak strata are present either above or below the coal seam.

- *Parametric Studies - Rock Brows*

This task aims to provide a set of general guidelines for mine operators to identify coal ribs with the potential to form brows. The scope of this subtask is limited to identifying the brow-forming potential of coal ribs. A summary of the analysis methodology regarding brow formation potential is provided as follows: (a) The results from the solid coal rib models were evaluated. (b) All models with higher than 5 ft mining height and RibFOS <1.5 cases were classified as a critical group. (c) An overlying rock layer with various thicknesses was added to these models, and (d) coal RibFOS were estimated again to ensure which cases have a rock brow potential. Forming a brow requires the relatively weak and failed coal unit(s) underlying the stronger potential brow unit in the rib. In this case, studied models with two and three coal and rock units for rib stability were evaluated regarding the brow potential.

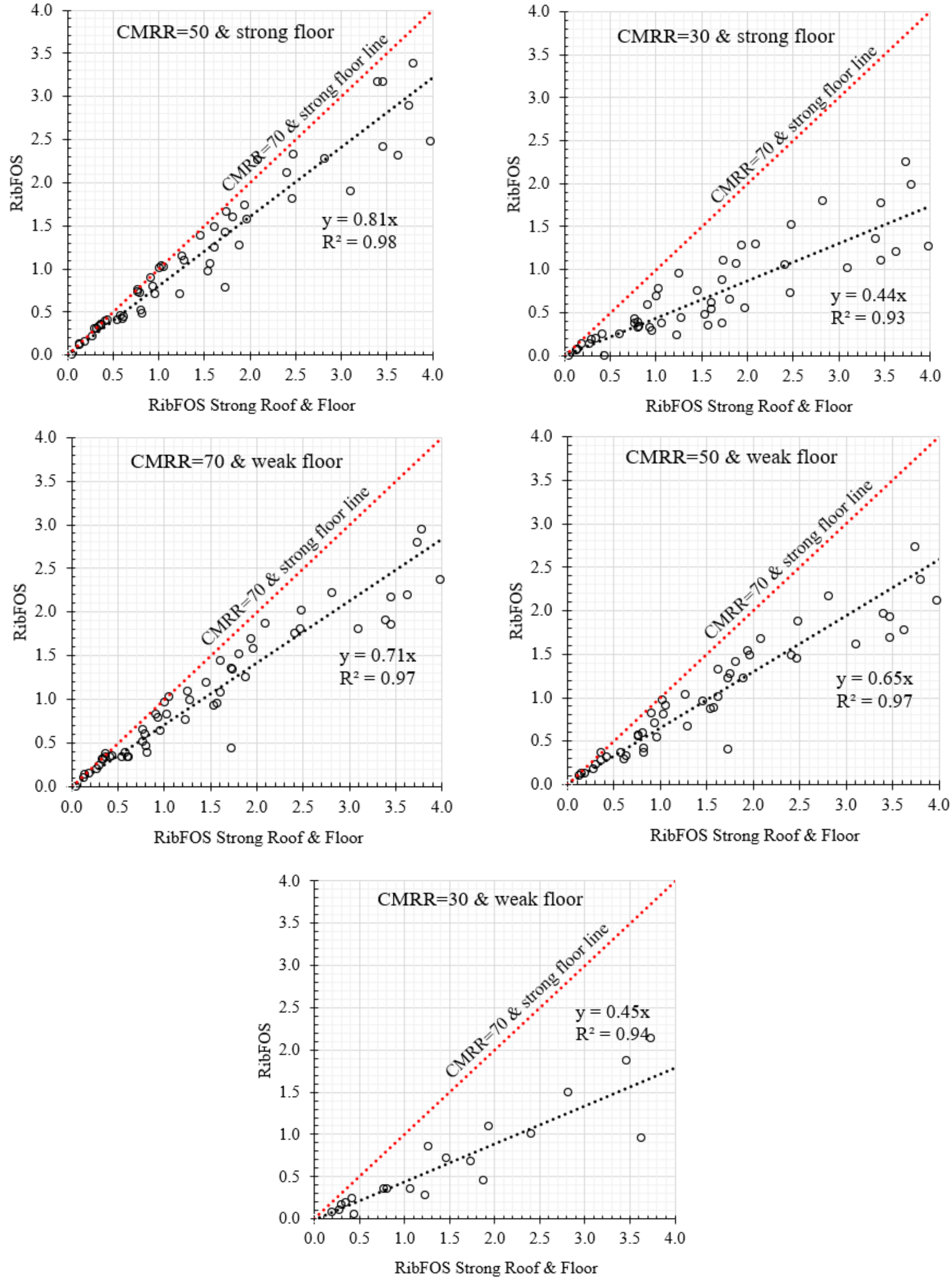


Figure 3.18 Plastic roof and floor model results and comparison with a strong case

As a result of this section, the conditions having a brow potential have been integrated into the developed CPRR calculation charts and tables. If the user falls within the critical conditions specified in these tables, the brow will most likely be formed. In brief, it was concluded that the following three criteria must be met for a brow to be formed:

1) Coal Rating (CR) value should be less than 50 (detailed information about CR can be found in the following section),

2) The upper rib unit should be composed of rock,

3) Calculated RibFOS value should be less than 1.5 (orange zone in the developed RibFOS calculation chart).

Developed tables and charts include a parameter called Rock Rating, which adds the quality of the rock on the rib to the CPRR calculation. One of the significant reasons to have the coal-rock interaction multiplier (M) in the CPRR calculation is to ensure that the users can easily predict the brow-forming potential.

The proposed rock-coal interaction factor (M), taking into account the multiplier Coal Rating (CR) and rock-coal position. If the user needs to use the red line (Figure 3.28), the case will have a brow potential when the RibFOS is <= 1.5. More details about the CR and RR parameters are presented in the next section. It is noteworthy to mention that through another collaborative effort with NIOSH, we recently started a new project to develop rib brow guidelines and integrate them into the CPRR system.

- *Parametric Studies - Inclusion of Discrete Discontinuities*

The impact of a single persistent joint on the stability of the coal rib is the main focus of this subtask. 3DEC allows our simulation to handle discontinuities explicitly and capture kinematic or combinations of kinematic and stress-driven failures. Spot bolting may be required in stable coal rib conditions when discontinuities are encountered.

Based on extensive field research, Mohamed et al. (2021b) suggest the RibFOS of 1.5 as a threshold value to delineate the boundary between supported and unsupported ribs. Our research also considers the same threshold value for the requirement of primary support, and the cases where the estimated RibFOS is higher than 1.5 will be analyzed in this part. In our numerical models, the roadway is assumed to be parallel to the maximum horizontal stress, and discontinuities that strike parallel to the roadway direction are explicitly introduced, simulating the most unfavorable condition. One base case scenario of the stable coal rib model is selected to present a better picture of the impact of joint geometric features on the stability of coal ribs. It should be noted that the same RibFOS calculation methodology is followed in these models. The strength reduction factor (SRF) is also applied for persistent joint properties in the RibFOS estimation to maintain consistent results with our previously completed simulations. It should be noted that we used the same material properties for both the discrete joint and the face cleat system. A solid coal rib composed of single dull coal with 800ft depth and 11 ft of mining height is selected for the analysis. The RibFOS for this case is estimated as 1.90, and no support is recommended.

In our analysis, the joint is assumed to intersect with the roadway around the mid-height of the rib. Figure 3.19 shows rib deformation plots of five representative cases.

Note that the presence of a persistent joint directly impacts the rib deformation response and intersections with either the roof or floor contact resulting in significant impacts on rib stability Figure 3.19-d and e). Although three distinct joint planes have already been defined (cleat set, roof-floor contact) with the inclusion of a persistent joint, they are not intersecting unless the introduced joint plane has a higher than 20° dip angle. The intersection of the three joint planes and the roadway leads to the formation of blocks or wedges, and this problem can be solved using block theory. However, as presented in Figure 3.19-e, the formed and unstable blocks may also have the potential to extend the unstable zones, and this response cannot be captured by any other analysis tools that utilize block theory (i.e., Unwedge).

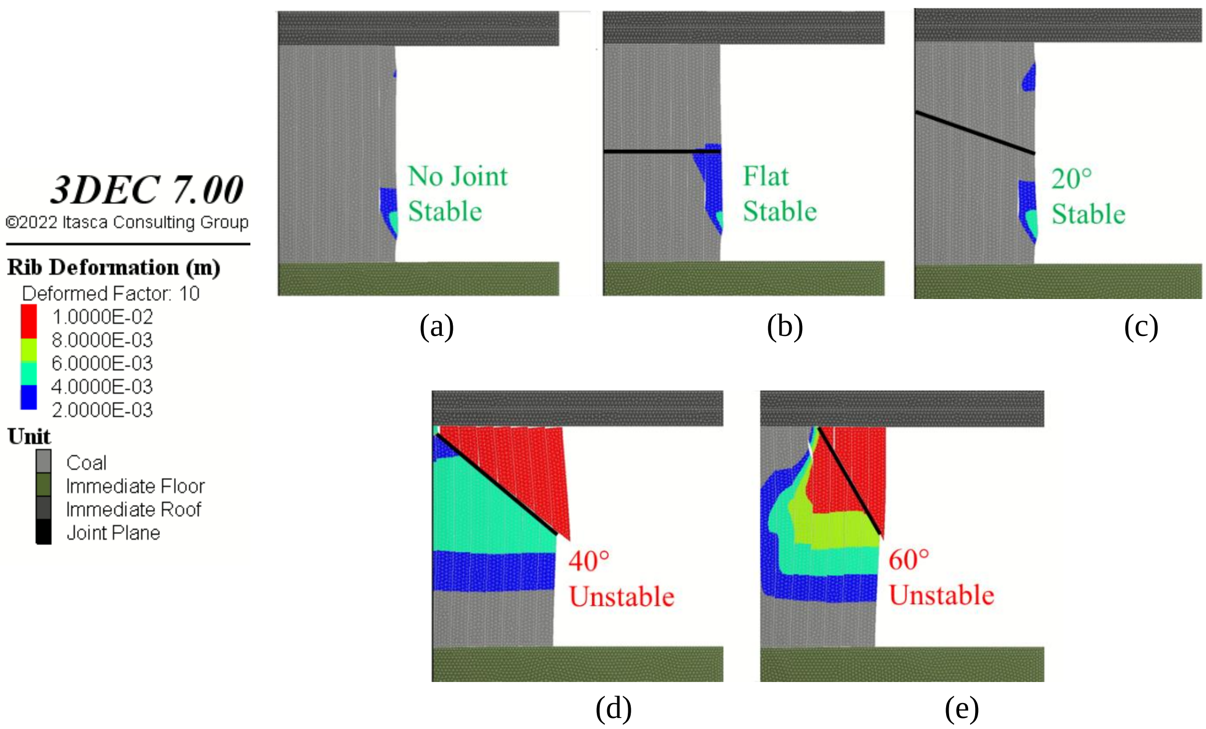


Figure 3.19 Simulated rib deformation response for (a) a base case, composed of single dull coal having 800ft depth with 11 ft of mining height, (b) rib having a horizontal joint, (c) rib having 20° dipping joint, (d) unstable rib having 40° dipping joint, (e) unstable rib having 60° dipping joint

Once we compared the stability condition of our preliminary models with a base case, simulations were extended to estimate the RibFOS for our models. Calculated RibFOS values and the impact of the presence of joint for each studied case are presented in Table 3.16.

Table 3.16 The impact of the presence of discrete discontinuities on rib stability

Dipping into the coal rib			
Dip	RibFOS	% Decrease	Normalized RibFOS
0°	1.90	0	1.00
20°	1.85	3	0.97
40°	0.50	74	0.26
60°	0.90	53	0.47

Although the presence of a flat joint leads to stress redistribution and slightly changes the rib deformation concentration location, it has no apparent impact on the coal rib stability. A similar response is observed for the 20° dipping joint as well. On the other hand, a crucial decrease in RibFOS is observed in coal ribs having persistent joints dipping higher than 20°. The RibFOS of the case with a 40° joint is estimated as 0.5. It is concluded that although the studied mining condition (single dull coal having 800ft depth with 11 ft of mining height) does not require any systematic support, a spot bolting application is necessary if the visually observed joint has a dip angle higher than 20° regardless of its dip direction. Notably, the filling characteristics significantly impact rib stability, and the simulated persistent joint has no filling. If the explicit joint has soft filling (i.e., clay), we recommend considering this weak link during the CPRR calculation (homogeneity and in-seam bedding rating sections) as well.

The presented single explicit joint case is also simulated with various overburden depths, mining heights, and coal-type cases. In all models, cases RibFOS is greater than 1.5 are considered. As a result, it has been observed that joint dip and dip direction are the most critical parameters together with the joint filling parameter. During our field visits, we observed malpractice in that, in some cases, mining professionals overtrust the contact strength of the persistent explicit joints. However, our results reveal that the joint orientation and the filling strength are the critical parameters that govern the stability of the block.

- *Parametric Studies - Preliminary Rib Support Modeling*

Although the main focus of this project is not analyzing the rib-support performance, which requires field instrumentation and in-situ tests, our research team has conducted preliminary research to reveal the maximum work done by the primary rib support system. This study has significance for determining the threshold value to delineate the boundary between the primary and secondary support requirements. In addition, this preliminary work is an important starting point for our new project, "*Improvement of Rib Support Design Utilizing Recent Advancements of the Coal Pillar Rib Rating (CPRR) System,*" supported by the Alpha Foundation. In our study, high-capacity fully grouted cable bolt parameters having different support densities and a wide range of overburden depth-mining height conditions for solid ribs were taken into account. We assumed such high-capacity rockbolts to understand the maximum work done by the primary rib support system.

To quantitatively analyze the effect of primary rib supports, the unsupported rib models were initially studied for three overburden depths (600, 800, and 1050 ft) and three mining heights (7, 9, 11 ft), then supported rib models with the various number of bolts, and bolt lengths were analyzed. Figure 3.20 shows the typical rib deformation responses for various support densities at 180 m overburden depth and mining height of 3.3 m. As seen in the rib displacement plots in Figure 3.20, the rib dilation was halted by introducing a single support. Also, note that SRF of 2.0 was used in all plots to compare the serviceability of the rib under the same coal mass properties. The support elements tend to limit the rib from relaxation by increasing confinement.

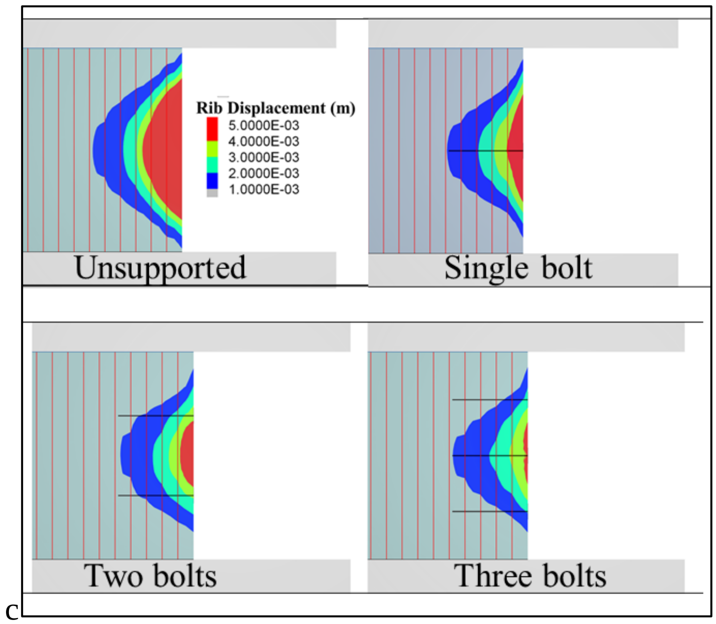


Figure 3.20 Effect of support density on rib deformation

Mohamed et al. (2021) suggest the RibFOS of 1.5 as a threshold value to delineate the boundary between supported and unsupported ribs in room-and-pillar mines. In this study, the same threshold value is considered to classify the ribs as *stable*. The RibFOS range between 1.0 to 1.5 is categorized as *marginally stable*, and RibFOS< 1.0 is identified as *unstable.* Mining height and depth of cover are two significant factors affecting rib response, as pointed out in the projects of Golder Associates (Stone,2016) which cover over 40 coal mines from Australia, New Zealand, the U.K., and Norway. They proposed the Rib Deformation Rating (RDR), which correlates mining height and depth of cover parameters with a multiplication factor to the support density. It is generally considered that a rib is evaluated to be in good condition for RDR rating of less than 500, which refers to the "no support required" condition. Moderate conditions range between 500–1000 RDR (Stone 2016) The results of the RibFOS analysis for unsupported cases are remarkably similar to Stone's (2016) findings that if RDR is less than 500, no support is required. The critical

RDR (mining height x overburden depth in m) for the primary support requirement is assessed to be 580 in Figure 3.21.

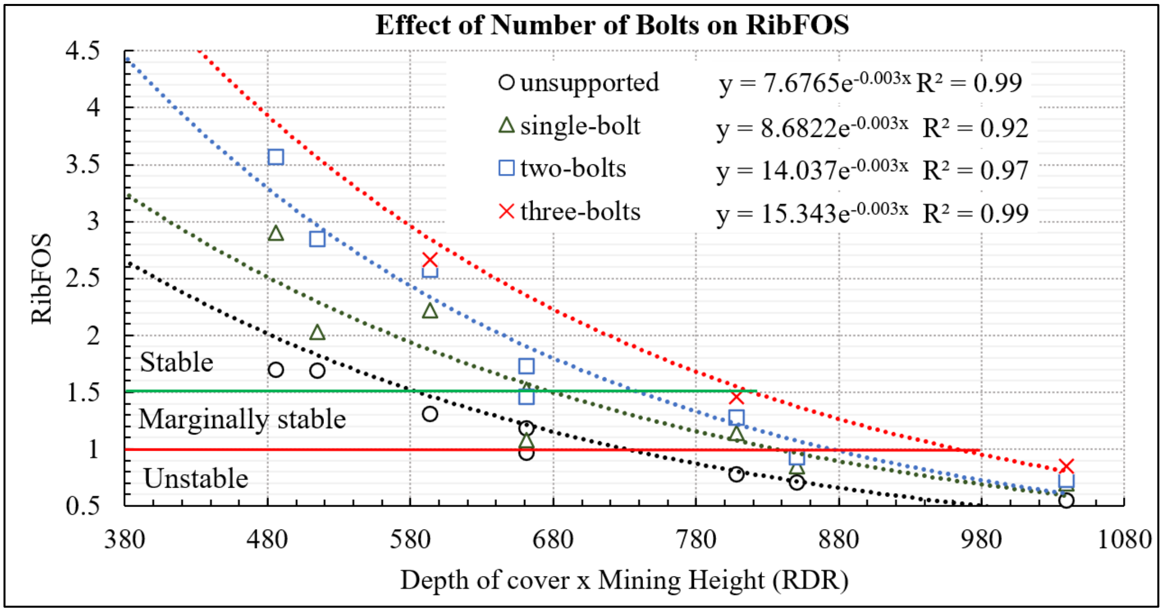


Figure 3.21 Effectiveness of primary support systems on rib stability

According to Figure 3.21, the support effects for the single-bolted to three-bolted rib cases are clearly differentiated. The work done by increasing bolt numbers can be much more prominent in all lower RDR values (i.e., <750). Moreover, it is concluded that RDR of 950 can be evaluated as a critical limit for primary rib support cases. If the RDR is above 950 for solid BBC coal, external rib support systems such as props, meshes, spray membranes, and pillar banding may require. Models with different bolt lengths are also conducted and included in the next stage of the study to make these results practically more suitable for field applications.

It should be noted that this section covers solid BBC coal type and a single rock bolt type. Therefore the common primary rib support density (PRSD) relation is not applicable for this task. As the analyses on the effect of bolt length and number of bolts on rib stability, we proposed a relationship between the supported RibFOS and parameters considered in this work. All model results are combined to propose a generic relationship (Figure 3.22), and it is given as the following equation (Equation 16) with a regression coefficient over 0.90. It should be noted that the proposed equation is only applicable to the solid coal rib of BBC.

$$RibFOS_{supported} = 230405 \text{ x } \left[\frac{RDR}{(L \times N)^{0.25}}\right]^{-1.876} \tag{16}$$

where RDR is the rib deformation rating (mining height × overburden depth in meters), L and N are the length of the rib bolt in meters and the number of rib bolts per row, respectively. This equation needs to be further updated by including the anchorage capacity, the spacing parameters of rib bolts, and the strength of the coal mass. From the field application point of view, if RibFOS of 1.5 is assumed to be a stable limit, a BBC solid coal rib with 305 m (1000 ft) depth and 2.4 m (8 ft) mining height can be stabilized with two bolts with a length of 1.5 m (2 x 5 ft) fully grouted bolts having 10 tonnes (22,000 pounds) of anchorage capacity.

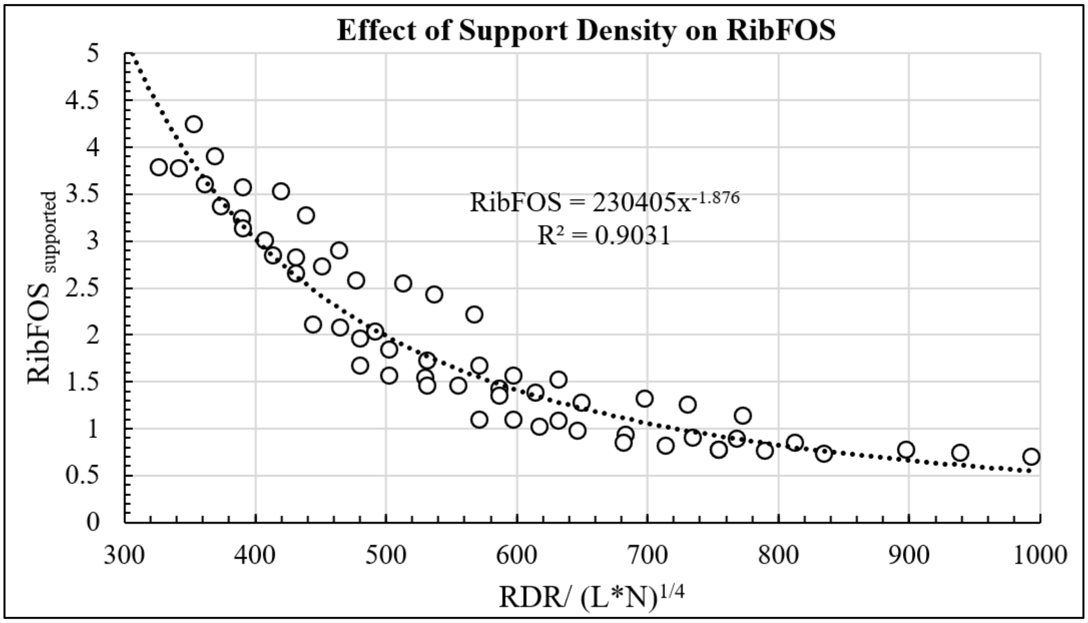


Figure 3.22 Combining all supported model results

The major outcome of this part for our ongoing research is that RibFOS of below 0.70 would not be stable with primary support, and this threshold value will be considered in the future parts of this project. It should be noted that the studied models consisted of a single coal unit with no partings or beddings and provided some preliminary insight into coal rib support performance.

3.4. Specific Objective 4: Develop a user-friendly CPRR and RIBFOS calculation sheet and methodology

3.4.1. Task #6: Improvement of the CPRR Calculation Sheet

- *CPRR Calculation Tables and Charts*

Employing individual numerical models to evaluate the stability of coal pillar ribs on a case-by-case basis is more accurate than relying on generalized regression model-based tables or charts, given that specific modeling guidelines adhere. Nevertheless, utilizing numerical modeling tools necessitates highly trained engineers, which may not always be feasible for most coal mines, especially smaller ones. A plausible alternative is to use tables and charts based on a vast number of calibrated numerical models and field survey data. Therefore, as a scope of this task, our research team developed simple, easy-to-use calculation sheets and charts for mine operators to determine the CPRR and the rib factor of safety for their conditions.

Our research team utilized various regression models to develop simple calculation charts and tables. After conducting over a thousand 3DEC models to determine the RibFOS of coal pillar ribs under various geometrical and geological conditions, a hypothesis was formulated to correlate the RibFOS with the investigated parameters in both weak and strong floor conditions (see Equation 17).

$$RibFOS = f(Z, H, CPRR, CMRR, floor\ strength) \tag{17}$$

where Z is the overburden depth, H is the rib height, and CPRR and CMRR are the Coal Pillar Rib Rating and Coal Mine Roof Rating, respectively.

The results of the modeling demonstrated that RibFOS is affected by several factors, including CPRR, CMRR, floor strength, overburden depth (Z), and rib height (H), regardless of the floor condition. However, while the components of Equation 17 are well-defined, the CPRR requires definition. It is a system that quantitatively assesses the strength of coal pillar ribs based on various parameters, including the thickness and strength of the rib units, the homogeneity of the coal beds, the bedding condition within the coal unit, the strength of the coal/rock interface, and the face cleat orientation with respect to the entry direction. Reliable measurement of CPRR requires proper understanding of the components of a typical coal pillar rib, which includes coal beds, rock units, and coal/rock interfaces. To develop a framework for calculating CPRR, the 3DEC models were used to analyze the various factors presented in Section 3.5.

Before the CPRR calculation, the user must reduce the rib composition into alternating coal beds and rock unit layers. This step merges the adjacent rock units and coal bands into single rock units and coal beds. Subsequently, the total thickness and the weighted average UCS of the rock units and coal beds are required. CPRR calculation consists of three parts; coal rating, rock rating, and cleat adjustment. The Coal Rating (CR) parameter, which is the summation of coal strength rating (CSR) and coal bedding rating (CBR) parameters, is calculated to assess the inherent quality of the coal bed.

$$CR = CSR + CBR \tag{18}$$

According to our regression models, CSR and CBR parameters can be calculated as follows:

$$CSR = 2.55 \times \frac{\sigma_{cb}}{\sigma_{BC}} \times \left(4 - \frac{1}{i_h}\right),\ i_h = min\left[\frac{min\left(\sigma_{c_i}, \sigma_{c_{i+1}}\right)}{max\left(\sigma_{c_i}, \sigma_{c_{i+1}}\right)}\right]_{i=1}^{i=m} \tag{19}$$

$$CBR = 15 \times \frac{\sigma_{cb}}{\sigma_{BC}} \text{ (coal beds with either no or strong in-seam bedding)} \tag{20}$$

$$CBR = 37 \times \frac{\sigma_{cb}}{\sigma_{BC}} \times ({r_i}^2 - r_i + 0.56) \text{ (coal beds with weak in-seam bedding)} \tag{21}$$

where σ_{cb} and σ_{BC} are the weighted average UCS of coal bed and the UCS of bright coal, respectively, i_h is the homogeneity index of the coal bed (ranges between 0.25 and 1.0), $\sigma_{c_i}\ and\ \sigma_{c_{i+1}}$ are the UCSs of adjacent coal bands "i" and "i+1", m is number of coal bands within coal bed, and r_i is the spatial position of the in-seam bedding (r_i), calculated by dividing the distance measured from the top of the coal bed by the total thickness of the coal bed (ranges between 0.2 and 0.8).

The second parameter, Rock Rating (RR), considers the spatial location of the rock unit within the coal pillar rib, weighted UCS, the total thickness of the rock unit and the CR parameters. According to our numerical models and site visits, we observed that the inherent quality of the coal bed has an impact on the rock parting behavior. Therefore, we included a function using a CR parameter for the calculation of the RR as a multiplier. In addition, since the spatial position of the rock unit and the contact between the rock unit and the coal has an impact on the rib response, separate regression constants were proposed for the calculation of the RR. The following equation is proposed for RR calculation:

$$RR = \gamma \times \left(\alpha \times r_k + \beta \times \frac{\sigma_{ck}}{\sigma_{BC}}\right) \times \sin(0.033 \times CR - 0.50) \quad (22)$$

where γ, α, and β are regression constants that depend on the spatial location of the rock unit within the coal pillar rib and the strength of coal/rock contact (Table 3.17), σ_{ck} is the weighted average UCS of rock unit, CR is the coal rating, and r_k is the rock percentage of rock unit/coal bed assembly.

Table 3.17 Values of regression constants for rock rating calculations

Spatial location of the rock unit	γ	Strength of coal/rock interface			
		Strong		weak	
		α	β	α	β
At top or bottom of coal pillar rib	0.57	120	4.5	60	6
Within coal pillar rib	0.68	60	13.5	15	7.5

The last parameter for the CPRR calculation is the cleat adjustment rating (R_{cleat}). If the face cleats have an angle greater than 20 degrees with respect to roadway direction and the coal pillar rib is classified as solid rib with no rock partings, an additional face cleat rating (R_{cleat}) must be added to the CPRR calculation. This cleat adjustment equation is directly gathered from the previous CPRR system and can be determined with the following equation:

$$R_{cleat} = 2.25 \times \left(\frac{\sigma_{cb}}{\sigma_{BC}} - 1\right) \quad (23)$$

In the end, knowing how to calculate the CPRR, a regression equation of RibFOS could be determined using the established models. To establish the RibFOS regression model, Equations 24 and 25, the 3DEC models were split into two distinct groups; the "*train*" group was utilized to construct the regression model, while the "*test*" group employed to verify the accuracy of the regression model. Equation (24) is used to calculate the RibFOS for a strong roof and floor, which is then adjusted for the quality of the roof and floor by multiplying it with the roof adjustment estimated through Equation (25). The roof and floor condition impact can be incorporated into the calculated RibFOS value by multiplying it with the roof adjustment factor.

$$RibFOS = (120 - 0.027 \times Z) \times \left(\frac{CPRR}{Z}\right)^{1.8} \times e^{0.162 \times (11-H)} \tag{24}$$

where Z and H are in feet.

$$\begin{aligned} Roof\ adjustment\ &= 0.666 \times ln(CMRR) - 1.817), \quad for\ strong\ or\ moderate\ \ floor \\ &= 0.325 \times ln(CMRR) - 0.654), \quad for\ weak\ floor \end{aligned} \tag{25}$$

The above-presented equations can be used for CPRR and RibFOS calculations. Despite the need for tedious calculations when performing a hand calculation, user-friendly charts and tables have been developed to simplify the process of calculating CPRR and RibFOS. It should be noted that the above-presented regression-analysis-based equations were used for developing CPRR and RIbFOS calculation charts.

The Coal Rating (CR) parameter, which is the summation of coal strength (CSR) and coal bedding (CBR) parameters, can be practically calculated by using two charts presented in Figure 3.23. The thicknesses of each coal unit and the weighted average UCS of the coal beds are required for CR calculation.

The coal strength rating (CSR) ranges between 6 and 40. The highest strength rating of 40 is assigned for homogeneous coal ribs (r = 1) dominated by strong coal units (UCS>=5000 psi). The coal bedding rating (CBR) ranges between 10 and 60. Three bedding conditions could be encountered in coal ribs: (i) no bedding, (ii) strong (clay-free) bedding, and (iiii) bedding filled with soft clay (weak). Our numerical model and field survey results showed no apparent difference in the coal rib stability between the strong bedding or the absence of any bedding on the coal. Therefore, the coal bedding rating for these conditions can be calculated by using the same line (no or strong bedding line) presented in Figure 3.23. If the bedding is weak, the user needs to calculate spatial in-seam bedding position. As can be seen, as the weak in-seam bedding gets closer to the middle of the coal, the CBR score decreases, thus negatively affecting rib stability. On the other hand, although the weak bedding position is almost insignificant in weak coal (UCS <=1000 psi), it has more significance in cases where the coal is strong. The strength and stiffness difference between the coal unit and the weak bedding has negatively impacted the rib if the bedding gets closer to the middle of the coal.

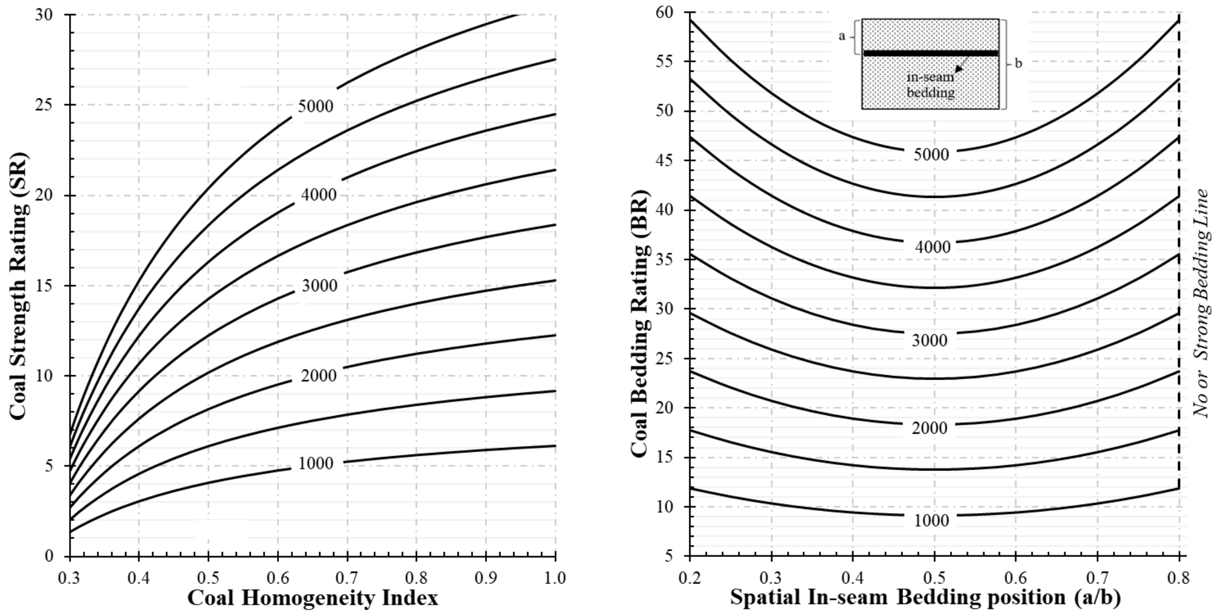


Figure 3.23 The Coal Rating (CR) parameter calculation charts

The second parameter, Rock Rating (RR), considers the spatial location of the rock unit within the coal pillar rib, weighted UCS, the total thickness of the rock unit, and the CR parameters. The RR parameter, the multiplication of RRu and coal-rock interaction multiplier parameters, can be practically calculated using two charts presented in Figure 3.24 and Figure 3.25. The CR parameter, rock percentage in the rib (10 to 50 % in practice), and the UCS of the rock are required for RR calculation.

The position of the rock unit and the contact between the rock and the coal are two significant parameters that govern the rib response. Rib responses are different and cannot be correlated according to the rock unit position. Therefore, for rock rating calculation, the user must select one of the charts presented in Figure 3.24 according to the studied case. The conditions under which charts are suitable for use are indicated with small sketches at the bottom.

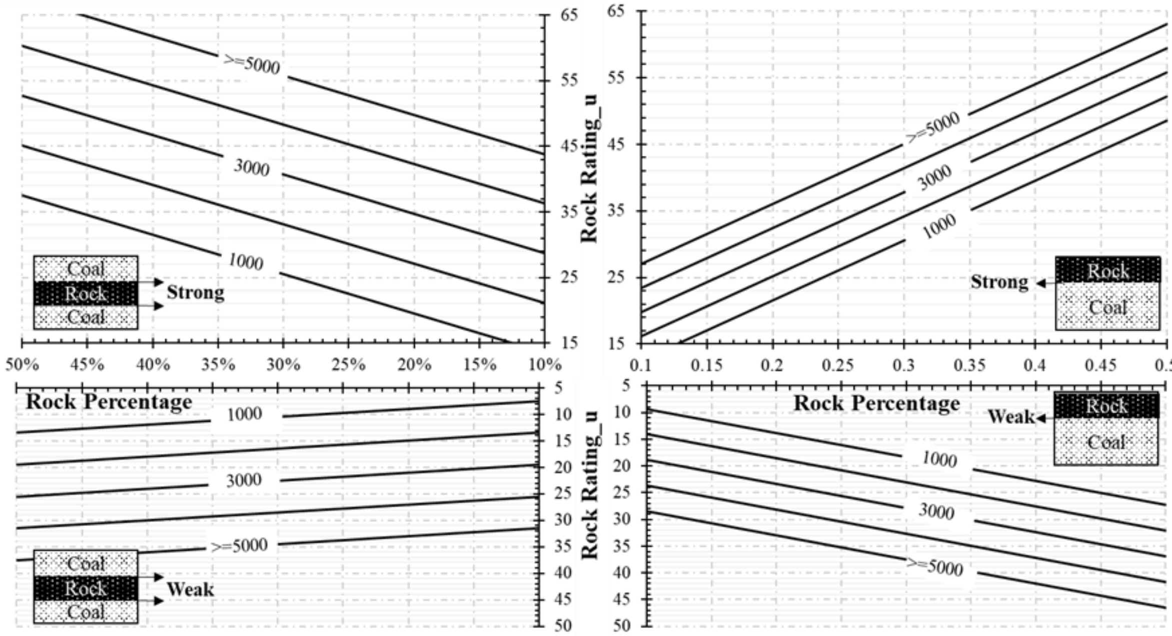


Figure 3.24 The Rock Rating (RR) parameter calculation charts

Once the uncorrected rock rating (RRu) is calculated, the user needs a coal-rock interaction multiplier to calculate the RR. CR and rock-coal position are necessary to calculate this multiplier (Figure 3.25). The red line in Figure 3.25 presents an important indicator: If the mine professional is using this line and the estimated RibFOS is below 1.5, the formation of a brow is highly probable in that case.

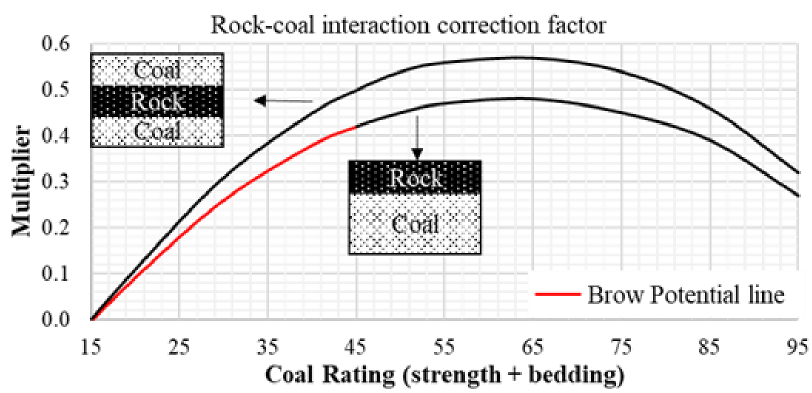


Figure 3.25 The Coal-rock interaction factor calculation chart

The last parameter for the CPRR calculation is the cleat adjustment rating (Rcleat). If the face cleats have an angle greater than 20 degrees with respect to roadway direction and the coal pillar rib is classified as solid rib with no rock partings, an additional face cleat rating (Rcleat) must be added to the CPRR calculation. This cleat adjustment equation is directly gathered from the previous CPRR system and can be determined by using a simple chart (see Figure 3.26)

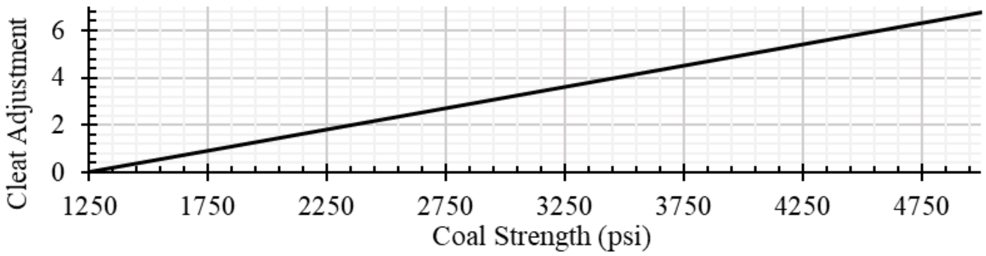


Figure 3.26 The Cleat adjustment factor calculation chart

Once coal rating (CR), rock rating (RR), and cleat adjustment factor (Rcleat) (if necessary) are calculated, the coal pillar rib (CPRR) is obtained by the summation of these three parameters. Finally, the user can estimate the rib factor of safety (RIBFOS) by using the calculated CPRR for their specific overburden depth (300-1100 ft) and mining height (5-11 ft) conditions with the help of Figure 3.27.

According to our field data that covers 30 underground US coal mines, most coal mines opt for rib support for RibFOS values less than 1.5. This value is the critical limit for recommending rib support in US coal mines, as indicated by the orange-colored regions in Figure 3.27.

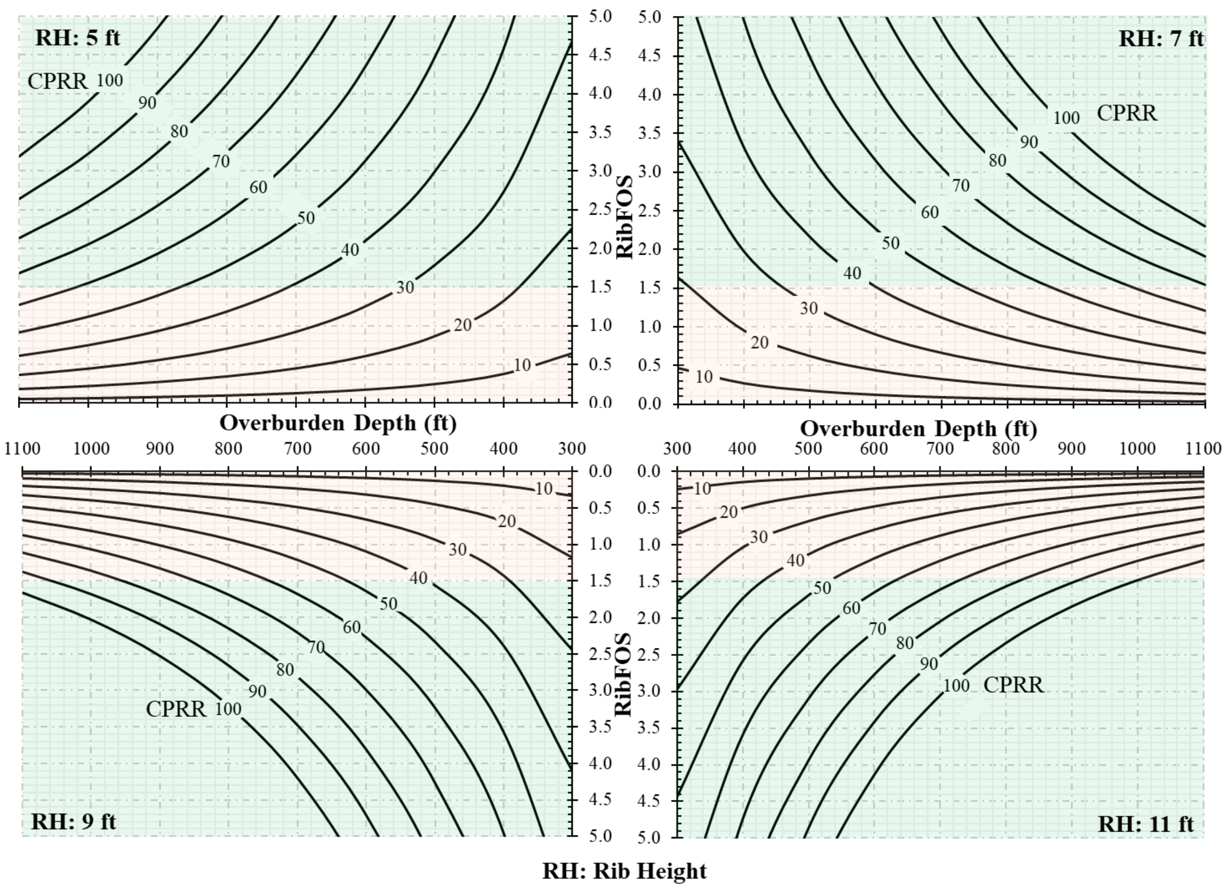


Figure 3.27 The RibFOS estimation charts

The roof and floor condition impact can be incorporated into the calculated RibFOS value by multiplying it with the roof adjustment factor. This factor can be obtained from Figure 3.28.

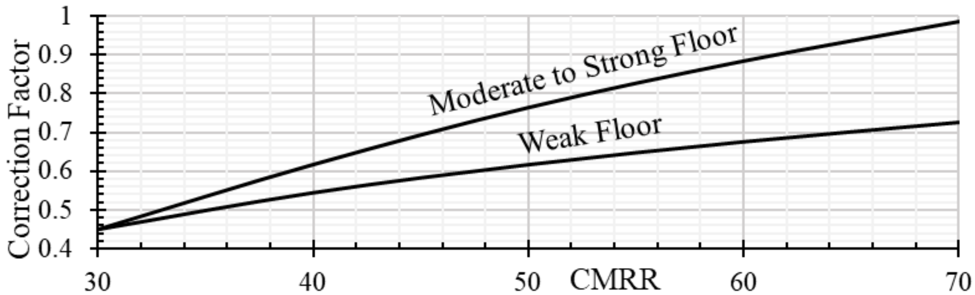


Figure 3.28 The inelastic roof-floor condition correction factor estimation chart

- <u>*Validation of the developed CPRR equations, charts, and tables*</u>

Based on the information presented in this section, the developed charts and tables for predicting RibFOS in coal pillar ribs have been validated successfully. Figures Figure 3.29 through Figure 3.32 provide a comprehensive analysis of the correlation between the RibFOS calculated using the regression model and 3DEC models for coal pillar ribs with different roof and floor strengths. The figures also show the lower and upper 95% confidence lines for predicting the 3DEC rib stability factor, which provides an effective way to evaluate the accuracy of the regression model.

The four quadrants (Q1, Q2, Q3, and Q4) determined by a previous study (Mohamed et al., 2021b) are also displayed in the figures. Most coal mines opt for rib support for RibFOS values less than 1.5, and the majority of the rib cases are located in Q1 and Q3, with a few in Q2 and Q4. The regression model underestimates the RibFOS in Q2 and overestimates it in Q4, indicating that rib cases in Q2 will be conservatively supported.

The R-squared values of the linear relationship between the developed equations, charts, and tables and the 3DEC models were above 0.90 for solid coal pillar ribs and ribs with rock units (partings), as shown in Figures Figure 3.29 through Figure 3.31. Similarly, for a wide range of roof and floor strengths, the R-squared value of the regression model is 0.88, Figure 3.32. These results demonstrate that the developed easy-to-use tools are able to accurately predict the RibFOS for a variety of coal pillar rib configurations and conditions, providing a reliable tool for evaluating rib stability in coal mines.

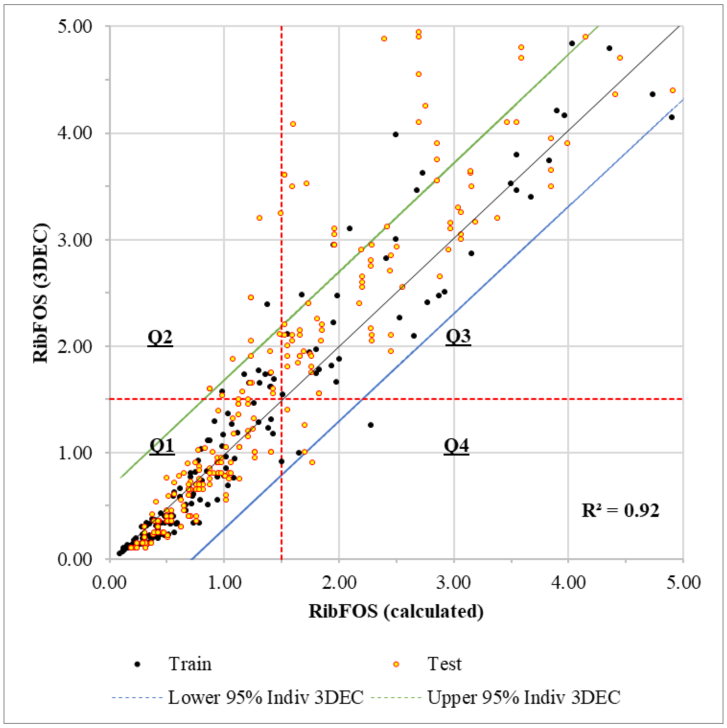


Figure 3.29 Developed and 3DEC model-based calculations of RibFOS for solid coal pillar ribs.

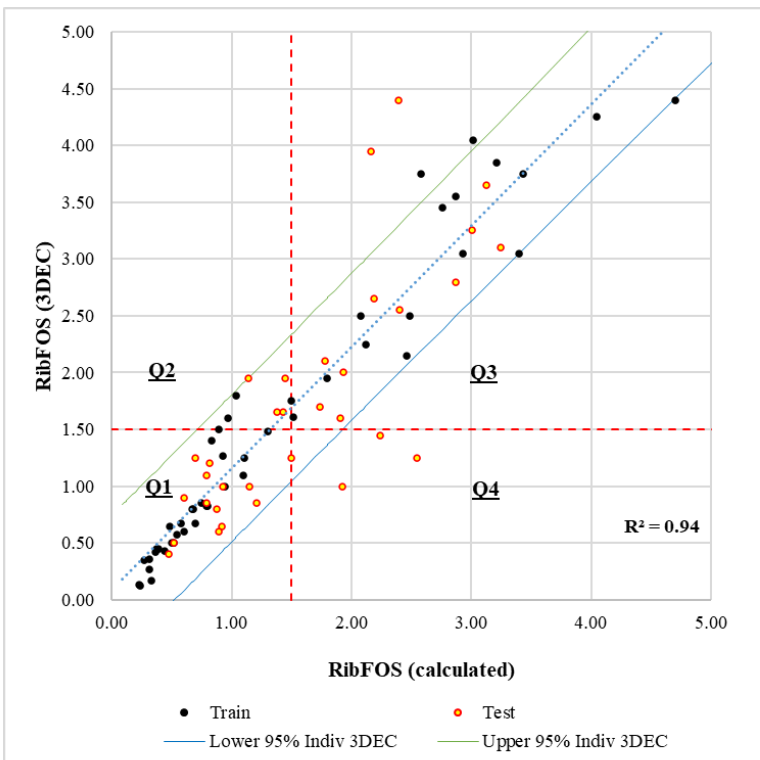


Figure 3.30 Developed and 3DEC model-based calculations of RibFOS for coal pillar ribs with rock units and strong rock/coal interface.

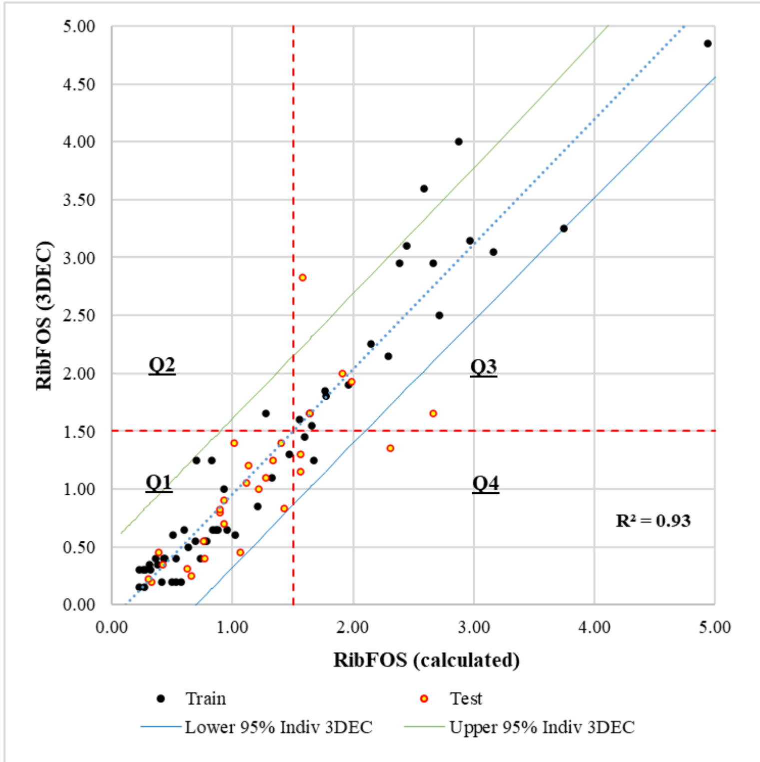


Figure 3.31 Regression model and 3DEC model-based calculations of RibFOS for coal pillar ribs with rock units and weak rock/coal interface.

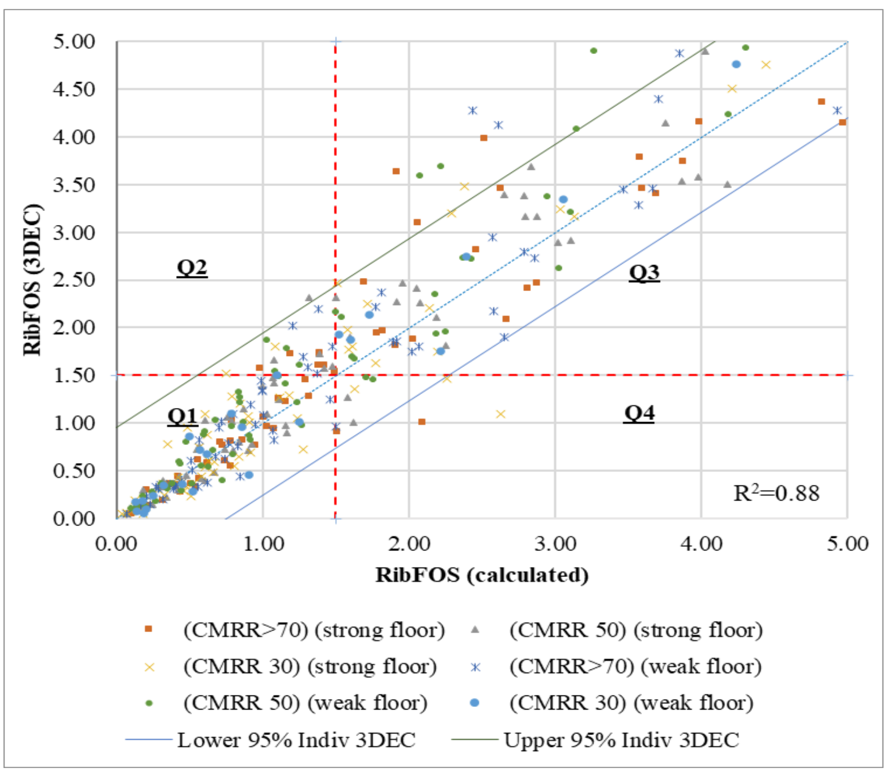


Figure 3.32 RibFOS calculated using regression model and 3DEC models for solid coal pillar ribs with varied roof and floor strengths.

As outlined in the project proposal, one of the primary aims of this research is to develop a CPRR calculation sheet that can estimate the stability of coal ribs in a practical manner that is suitable for mine operators. Furthermore, the aim was to enhance the CPRR calculation process by producing easy-to-use charts that can estimate RibFOS values comparable to those predicted by 3DEC numerical models. To validate the accuracy of the proposed charts, we conducted simulations on surveyed rib cases under varying conditions. This section presents the results of three validation cases, which demonstrate that the RibFOS values obtained from the charts align well with both field observations and numerical model results.

Case A: In the first case, mining takes place in the Springfield seam, and the mined coal is 52" thick at depths of 450 ft. The coal seam is immediately overlain by black shale. The immediate floor consists of approximately 3 ft of green shale. The rib height is 6'7". Three coal units were identified in this rib having 9", 24", and 19" thicknesses. Coal unit strengths from top to bottom are determined as 3500 psi, 4750 psi, and 5200 psi, respectively. A clay band separates the top and middle coal units. A weak contact is noted between the bottom coal and the parting and is marked as the most critical. The rib is not supported, no rib sloughing was observed, and the face cleat system is almost perpendicular to the entry direction in this case.

Our numerical model estimates the RibFOS of this case to be higher than 5.0. Figure 3.33-a shows the deformation response of the rib with an applied SRF of 5.0. Similar to field observation, the critical rib component is the weak contact between the bottom coal and the parting. Our 3DEC results confirm the decision of the mine: This rib is stable, and no support is required. By utilizing the survey data and the charts that were developed, we have estimated that the RibFOS is greater than 5.

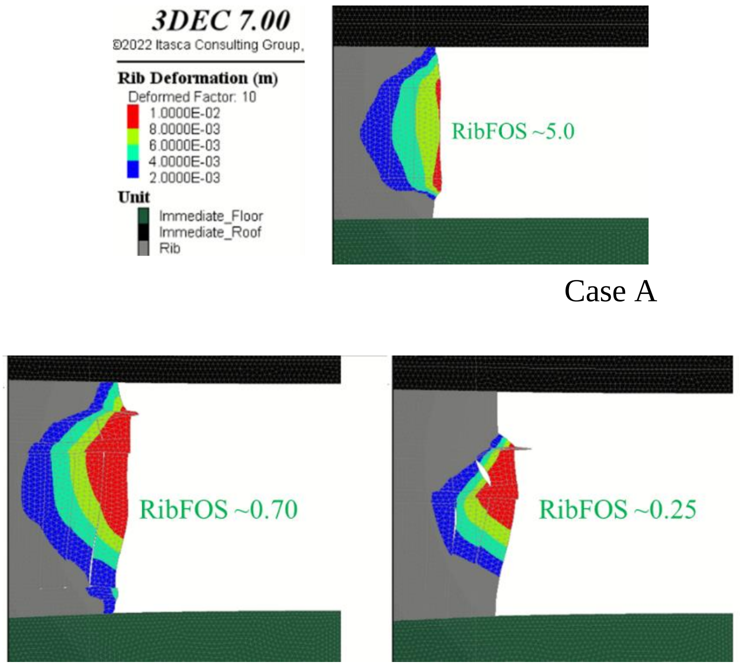
Case B: A mine located in Pennsylvania, extracts from the Pittsburgh seam at depths of over 700 ft. The rib height of the surveyed case is 9 ft and buried at a depth of 770 ft below the ground surface. The immediate roof and floor consist of relatively competent shale, and 19" thick shale is the top rib member. Three coal units were identified in this rib, having 9", 48", and 12" thicknesses. An 11" thick weak claystone layer, the weakest component of the rib, separates the top and middle coal units. Middle and bottom coal units have almost identical strengths of 3000 psi, and slightly weaker top coal has 1450 psi strength. The coal rib can be considered a friable condition with a 1 to 2" spall size. The face cleat orientation was measured almost parallel to the roadway orientation. Current rib support practices at the mine include the use of 3-foot-long, 5/8" diameter, grade 60 mechanical bolts installed with 16" × 16" bearing plates (pizza pan). Typically, one row of a bolt and a steel W-strap are installed around the mid-height of the rib as primary support. The secondary support system consists of two additional rows of bolts having 4 ft row spacing and 8 ft spacing in conjunction with 8 ft length plastic meshes.

Our 3DEC model result also predicts that the rib is potentially a ground control hazard for the mine. The RibFOS of this case is estimated as 0.7, which is the same as our proposed critical threshold value for the installation of a secondary support system. Therefore, this rib would not be stable with a primary support system, and secondary support would be required. As presented in Figure 3.33-b, the claystone parting unit tends to slide into the roadway, and the rib starts sloughing from the mid and top coal section. Therefore, the best primary support location is below the weak claystone. Developed charts estimate the RibFOS for this case to be in the range of 0.70-0.80, which is quite similar to the one we estimated with our 3DEC model.

Case C: This mine extracts from the Pittsburgh seam as well. The surveyed rib has 72" thick coal in total at depths of 1050 ft. Surveyed rib members and strengths are near identical to Case B except for the immediate floor. A particular portion of relatively strong coal having 3000 psi strength was kept as an immediate floor. The weakest member of the rib is a 15" thick weak claystone layer that separates the top and middle coal units. The face cleat system is parallel to the entry direction in this case. Although this mine has a shorter mining height, due to the higher overburden depth, 4 ft length mechanical bolts are used for both primary and secondary support. Primary bolts, having 4ft spacing, are installed around the mid-height of the rib. The secondary support system consists of two additional rows of straight bolts at a 1 ft distance between the roof and floor. Due to the friable nature of the rib, 7 ft length plastic meshes are used to hold broken coal in place. The rib is beyond the slight skin damage and more than 6" sloughage is noted.

This case has the worst rib condition among the three cases; our numerical model estimates the RibFOS to be around 0.25. Similar to Case B, the weak clay parting and the contacts of this unit make this rib a critical ground control hazard for the mine Figure 3.33-c). Secondary support is strongly recommended for this case. Closer bolt spacing and longer rib bolts are required for this case compared to Case B. Our field observation qualitatively verifies our numerical model. The mine increased the bolt length from 3 ft to 4 ft and reduced the bolt spacing from 8 ft to 4 ft to keep the rib stable. Similar to the numerical model output, the estimated RibFOS from developed charts is 0.30.

The presented three validation cases clearly indicate that the developed charts have a great potential to estimate RibFOS in a practical manner. The calculated RibFOS results using the developed charts agree well with qualitative field observations and numerical simulation results.



Case A

Case B Case C

Figure 3.33 Unstable rib deformation plots for three validation cases

4.0 Research Findings and Accomplishments

This section presents detailed documentation and a discussion of the research findings and accomplishments. Research findings and accomplishments are summarized by classifying them into relating to the specific objectives of this project.

4.1. Specific Objective 1: Expanding the CPRR Empirical Data Set

Research findings for this specific objective cover i) the expanding of the CPRR empirical data set, ii) the evaluation of our questionnaire results, and iii) the prepared rib data collection safety protocol, the data collection procedure, and the updated CPRR data collection sheet.

- *Coal Pillar Rib Survey*

Rib failure in coal mines is a complex phenomenon, with potentially significant variations in the mechanism of failure across different mine sites and even locally within a single mine. The initial form of the CPRR system was based on the empirical study of 22 coal mines within the United States. In collaboration with our industry partners and NIOSH researchers, we expanded this data set and surveyed 20 more coal ribs, with a particular focus on coal units with rock partings and in-seam (strong and weak) beddings. As a scope of this task, our research team successfully surveyed eight mine sites located in Illinois, Indiana, Pennsylvania, and West Virginia. A sample of the rib survey data collected from one of the site visits is presented in Figure 3.34, and the collected data is presented in Appendix B.

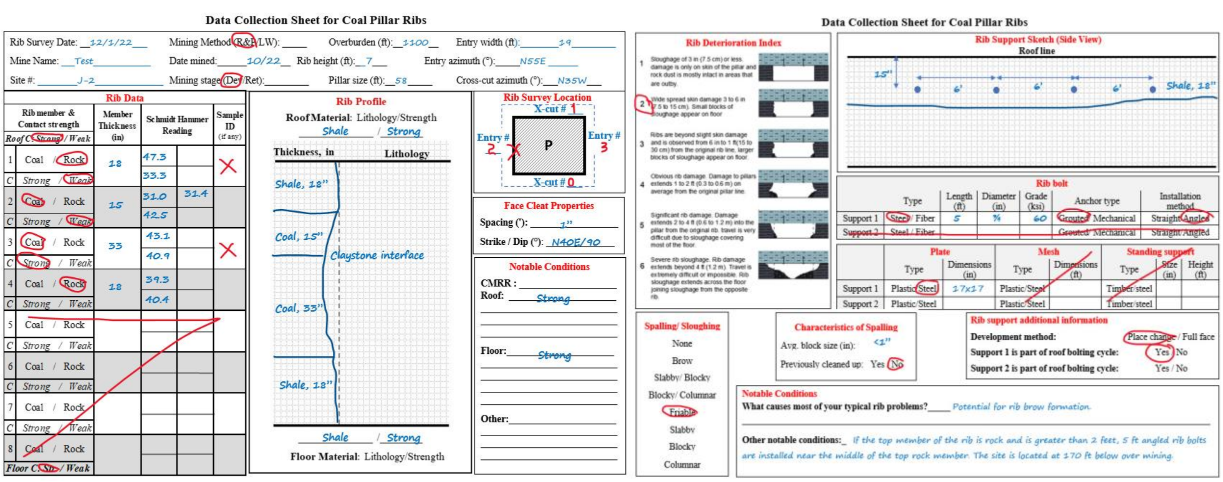


Figure 3.34 A sample of the collected rib survey data from the initial site visit

- *Questionnaire results*

The questionnaire is divided into two parts. The first part aims to assess the ability of mine professionals to effectively use a rib rating system and their strategies for controlling the rib based on their experience. The second part of the questionnaire aims to analyze and verify the impact of various parameters when deciding the type and density of pillar rib support.

The agreement rates of the mine professionals for the given statements are presented in Table 3.18 with descending agreement percentages. Table 3.18 shows that over 80% of the respondents agree with the first six statements. On the other hand, no consensus has been reached on statements 7 to 9.

Table 3.18 The agreement rates of the mine professionals (part a)

Q. #	Agreement	Statement
1	90%	Classifying pillar ribs based on their stabilities may be useful for us to determine preliminary support designs.
2	89%	Our current rib support system is mainly based on our local practices and experiences.
3	89%	Rib control experiences of other US coal mines may be useful for us.
4	85%	Would you consider using a rating system where you can estimate the factor of safety and primary support density of your pillar rib in a more practical way?
5	84%	Roof and floor conditions have an impact on our rib stability.
6	82%	It is necessary to quantify the current state of our ribs
7	55%	A standard rib control methodology can be introduced for all US coal mines.
8	55%	I prefer to use a calculation sheet(s) for classifying pillar ribs instead of a computer application.
9	47%	We encounter unpredictable instability problems in pillar ribs that appear to be stable

According to the results of this section, it has been concluded that the mine professionals have a positive opinion toward a CPRR system and may use this system for their operations. However, it was observed that they approached the statement of introducing a standard rib control methodology and guidelines for US coal mines issue more distantly.

The agreement rates of the mine professionals for the influence of the given parameters when deciding their rib support are presented in Table 3.19 with descending impact percentages. Table 3.19 shows that over 75% of the respondents agree with the strong impacts of the first seven listed parameters. On the other hand, most mine professionals believe coal brightness is not a useful measure to evaluate the strength of coal mass.

Based on the collected feedback from mining professionals, we have revised our data collection sheet. The revised sheet no longer includes the coal brightness profile. However, we decided to keep the rib deterioration index (sloughage level) section as it is conventionally used for assessing the condition of the rib.

Table 3.19 The agreement rates of the mine professionals for the influence of the given parameters when deciding their rib support

Parameter #	Agreement	Statement
1	97%	Mining Depth
2	95%	Rib Height
3	84%	Coal Strength
4	82%	Presence of clay bedding
5	80%	Face Cleat Orientation with respect to entry direction
6	80%	In-Seam Parting Thickness
7	77%	Number of Rib Units
8	68%	Rib Sloughage Level
9	20%	Coal Brightness (Bright to Dull)

- *Rib data collection procedure, data collection safety protocol, and updated data collection sheets*

In light of the knowledge, we gained from conducting 8 coal mine surveys under the project's scope, we developed a "rib data collection procedure and safety protocol" in collaboration with NIOSH researchers. This section presents the prepared rib data collection safety protocol, data collection procedure, and updated data collection sheets. In addition to the standard safety measures associated with underground work that should be followed in any underground operations, we listed ten extra safety precautions to be followed during the rib data collection. These precautions are presented in Table 3.20**Error! Reference source not found.**.

The data collection sheet used by NIOSH for CPRR studies has been significantly updated, making it more practical and easier to use. The updated data collection sheet consists of 2 pages. The main purpose of this update was to enable CPRR users to provide the data needed to estimate CPRR and RibFOS more efficiently and quickly. While these updates were being made, our team asked mine professionals' opinions during in-person interviews, and the sections they agreed were not necessary or complex were removed or updated. The coal brightness profile section is a good example of this. These brightness profiles provide an alternative coal strength determination method included in the previous data collection sheet. Our in-person meetings revealed that more than 80 % of the mine professionals are against using these profiles, and we removed this section from the data collection sheets. The updated rib data collection sheet is presented in Figure 3.35 and Figure 3.36**Error! Reference source not found.Error! Reference source not found.**.

Table 3.20 Safety Protocol for Rib Data Collection

	Safety Precautions for Rib Data Collection
0	Follow standard safety measures associated with underground work.
1	Walk in the middle of the mine entries and cross-cuts, away from the mine ribs, whenever possible.
2	Avoid contact with severely damaged corners. If you observe loosened blocks at the roof or the higher rib portions, stay out of that area and avoid surveying it.
3	Inspect the condition of the rib carefully from a distance; check rock slippage contacts, smooth or slickensided rock surfaces, rock layers, and questionable contact points.
4	Be particularly cautious around ribs higher than a person's height, as ribs greater than 6' require extra caution.
5	Do not get close to the rib for data collection until steps 2-4 have been completed.
6	Do not turn your back on a rib during the survey.
7	Do not use a geological hammer or Schmidt hammer for data collection unless you have a "buddy" watching the rib during contact.
8	Continuously inspect the rib and listen for any unusual sounds during the data collection.
9	Check the rib after using the Schmitt hammer or geological hammer for data collection; the rib may loosen the integrity with the impact force exerted by the tools.
10	Do not walk to another cross-cut for data collection without notifying your escort.

The required tools for rib data collection are a geological hammer, a Brunton compass, a measuring tape, an L-type (low energy) Schmidt hammer with the mushroom plunger, and a sample collection bag (if UCS or point load tests will be conducted).

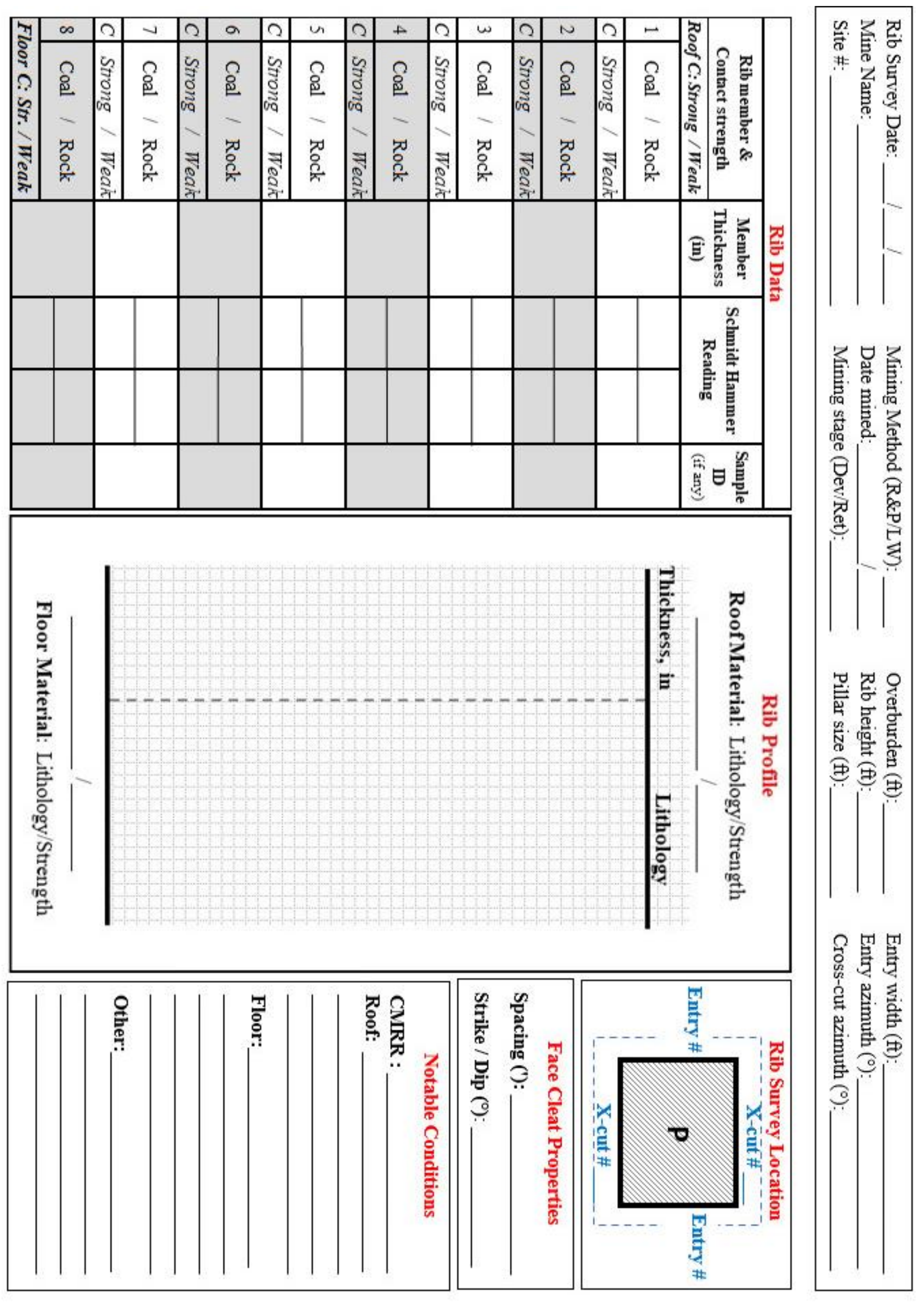
The first page consists of three sections. The general data about the mine is located at the top of these sections. This part needs the following data: the surveyed site, including mine name, mining method, overburden depth, entry dimensions, and entry direction.

Rib data section: Column 1 contains the ID of rib units, counted from the roof line to the floor line, and the contact strength. Rib units are only included in the count if their thickness is greater than 6 inches; if the rib member is less than 6 inches, it will be combined with the lower rib unit. Since a maximum number of 8 rib units were noted during our rib surveys, this section consists of 8 lines. Users must select the rib unit type (coal or rock). As the interface has an impact on rib response, the user needs to mark the condition of the interface. The user should select the interface strength as strong or weak with the help of the geological hammer. Column 2 in this section lists the rib units' thicknesses that are greater than 6 inches. Column 3 contains the average measured Schmidt rebound numbers for each rib unit. The user can mark Column 4 whenever samples are collected from rib units. Collecting samples from critical rib units for compression strength testing is recommended. This will ensure that the results obtained from the tests are accurate and reliable.

Rib profile section: In this section, the rib profile should be sketched, showing the spatial positions of coal and rock units, including their lithological descriptions. In addition, roof and floor lithologies and strengths (if available) should be noted as well.

Survey location and other conditions section: Rib survey location, face cleat properties, and other notable conditions are the main data to be noted in this section. Face cleat direction is essential since we proposed a cleat adjustment parameter by considering it concerning the entry direction. Coal Mine Roof Rating (CMRR) value is also necessary if the user wants to include the impact of the roof in their RibFOS estimation.

Page 2 of the data collection sheet contains the data for the characteristics of the rib and the support system. It features a rib deterioration index that ranks rib quality from the best to worst on a scale of 1 to 6, providing a comprehensive overview of rib degradation. On the left bottom of page 2, the nature of rib spalling/sloughing and the average block size of rib spalling are also listed, enabling a rational assessment of the severity of rib damage. Furthermore, a sketch of the rib support pattern (if applicable) is provided at the top right of page 2, depicting the spatial position of rib bolts concerning the roof line and allowing for a comprehensive evaluation of rib support. The accompanying tables are used to summarize the properties of rib support, including bolt type, length, size, grade, plate type, and dimensions. These tables provide a detailed breakdown of rib support components.



Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: ___/___/___ Mining Method (R&P/LW): ___/___ Overburden (ft): ___ Entry width (ft): ___
Mine Name: ___ Date mined: ___/___ Rib height (ft): ___ Entry azimuth (°): ___
Site #: ___ Mining stage (Dev/Ret): ___ Pillar size (ft): ___ Cross-cut azimuth (°): ___

Rib Data

Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock				
C Strong / Weak				
2 Coal / Rock				
C Strong / Weak				
3 Coal / Rock				
C Strong / Weak				
4 Coal / Rock				
C Strong / Weak				
5 Coal / Rock				
C Strong / Weak				
6 Coal / Rock				
C Strong / Weak				
7 Coal / Rock				
C Strong / Weak				
8 Coal / Rock				
Floor C: Str. / Weak				

Rib Profile

Roof Material: Lithology/Strength ___/___

Thickness, in Lithology

___/___ Floor Material: Lithology/Strength

Rib Survey Location

X-cut # ___ Entry # P Entry # X-cut # ___

Face Cleat Properties

Spacing (): ___
Strike / Dip (°): ___

Notable Conditions

CMRR: ___
Roof: ___
Floor: ___
Other: ___

1 of 2

Figure 3.35 Data Collection Sheet for Coal Pillar Ribs (Page-1)

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

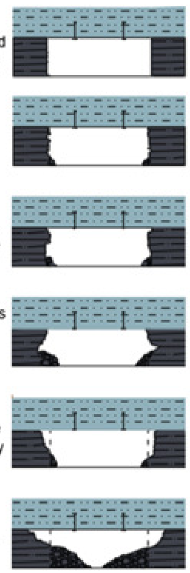
2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

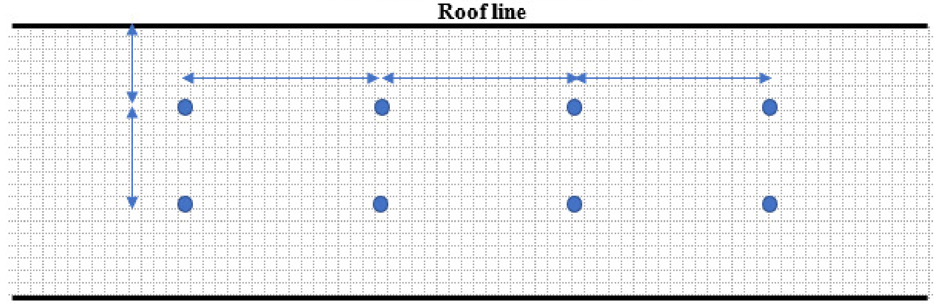
4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



Rib Support Sketch (Side View)



Rib bolt						
	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
Support 1	Steel / Fiber				Grouted/ Mechanical	Straight/Angled
Support 2	Steel / Fiber				Grouted/ Mechanical	Straight/Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
Support 1	Plastic/Steel		Plastic/Steel		Timber/steel		
Support 2	Plastic/Steel		Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None

Brow

Slabby/ Blocky

Blocky/ Columnar

Friable

Slabby

Blocky

Columnar

Characteristics of Spalling

Avg. block size (in): _______

Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face

Support 1 is part of roof bolting cycle: Yes / No

Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems?___________________________

____

____

Other notable conditions:___________________________

____

____

2 of 2

Figure 3.36 Data Collection Sheet for Coal Pillar Ribs (Page-2)

4.2. Specific Objective 2: Adapting the Coal-Mass Constitutive Model

The research team adapted the coal-mass constitutive model, which was originally developed by NIOSH researchers for use in CPRR numerical simulations with FLAC3D, to make it applicable for use in distinct element-based solvers, such as 3DEC.

Our team accomplished this specific task by conducting two sets of validations to demonstrate our progress. Firstly, the adapted coal-mass constitutive model was validated by simulating pillar-scale uniaxial compressive strength (UCS) and triaxial compressive strength (TCS) tests. Subsequently, additional validation simulations were carried out to estimate the RibFOS for solid coal ribs using 3DEC, and the results were compared to those obtained using the FLAC3D version of the Coal-mass constitutive model.

The simulation results correctly reproduced the elastic response and post-peak strength behavior observed in the UCS and TCS test simulations, indicating the accurate performance of the coal-mass constitutive model. The validation study at the pillar scale yielded nearly identical coal responses. Similarly, the solid coal rib scale model was validated by comparing the factor of safety (FOS) values obtained from the 3DEC models with those obtained using FLAC3D-v7. Detailed information about the validation process is provided in Section 3.2.

Furthermore, we shared the developed constitutive model and updated models with the NIOSH research team, contributing to the early stages of CPRR development in collaboration with them.

4.3. Specific Objective 3: Expanding the CPRR Calculation Through DEM-Based Numerical Simulations

A comprehensive rib stability analysis was conducted using 3DEC modeling, considering several parameters such as overburden depth, rib height, the strength of rib units, number and thickness of rib units, bedding condition, and roof and floor conditions.

The stability of underground openings is influenced by various factors, and one important parameter is the span. In the majority of coal mines in the U.S., entry widths typically range from 4.5 to 6 meters. During the rib survey conducted, it was observed that the entry width had minimal impact on rib stability. To validate this observation, we tested 24 base models, and the results led us to conclude that a 1.5-meter change in excavation width for coal rib did not significantly impact the stability of the rib.

It is anticipated that plastic roof and floor conditions may have different effects depending on the change in rib composition. This variable impact is also observed in the model results. Since the project's main objectives are to propose simple and functional equations that mining professionals can use, it aims to quantitatively present the effect of the plastic roof and floor conditions on global scale rib stability (RibFOS) rather than proposing complex rib composition-dependent equations. The main findings of incorporating plastic roof and floor conditions in coal rib stability is two equations. These equations are helpful if mine professional wants to include the impact of the roof and floor condition on rib stability evaluation. CMRR is the only required parameter for including the impact of roof conditions on RibFOS. If floor conditions are strong or moderate, the updated Rib factor of safety ($\mathrm{RibFOS_u}$) can be calculated by Equation 26:

$$\mathrm{RibFOS_u} = \mathrm{RibFOS} \times 0.666 \times (ln(CMRR) - 1.817) \tag{26}$$

If the floor is weak, the following equation can be used for combining the roof and floor impact on Rib stability:

$$\mathrm{RibFOS_u} = \mathrm{RibFOS} \times 0.325 \times (ln(CMRR) - 0.654) \tag{27}$$

The outcomes of conducted parametric analysis provide a set of general guidelines for mine operators to identify coal ribs with the potential to form brows. Our team integrated an easy-to-use methodology for identifying coal ribs with the potential to form brows into the developed CPRR calculation charts and tables. The brow will most likely be formed if the user falls within the critical conditions specified in these charts and tables.

The impact of a single persistent joint on the stability of the coal rib was studied as a scope of parametric studies as well. Model results reveal that the joint orientation and the filling strength are the critical parameters that govern the stability of the block. Mining professionals can follow the steps listed below, regardless of the strength characteristics of the persistent joints:

- It is recommended to conduct joint mapping just after the entry is excavated.
- If the joint dipping is steeper than 20 degrees and the dipping orientation is into the roadway, spot bolting should be done regardless of the global rib stability.
- The bolt length is a function of both the mining height and the joint dip angle. If the joint is dipping between 20 - 45 degrees and the roof is stronger than the block, nailing the block to the roof with an angled bolt may be a more practical solution.
- If the joint dipping is greater than 45 degrees, applying a spot bolt approximately half the mining height in a horizontal or downward direction is recommended.

4.4. Specific Objective 4: Develop a user-friendly CPRR and RIBFOS calculation sheet and methodology

The major findings and the deliverables of this specific aim are simple, easy-to-use calculation tables and charts for mine operators to determine the CPRR and the rib factor of safety (RibFOS) for their conditions. Our research approach for developing these charts and tables is explained in Section 3.4.

The charts developed and presented in the research approach section have been combined into 2-page calculation sheets so the user can use them more effectively. CPRR and RibFOS can be found with the help of charts on page 1 and page 2, respectively (See Figure 3.37***Error! Reference source not found.*** and Figure 3.38). Using tables are also common practice for rating estimation. Inspired by widely used rock mass classification systems, our research team prepared tables for CPRR and RiBFOS calculation. The prepared tables are presented in Figure 3.39***Error! Reference source not found.***.

It should be emphasized that even though a regression model can be developed based on a large number of calibrated numerical models, it cannot replace the detailed analysis provided by numerical modeling. This is because the regression model is not able to consider all the factors and their interactions that affect rib stability, making it an approximation at best. Therefore, it is crucial to validate the regression model by comparing it with numerical modeling results to ensure its reliability and accuracy in assessing coal pillar rib stability.

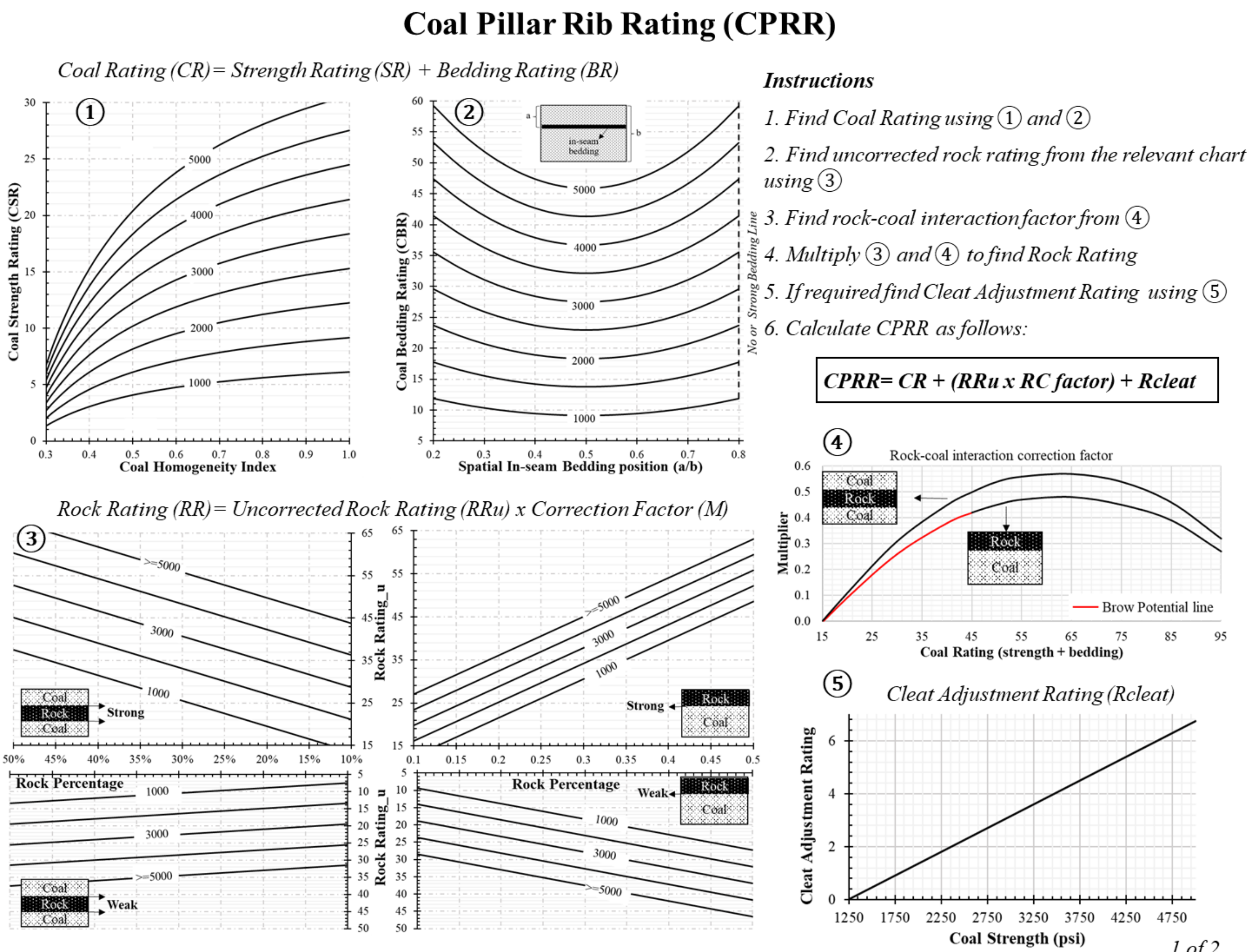


Figure 3.37 Developed CPRR calculation sheet

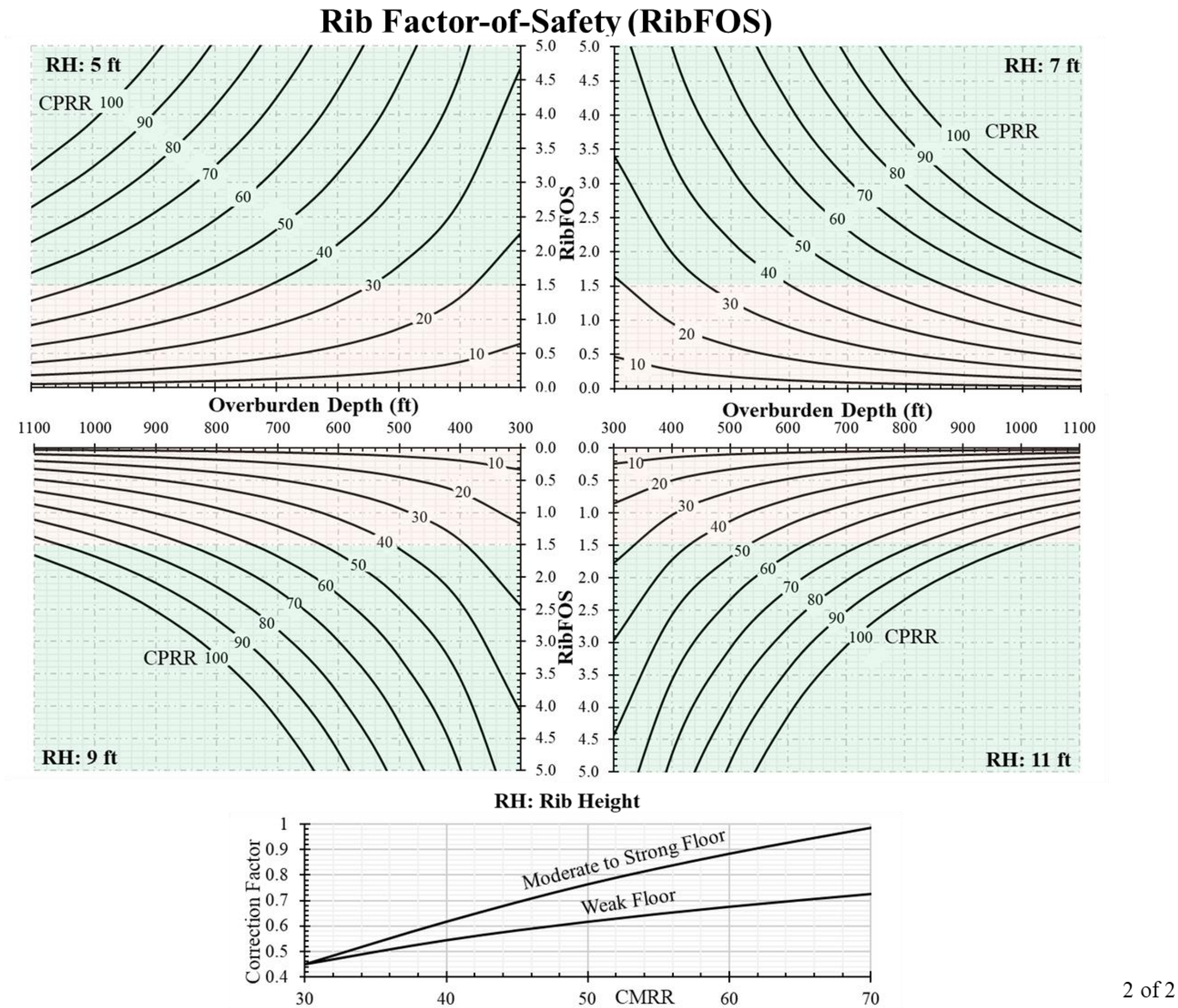


Figure 3.38 Developed RibFOS calculation sheet

Coal Pillar Rib Rating (CPRR)

Step 1: Coal Rating (CR) = Coal Strength Rating (CSR) + Coal Bedding Rating (CBR)

Table 1	*Coal Strength Rating*				
Homogeneity index	**Weighted Coal Strength (psi)**				
	<=1000	*2000*	*3000*	*4000*	*>=5000*
<=0.3	1	3	4	5	7
0.65	5	10	15	20	25
1.00	6	12	18	24	31

Table 2	*Coal Bedding Rating*				
Position	**Weighted Coal Strength (psi)**				
	<=1000	*2000*	*3000*	*4000*	*>=5000*
Close to the coal boundary*	12	24	36	47	59
Upper/lower mid	10	21	31	41	52
Around mid	9	18	28	37	46

* If no or strong bedding, use this row

Step 2: Rock Rating (RR) = Uncorrected Rock Rating (RRu) x Correction Factor (M)

Table 3 Uncorrected Rock Rating

i) Rock parting is overlain and underlain by coal
ii) Rock coal contact is ***strong*** (Coal / Rock / Coal → Strong)

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	13	21	29	36	44
20%	19	27	35	42	50
30%	25	33	41	48	56
40%	31	39	47	54	62
>=50%	37	45	53	60	68

i) Rock parting is above or below the coal unit
ii) Rock coal Contact is ***strong*** (Rock / Coal → Strong)

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	13	16	20	23	27
20%	22	25	29	32	36
30%	31	34	38	41	45
40%	40	43	47	50	54
>=50%	49	52	56	59	63

i) Rock parting is overlain and underlain by coal
ii) Rock coal contact is ***weak*** (Coal / Rock / Coal → Weak)

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	8	13	20	26	32
20%	9	15	21	27	33
30%	11	17	23	29	35
40%	12	18	24	30	36
>=50%	13	20	26	32	38

i) Rock parting is above or below the coal unit
ii) Rock coal Contact is ***weak*** (Rock / Coal → Weak)

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	9	14	19	24	29
20%	14	19	23	28	33
30%	18	23	28	33	38
40%	23	28	32	37	42
>=50%	27	32	37	42	47

Table 4	*Correction Factor (Rock-coal interaction factor)*								
Parting Position	*Coal Rating (coal strength rating + coal bedding rating)*								
	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Coal / Rock / Coal	0.11	0.30	0.45	0.53	0.56	0.55	0.50	0.38	0.22
Rock / Coal	0.09	0.26	0.38	0.45	0.47	0.46	0.41	0.32	0.18
	Brow Forming Potential								

Step 3: Cleat Adjustment Rating

Table 5	*Cleat orientation Adjustment Factor*			
Coal Strength (psi)				
<=1250	**2000**	**3000**	**4000**	**>=5000**
0	1	3	5	7

Figure 3.39 Practical CPRR calculation table

4.4.1. How to Use the Developed Charts

This section provides two clear examples of RibFOS estimation using the developed charts.

Example 1

In the first example, the mined coal is 108 inch thick at depths of 700 ft. The coal seam is immediately overlain and underlain by strong black shale. Two coal units were identified in this rib having equal thicknesses. The UCS of the top and bottom units are estimated as 4000 and 3000 psi, respectively. Coal units are separated by strong bedding. Rib bolting was not in use, no rib sloughing was observed, and the face cleat orientation was almost perpendicular to the entry direction.

First of all, the rib homogeneity index, the ratio of uniaxial compressive strengths of the weakest coal unit to the neighbor coal unit, should be calculated. In our case, the rib homogeneity index is 0.75 (3000 psi/ 4000 psi). As coal units have equal thicknesses, the weighted coal strength of the rib is equal to the average coal strength of 3500 psi.

According to chart 1, the coal strength rating (CSR) is calculated as **19**. The coal bedding rating (CBR) is calculated from chart 2. Strong bedding separates two coal units; therefore, the intersection of the dashed vertical line and 3500 psi curve is the CBR, and it is determined as **42**. Since the rib is composed of only two coal units, the rock rating (RR) will be 0 in this case (no need to use charts 3 and 4). The last parameter is the cleat orientation adjustment rating (Rcleat). Since the face cleat orientation with respect to the entry direction is ≥ 20°, this adjustment is applicable in this case. According to chart 5, Rcleat is found as **4** for 3500 psi coal strength. Finally, the CPRR of the coal rib is calculated as follows:

$$CPRR = SR + BR + (RRu \times RC\ factor) + Rcleat = 19 + 42 + 0 + 4 = \mathbf{65} \qquad (28)$$

The RibFOS of this given case is calculated as 2.0. This rib is stable, and no support is required. Each attribute of the CPRR calculations and RibFOS estimation is shown by blue markings on the developed charts in Figures Figure 3. 40 and Figure 3. 41, respectively.

Example 2

The second example has both rock partings and weak beddings. The mining height of this example is 84" buried at a depth of 600 ft below the ground surface. The roof (CMRR=55) and floor strata are competent, and the coal seam is immediately overlain by 24" black shale with 5000 psi UCS, the top unit of the rib. Three coal units were identified in this rib with 24", 18", and 18" thicknesses. The middle coal unit, the weakest component of the rib, has a UCS of 1250 psi. Top and bottom coal units have almost identical strengths of 2500 psi. Coal beddings are classified as weak. The face cleat orientation was measured almost parallel to the roadway orientation in this example. The rib homogeneity index is determined as 0.50 (1250 psi/ 2500 psi), and the rock percentage of the rib is calculated as 0.29 (2 ft /7 ft). The weighted coal strength can be calculated as follows:

$$\text{Weighted coal strength} = \frac{(2 \times 2500) + (1.5 \times 1250) + (1.5 \times 2500)}{2 \ + 1.5 \ + 1.5} = \mathbf{2125}\ \text{psi} \quad (29)$$

Based on chart 1, the coal strength rating (CSR) is determined to be **9**. To calculate the coal bedding rating (CBR), we refer to chart 2. In this case, multiple weak in-seam beddings are present, so spatial in-seam bedding position is taken as 0.5, corresponding to a CBR of **19**. The rib consists of one rock parting at the top; by using chart 3, the uncorrected rock rating (RRu) is determined to be **37**, and the rock-coal interaction factor (RC factor) is estimated as **0.22** (see chart 4 for this parameter). The Rcleat adjustment is not applicable since the face cleat orientation is nearly parallel to the entry direction. Finally, the CPRR of the coal rib is calculated as follows:

$$CPRR = CSR + CBR \ + \ (RRu \ \times \ RC\ factor) + \ Rcleat$$

$$= 9 + 19 + (37 \ \times 0.22) + 0 \quad = \mathbf{36} \quad (30)$$

According to Figure 3. 41, the RibFOS for this case is estimated as 1.2. The CMRR is given as 55 for this case, and floor conditions are strong or moderate. Considering the roof and floor conditions, the updated Rib factor of safety (RibFOSu) is determined to be around 1.0 (1.2 x 0.82). Most coal mines opt for rib support for RibFOS values less than 1.5. Therefore, rib support is recommended for this case. It should be noted that our proposed critical threshold value for installing a secondary support system is RibFOS of 0.7, so secondary support might not be necessary for this case.

The charts indicate that brow-forming potential is another critical issue in this example. The coal rating (CR) is estimated as less than 50, the red line is used in chart 4, and the estimated RibFOS is below 1.5; therefore, the formation of a brow is highly probable. The calculated ratings of this case are marked in green in Figures Figure 3. 40 and Figure 3.41.

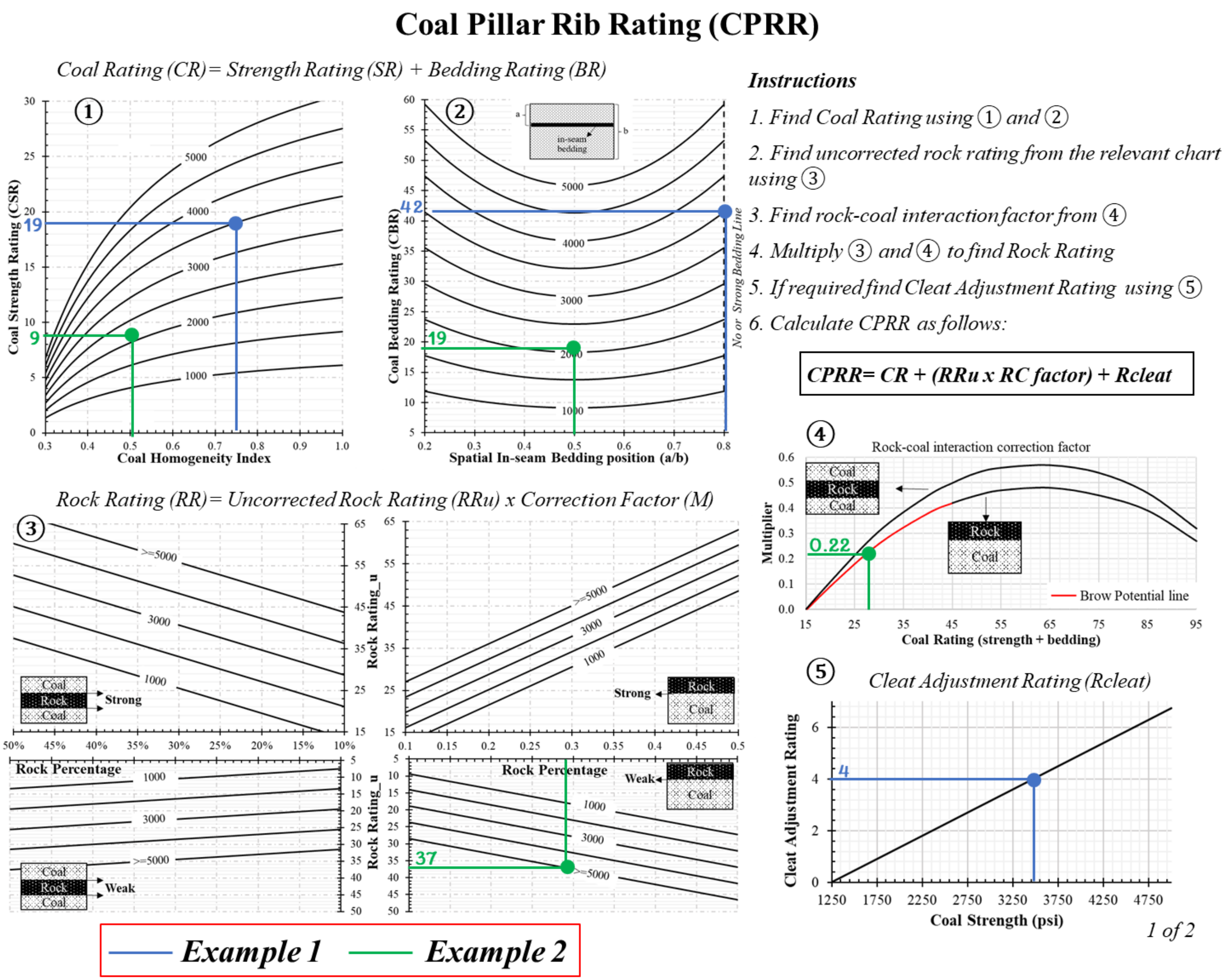


Figure 3. 40 CPRR Estimation Examples

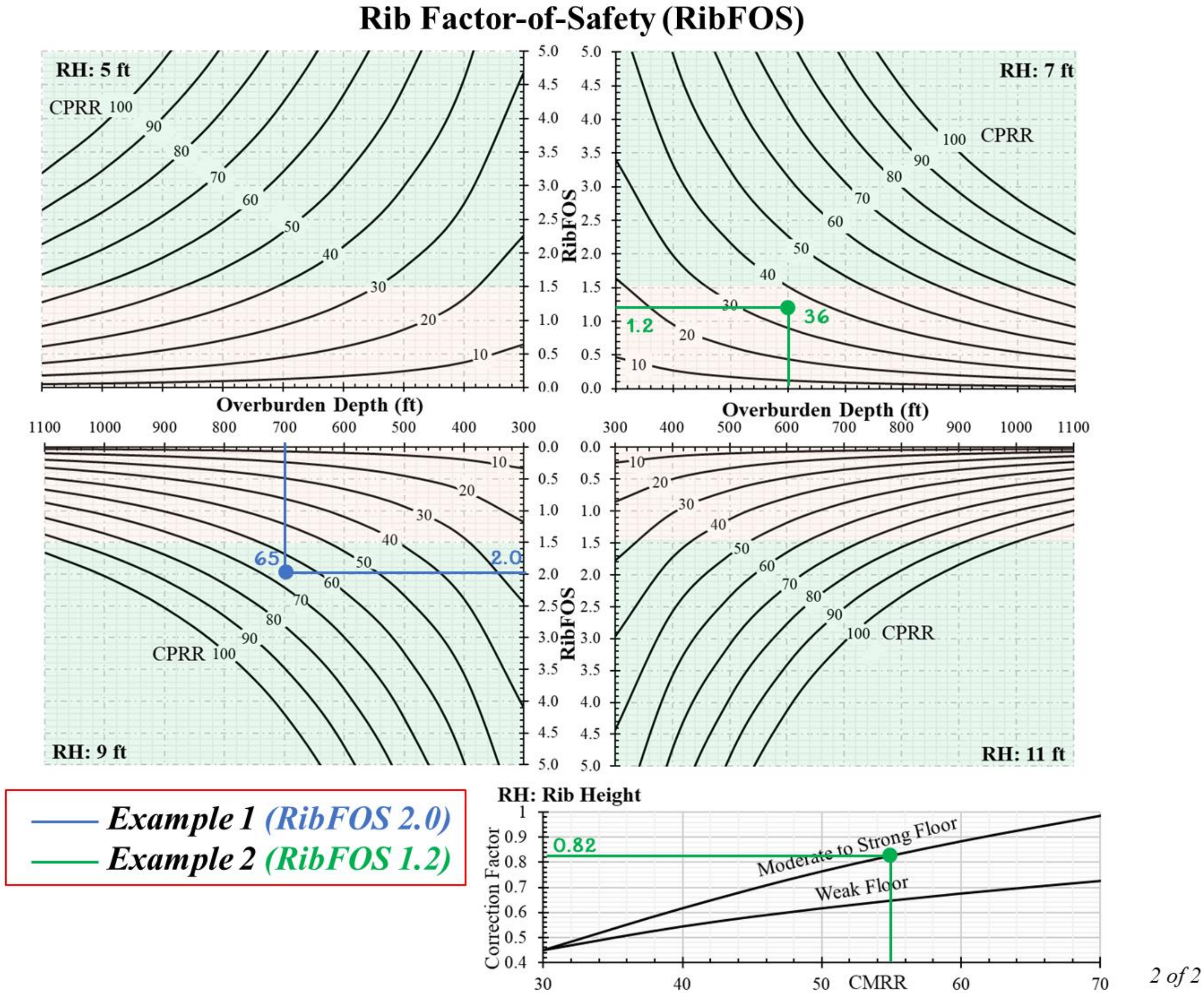


Figure 3. 41 RibFOS Estimation Examples

5.0 Publication Record and Dissemination Efforts

The results of this project were shared at two conferences and included in conference proceedings, as well as journal publications. One of the conference papers, Guner et al. (2022), was selected as one of the "The Best of Ground Control 2022" presentations at the 41st International Conference on Ground Control in Mining and is currently being considered for the Mining, Metallurgy & Exploration (MME) journal's Collection on Ground Control in Mining II, published by the Society for Mining, Metallurgy & Exploration.

Presentations and papers:

Guner, D., Nowak, S., Sherizadeh, T., Sunkpal, M., Mohamed, K., & Xue, Y. (2023). Review of Current Coal Rib Control Practices. Underground Space. 9, 53-75. DOI: https://doi.org/10.1016/j.undsp.2022.04.011.

Mohamed, K., Sears, M., Guner, D., Nowak, S., Kirmaci A., Sherizadeh, T. (2023). Analysis of coal pillar rib stability using distinct element method (3DEC). In Proceedings of the 42th International Conference on Ground Control in Mining (ICGCM 2023).

Guner, D., Sherizadeh, T., Nowak, S., & Karadeniz, K.E., (2023). Distinct Element Analysis for The Effectiveness of Preliminary Coal Pillar Rib Support Systems Based on The Strength Reduction Method. Proceedings of the 2023 SME Annual Conference and Expo. (Invited for the Best of Ground Control Session).

Sherizadeh, T., Guner, D., Karadeniz, K.E., Kirmaci A., (2023). A New Strain-Softening Anisotropic Constitutive Model for Coal Mine Roof Simulation. In Proceedings of the 42th International Conference on Ground Control in Mining (ICGCM 2023).

Guner, D., Sherizadeh, T., Nowak, S., Karadeniz, K.E., Sunkpal M. (2023). Distinct Element Analysis for The Effectiveness of Preliminary Coal Pillar Rib Support Systems Based on The Strength Reduction Method. Mining, Metallurgy & Exploration. (Invited paper) (Under review).

Guner, D., Mohamed, K., Sherizadeh, T., Nowak, S., Karadeniz, K.E., (2023) A new update on the Coal Pillar Rib Rating System. (in preparation).

Regular monthly online meetings were held with NIOSH researchers from the Pittsburgh branch on various occasions to receive input and discuss project progress and outcomes. In addition, the project objectives and outcomes were also discussed with mining professionals during our site visits. It should be noted that the following research outcomes were shared with NIOSH Pittsburgh branch:

- An updated version of the Coal-mass constitutive model
- The collected field data and rock mechanics laboratory test results
- Numerical model results
- CPRR data collection sheet
- Developed easy-to-use CPRR and RibFOS calculation charts and tables

The primary achievement of this project is the significant improvement of the CPRR system, which is the result of the outcomes of this researc and collaborative effort of researchers from NIOSH and Missouri S&T. In addition, this project produced useful charts and tables that mine professionals can utilize to determine the CPRR and rib factor of safety at the mine site. The major outcome of this project is that t*he CPRR system is notably updated with the help of our findings* and the collaborative effort between NIOSH and Missouri S&T researchers. Another notable output of this project is the developed charts and tables. Mine professionals can easily determine the CPRR and the rib factor of safety for their conditions with the help of these tables and charts.

6.0 Conclusions and Impact Assessment

The research presented in this report has produced several practical outputs that will certainly have a measurable impact on mining health and safety regarding coal rib control.

During the initial phase of this study, the effectiveness and weakness of the existing rib stability systems were analyzed. According to this phase, the Australian rating system, Analysis and Design of Rib Support (ADRS), and the new U.S. rating system, Coal Pillar Rib Rating (CPRR), are evaluated as highly applicable to their regions.

Secondly, in-person interviews have been conducted with mine professionals to make a systematic evaluation of their views on using the rib rating system and the parameters that they believe impact the rib behavior based on their field experience. These interviews indicate that the mine professionals have a positive attitude toward a CPRR system and may use this system for their operations. However, it was observed that they approached the statement of introducing a standard rib control methodology and guidelines for US coal mines issue more distantly. Moreover, these interviews allowed us to update our data collection sheet. According to the mine professionals' comments the coal brightness profile was removed from the data collection sheet. In addition, it was decided to keep the rib deterioration index (sloughage level) section as it is conventionally used for checking the condition of the rib.

In the scope of the survey of coal ribs in U.S. coal mines, the CPRR empirical data set was expanded from its 22 surveyed coal seams by conducting coal rib surveys at eight more underground coal mines with the support of our industry partners. Over one hundred uniaxial compressive strength tests have been conducted from coal and shale samples at the Missouri S&T rock mechanics laboratories.

The research team modified the coal-mass constitutive model, which was originally developed by NIOSH researchers for use in CPRR numerical simulations with FLAC3D, to make it applicable for use in distinct element-based solvers, such as 3DEC. This adaptation enabled the team to simulate kinematic and stress-driven failures simultaneously, providing a more accurate representation of the conditions present in underground coal mines. Furthermore, the updated and validated model will assist in implementing and designing effective support systems using this modeling approach for future projects.

During the numerical modeling stage, the research team initially examined the impact of excavation width on coal rib stability. Most of the coal mines in the U.S. utilize entry widths between 4.5 and 6 m. It was observed that the 1.5 m change in entry width might not significantly affect the general rib stability. Then the impact of the inelastic roof and floor condition on rib stability was analyzed. Two equations are proposed, which can be used by mine operators to assess the impact of the roof and floor condition on rib stability. CMRR is the only required parameter for including the impact of roof conditions on RibFOS. If floor conditions are strong or moderate, the updated Rib factor of safety ($\mathrm{RibFOS_u}$) can be calculated by:

$$\mathrm{RibFOS_u} = \mathrm{RibFOS} \times 0.666 \times (ln(CMRR) - 1.817)$$

If the floor is weak, the following equation can be used for combining the roof and floor impact on Rib stability;

$$\mathrm{RibFOS_u} = \mathrm{RibFOS} \times 0.325 \times (ln(CMRR) - 0.654)$$

As one of the scopes of parametric studies, the project team analyzed all critical models to identify coal ribs' brow-forming potential. The conditions having a brow potential have been integrated into the developed CPRR calculation charts and tables. The Brow potential is associated with Coal Rating, the spatial location of the rock unit, and the RibFOS. The developed charts and tables directly inform the user about the brow forming potential.

The outcomes of numerical models were used to develop straightforward CPRR and RibFOS calculation schemes. By combining field survey data and numerical model efforts, the CPRR calculation steps were significantly updated. The updated CPRR quantitatively assesses the strength of coal pillar ribs based on various parameters, including the thickness and strength of the rib units, the homogeneity of the coal beds, the bedding condition within the coal unit, the strength of the coal/rock interface, and the face cleat orientation with respect to the entry direction. A regression equation of RibFOS was determined using the regression models. Mine professionals directly estimate the current stability of the rib with their CPRR value with the following equation.

$$RibFOS = (120 - 0.027 \times Z) \times \left(\frac{CPRR}{Z}\right)^{1.8} \times e^{0.162 \times (11 - H)}$$

The R-squared values of the linear relationship between the developed equations, charts, and tables and the numerical models were above 0.90 for solid coal pillar ribs and ribs with rock units. These results demonstrate that the developed easy-to-use tools are able to accurately predict the RibFOS for a variety of coal pillar rib configurations and conditions, providing a reliable tool for evaluating rib stability in coal mines. Finally, the rib data collection safety protocol and data collection procedure have been prepared to aid mine professionals. Data collection sheets have also been updated in light of the experience obtained from coal mine surveys.

The project team believes that the achieved developments to the existing CPRR system will benefit the coal mining industry. This system is now more applicable to a wider array of geologic and geotechnical situations.

7.0 Recommendations for Future Work

Undoubtedly, integration of a brow evaluation section to the CPRR would aid in estimating the brow-forming potential of the coal rib. However, an urgent need is to assess the actual stability of the formed brows and brow control methodology. Additional work may be done on developing rib brow management by integrating the outcomes of this research. In addition, investigating and evaluating the effectiveness of different support systems, such as steel and timber props and spray membranes, to enhance brow stability is strongly recommended.

The main focus of this project was not analyzing the rib-support performance, which requires field instrumentation and in-situ tests. Preliminary research presented in this report is an important starting point for further research. The updated CPRR system is useful for assessing the current unsupported condition of the coal ribs and deciding if the coal rib requires support. Developing an intuitive rib support design methodology and integrating this methodology into the CPRR system is an important research subject. The ongoing project, "*Improvement of Rib Support Design Utilizing Recent Advancements of the Coal Pillar Rib Rating (CPRR) System,"* supported by the Alpha Foundation, addresses this topic.

The updated version of the CPRR measures the quality of coal ribs under development loading conditions. The effect of mining-induced stresses, abutment, or multiple-seam interaction conditions is not the scope of this project. Incorporating these conditions into the CPRR system is recommended for future work.

Improving numerical models by incorporating 3D mine geometries is also vital for evaluating the rib stability at the pillar corners. In addition, further study is required to identify how the failure behavior of the formed brow can be more realistically simulated using DEM.

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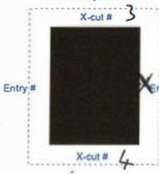
9.0 Appendices

9.1. Collected data from field rib surveys

Data Collection Sheet for Coal Pillar Ribs

Rib survey date:	Date mined:	Mining stage (Dev/Ret):
Mine name:	Overburden (ft): 180 ft	Pillar size (ft): 57L - 56
Mining method (R&P/LW):	Entry/rib height (ft): 6.4 ft	Entry width (ft): 22 ft
Site #:	Entry azimuth (degree): 10°	Cross-cut azimuth (degree): 100°

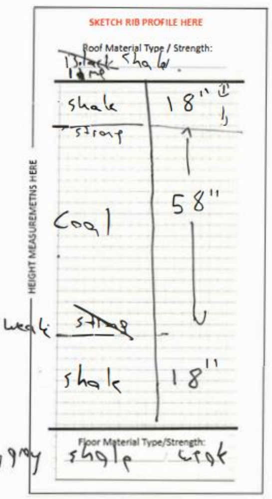
Rib survey location



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Rock		18	1"	N80°E	90°	37.2	35.8	39.8			
	strong										
Coal		58				31.0	41.0				
						35.6	40.4				
	Strong weak										
Shale		18				21.0					
						18.7					

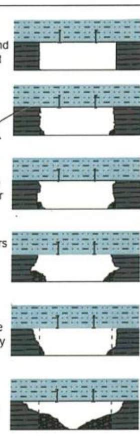


Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1. Sloughage of 3 in (7.5 cm) or less, damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor ✓
3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.
5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



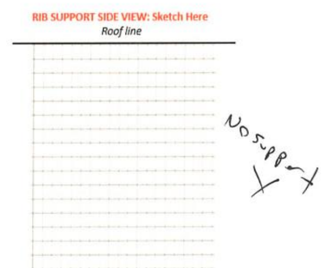
Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) :

Previously cleaned up : Yes / No



Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

Rib support additional information

Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

Support 2 is part of roof bolting cycle: Yes/ No

What causes most of your typical rib problems?
- Bottom shale is slickensided.
- Top black shale is laminated

Other Notable Conditions:
- The weakest composition is Top Shale
- Dense cleat system (coal)

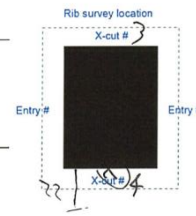
~~Corners~~ Corners have slight sloughing

Page 2 of 2

#2

Data Collection Sheet for Coal Pillar Ribs

Rib survey date:	Date mined: 2003	Mining stage (Dev/Ret): Dev
Mine name:	Overburden (ft):	Pillar size (ft):
Mining method (R&P/LW):	Entry/rib height (ft): 8'4"	Entry width (ft): 22' 10' (?)
Site #:	Entry azimuth (degree): L10	Cross-cut azimuth (degree):



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties			Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
			Spacing (in)	Strike (degree)	Dip (degree)						
Shale	*Roof line*		1'	N80E	90'	33.6					
	Strong										
Coal						use data #1					
	Weak										
Shale											

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Lime Shale /

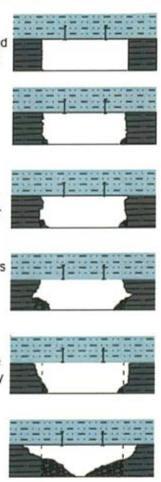
HEIGHT MEASUREMETNS HERE

Rock	14"
Strong	
Coal	60"
~~Strong~~ Weak	
Gray shale	30"

Floor Material Type/Strength: Gray shale / Weak

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index



1. Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor
3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.
5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : ______

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Other Notable Conditions:

Rib support additional information

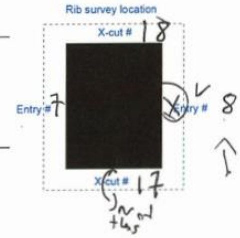
Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

Support 2 is part of roof bolting cycle: Yes/ No

Page 2 of 2

Data Collection Sheet for Coal Pillar Ribs



Rib survey date: 3-15
Mine name:
Mining method (R&P/LW): R&P
Site #: -

Date mined: 8/2018
Overburden (ft): 270 ft
Entry/rib height (ft): 7' 9" ft
Entry azimuth (degree): 230°

Mining stage (Dev/Ret):
Pillar size (ft): 52 ft L - 51 W
Entry width (ft): 17 ft
Cross-cut azimuth (degree): ~~150°~~ 140°

Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable UCS = 1,250 psi	45-90 % Bright, semi-block UCS = 2,900 psi	10-45 % Bright, semi-block to blocky UCS = 4,850 psi	>10% Bright, Blocky UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Face cleat properties: Strike (degree)	Face cleat properties: Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Shale		30	<1"	N65E	90	28.0	17.3	100			
	Weak										
Coal		18				38.2	41.0				
	Weak										
Coal		31				40.5					

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Black shale / weak

HEIGHT MEASUREMETNS HERE

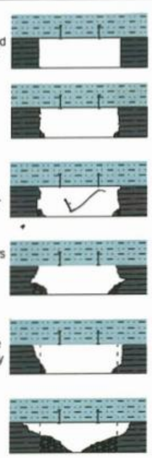
Black shale 30"
weak
Coal 18"
weak
Coal 31"

Floor Material Type/Strength: Gray shale / weak

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index



1	Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2	Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor
3	Ribs are beyond slight skin damage and is observed from 6 in to 1 ft (15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
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5	Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6	Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : 1"- 1ft

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

No support

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?
weakest unit: top black shale + weak inseam bedding!!

Other Notable Conditions:

Rib support additional information

Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

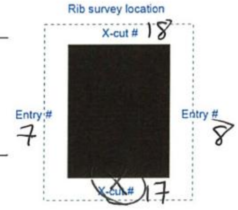
Support 2 is part of roof bolting cycle: Yes/ No

Page 2 of 2

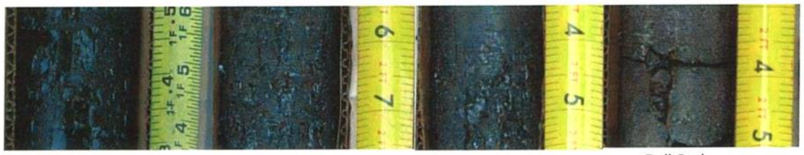
Data Collection Sheet for Coal Pillar Ribs

Rib survey date:	Date mined: 8/2018	Mining stage (Dev/Ret):
Mine name:	Overburden (ft): 270 ft	Pillar size (ft): 52-50
Mining method (R&P/LW):	Entry/rib height (ft): 6'10"	Entry width (ft): 18 ft
Site #:	Entry azimuth (degree): 160°	Cross-cut azimuth (degree): 230°

Rib survey location



Coal brightness guide



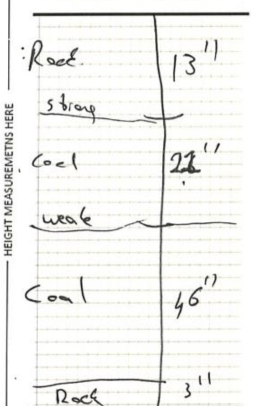
Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)	Sample collected (Y/N)
	Roof line						
Rock			N65E		80'	23.7 ✓ use same readings	
	13						
Coal							
	21						
Coal						33.3 37.3	
	46						
	3						

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: /

HEIGHT MEASUREMETNS HERE

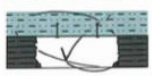


Floor Material Type/Strength: big shale / rock

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1	Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.	
2	Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor	
3	Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.	
4	Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.	
5	Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.	
6	Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.	

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) :

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

20

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Other Notable Conditions:

Rib support additional information

Development method: Place Change/Full Face

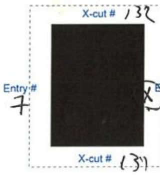
Support 1 is part of roof bolting cycle: Yes/ No

Support 2 is part of roof bolting cycle: Yes/ No

Page 2 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 03/15/2022	Date mined: 11/2021	Mining stage (Dev/Ret):
Mine name:	Overburden (ft): 450 ft	Pillar size (ft): 64 width 63 l
Mining method (R&P/LW): R&P	Entry/rib height (ft): 6' 7" ft	Entry width (ft): 17' 7"
Site #:	Entry azimuth (degree): 325°	Cross-cut azimuth (degree): 340°



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Ro		11	4''	N60E	39°	28.0	42.8	31.8			
	str										
coal		9				28.5	41.3	30.0			
	weak										
coal		24				44.6	37.0	40.8			
	strong										
coal		19				52.2	40.8				
	weak										
Rock		11				20.8					

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Black shale

HEIGHT MEASUREMETNS HERE

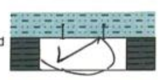
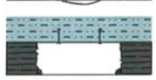
Shale	11''
Strong	
Coal	9''
weak	
Coal	24''
Strong	
Coal	19''
weak	
Rock	11''

Floor Material Type/Strength: Gray shale weak

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1	Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.	
2	Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor	
3	Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.	
4	Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.	
5	Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.	
6	Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.	

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

?

Characteristics of rib spalling

Average block Size (in) : ——

Previously cleaned up : Yes/ No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

No supp-y

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?
belt entr supported · 2 rows · 4 feet 5/6

Other Notable Conditions: No roof cutter here

Rib support additional information	
Development method:	Place Change/Full Face
Support 1 is part of roof bolting cycle:	Yes/ No
Support 2 is part of roof bolting cycle:	Yes/ No

Page 2 of 2

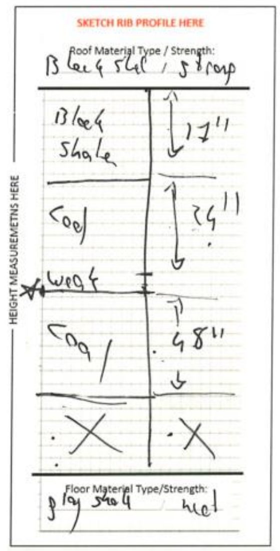
Data Collection Sheet for Coal Pillar Ribs

Rib survey date:		Date mined:	7/2021	Mining stage (Dev/Ret):	
Mine name:		Overburden (ft):	320 ft	Pillar size (ft):	63 ft 64 L
Mining method (R&P/LW):		Entry/rib height (ft):	7'3" ft	Entry width (ft):	18' 4"
Site #:		Entry azimuth (degree):	230°	Cross-cut azimuth (degree):	320°

Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Bl shale	strong	17	<1"	N80E	8'	26.9	21.3	18.2	19.2		
Coal		24				23.5	21.3				
	weak										
Coal		48				47.3	27.9	28.4	33.7		

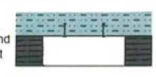


Page 1 of 2

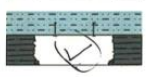
Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

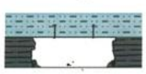
1. Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.



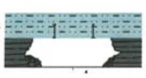
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor



3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft (15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

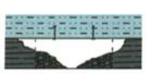


4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.



5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : ______

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems? Corners sloughing due to weak in-seam bedding. Bottom coal cannot hold itself

Other Notable Conditions: Brow may form at corner. But not serious problem.

- 3 inches clay -

Corners critical

Rib support additional information	
Development method:	Place Change/Full Face
Support 1 is part of roof bolting cycle:	Yes/ No
Support 2 is part of roof bolting cycle:	Yes/ No

Page 2 of 2

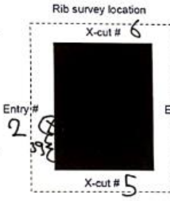
Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 6/16/2022
Mine name: –
Mining method (R&P/LW): LW
Site #: 1

Date mined: 01/XX/2022
Overburden (ft): 850-900
Entry/rib height (ft): 8'10"
Entry azimuth (degree): 120

Mining stage (Dev/Ret): Dev
Pillar size (ft): 39
Entry width (ft): 15
Cross-cut azimuth (degree): 210

Rib survey location



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
Shale	*Roof line*	17"									
	Weak										
Roof Coal		10"									
	Weak										
Claystone		8"				16.6					
Coal	Weak	29"				38.9					
Coal	Weak	25"	<1"	285	90	30.1					
Coal	Weak	10"				22.1					
Shale	Strong	5"									
						29.7					

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Shale /

HEIGHT MEASUREMETNS HERE

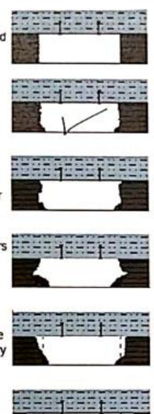
Shale
Roof Coal
Claystone
Coal
Coal
Coal
Shale

Floor Material Type/Strength: Shale /

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index



1. Sloughage of 3 in (7.5 cm) or less, damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor
3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft (15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.
5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Nature of rib spalling/sloughing

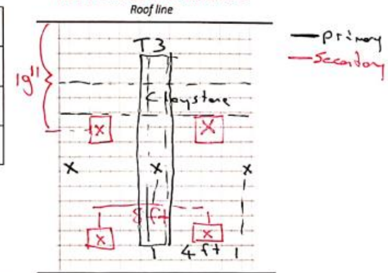
None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : 2

Previously cleaned up : Yes/ No

RIB SUPPORT SIDE VIEW: Sketch Here



Support	Specifications	Support 1	Support 2
Bolt	Type	Steel/ Fiber	Steel/ Fiber
	Length (ft)	3 ft	3 ft
	Diameter (in)	5/8	
	Grade (ksi)	75	75
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		Pizza Pan
	Dimensions (in)		18" x 18"
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		8 ft length 2-1 tensar
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Other Notable Conditions: Claystone is weaker when in contact to moisture or water
*Secondary support installed 2 to 3 days later than Primary support

Rib support additional information

Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

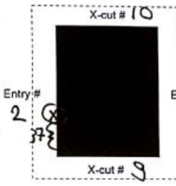
Support 2 is part of roof bolting cycle: Yes/No

Page 2 of 2

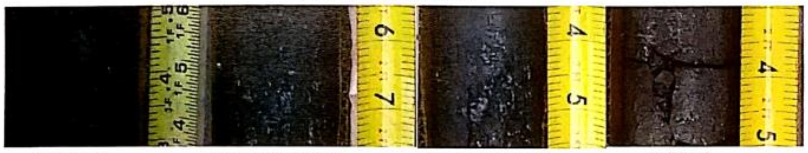
Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 6/16/2022	Date mined: 01/XX/2022	Mining stage (Dev/Ret): Dev
Mine name: —	Overburden (ft): 1080	Pillar size (ft): 37
Mining method (R&P/LW): LW	Entry/rib height (ft): 8	Entry width (ft): 16
Site #: 2	Entry azimuth (degree): 125	Cross-cut azimuth (degree): 215

Rib survey location



Coal brightness guide



Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
Shale	Roof line	14				37.1					
	Strong										
Roof Coal		11				32.0					
	Weak										
Claystone		10				14.5					
	Weak										
Coal		24				32.4					
	Strong										
Coal		24	<1"	285	80	38.0					
	Strong										
Coal		19				32.2					
	Strong										
Shale		3									
	Strong										

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Shale /

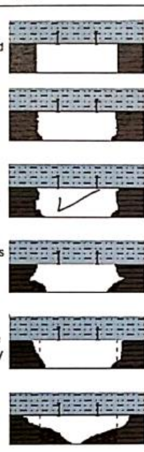
HEIGHT MEASUREMETNS HERE

Shale
Roof Coal
Clay Stone
Coal
Coal
Coal
Shale

Floor Material Type/Strength: Shale /

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index



1. Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor
3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft (15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.
5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Nature of rib spalling/sloughing

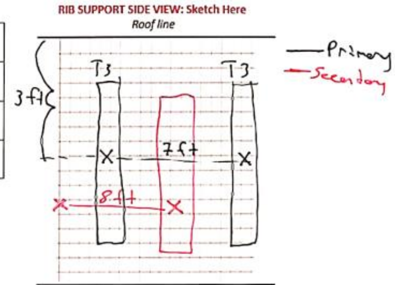
None	✓ Friable
Brow	✓ Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : ———

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here



Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)	3 ft	3.5 ft
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type T3		No plates
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		8 ft length 2-3 tensor
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems? ____________

Other Notable Conditions: Large Slabs observed at the corner

Rib support additional information

Development method: Place Change/Full Face

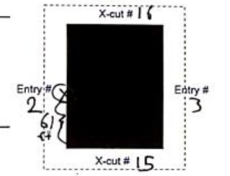
Support 1 is part of roof bolting cycle: Yes/No

Support 2 is part of roof bolting cycle: Yes/No

Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 6/16/2022	Date mined: 01/XX/2022	Mining stage (Dev/Ret): Dev
Mine name: ——	Overburden (ft): 770	Pillar size (ft): 61 ft
Mining method (R&P/LW): LW	Entry/rib height (ft): 9	Entry width (ft): 16
Site #: 3	Entry azimuth (degree): 125	Cross-cut azimuth (degree): 215

Rib survey location



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties: Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)	Sample collected (Y/N)
	Roof line						
Shale		22"	<1"	285	80		
	strong						
Roof coal		9"				29	
	weak						
Claystone		11"				15.4	
	weak						
Coal		48				37.5	
	strong						
Coal		12"				40.5	
	strong						
Shale		2"					

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Shale /

HEIGHT MEASUREMETNS HERE

Shale

Roof coal

Claystone

Coal

Coal

Shale

Floor Material Type/Strength: Shale /

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1	Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.	
2	Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor	
3	Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.	
4	Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.	
5	Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.	
6	Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.	

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

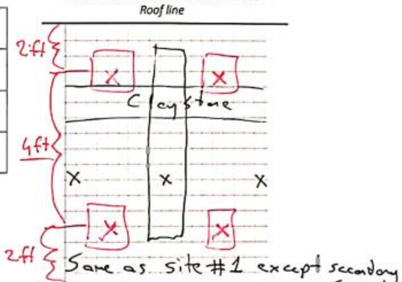
Characteristics of rib spalling

Average block Size (in) : 1-2

Previously cleaned up : Yes/No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line



Support	Specifications	Support 1	Support 2
Bolt	Type	Steel/ Fiber	Steel / Fiber
	Length (ft)	3	
	Diameter (in)	5/8	
	Grade (ksi)		
	Anchor type	Grouted/Mechanical	Grouted/Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		Pizza Pan
	Dimensions (in)		18"x18"
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		8 ft length 2-3 faster
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Other Notable Conditions:

Rib support additional information

Development method: Place Change/Full Face

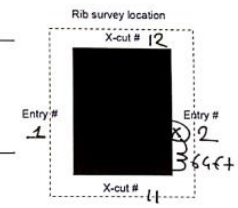
Support 1 is part of roof bolting cycle: Yes/No

Support 2 is part of roof bolting cycle: Yes/No

Page 2 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib survey location

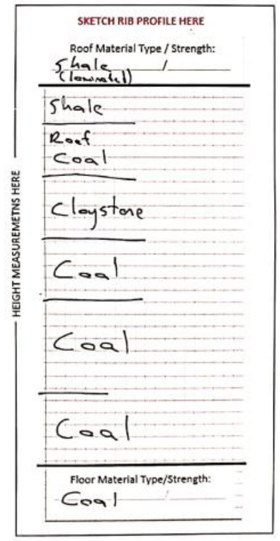


Rib survey date: 6/17/2022	Date mined: 01/XX/2021	Mining stage (Dev/Ret): Dev
Mine name:	Overburden (ft): 920	Pillar size (ft): 64
Mining method (R&P/LW): LW	Entry/rib height (ft): 7	Entry width (ft): 16
Site #: 1	Entry azimuth (degree): 115	Cross-cut azimuth (degree):

Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)						Sample collected (Y/N)
	Roof line											
Shale		12										
	Weak											
Roof Coal		7				18.9						
	Weak											
Claystone		12				9.7	22.3	10.9				
	Weak											
Coal		32	<1"	110°	90°	22.6	31.6	23.5				
	Strong											
Coal		10	"	"	"	18.7						
Coal		20	"	"	"	34.6						

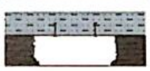


Data Collection Sheet for Coal Pillar Ribs

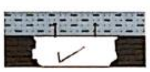
Rib deterioration index

1 Sloughage of 3 in (7.5 cm) or less damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby

2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor



3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.



4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib

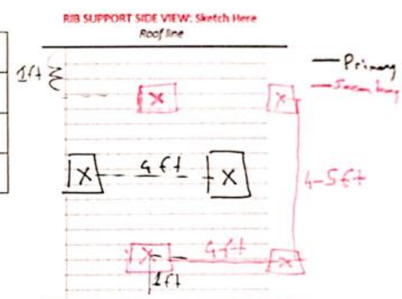
Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : 1–2"

Previously cleaned up : Yes / No



Support	Specifications	Support 1	Support 2
Bolt	Type	Steel/ Fiber	Steel / Fiber
	Length (ft)	4 ft	4 ft
	Diameter (in)	5/8	5/8
	Grade (ksi)		
	Anchor type	Grouted/Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled → top row; Bottom row
Plate	Type	Pizza Pan	
	Dimensions (in)	18"	
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		4 ft
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Rib support additional information

Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

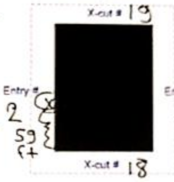
Support 2 is part of roof bolting cycle: Yes/No

Other Notable Conditions:
Cross cuts looks better than the entry

Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 6/17/2022	Date mined: 1/xx/2021	Mining stage (Dev/Ret): Dev
Mine name:	Overburden (ft): 1050 ft	Pillar size (ft): 59'
Mining method (R&P/LW): LW	Entry/rib height (ft): 7' 10"	Entry width (ft): 15' 9"
Site #: 2	Entry azimuth (degree): 125°	Cross-cut azimuth (degree):

Rib survey location



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Shale		23				34					
	Strong										
Roof Coal		12				13.9	35.2	28.6			
	Weak										
Claystone		15				30.2					
	Weak										
Coal		17	≤1"	110°	90°	51.2	49.6	45.0			
	Strong										
Coal		12	"	"	"	38.6					
	Strong										
Coal		20	"	"	"	42.0 / 43.0					

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Shale /

HEIGHT MEASUREMENTS HERE

Shale

Roof Coal

Claystone

Coal

Coal

Coal

Floor Material Type/Strength: Coal

Page 1 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : 1-3"

Previously cleaned up : Yes / No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

Same with site #1
except
Secondary bolt spacing
Doubled
(8 ft)

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

What causes most of your typical rib problems?

Other Notable Conditions:
Cross cuts have floor heaving issue

Rib support additional information

Development method: Place Change/Full Face

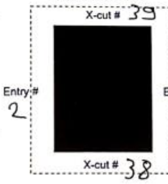
Support 1 is part of roof bolting cycle: Yes/ No

Support 2 is part of roof bolting cycle: Yes/ No

Page 2 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib survey date: 6/17/2022	Date mined: 1/XX/2021	Mining stage (Dev/Ret): Dev
Mine name: —	Overburden (ft): 750	Pillar size (ft): 28'
Mining method (R&P/LW): LW	Entry/rib height (ft): 8'	Entry width (ft): 16'
Site #: 3	Entry azimuth (degree): 125°	Cross-cut azimuth (degree): —



Coal brightness guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
>90 % Bright, friable	45-90 % Bright, semi-block	10-45 % Bright, semi-block to blocky	>10% Bright, Blocky
UCS = 1,250 psi	UCS = 2,900 psi	UCS = 4,850 psi	UCS = 5,100 psi

Rib member Coal/ Rock	In-seam bedding, rock/coal interface	Member Thickness (in)	Face cleat properties Spacing (in)	Strike (degree)	Dip (degree)	Schmidt hammer reading (Coal/Rock)					Sample collected (Y/N)
	Roof line										
Coal		5"									
	strong										
Shale	strong	39"				35.1	37.3				
Shale	weak	3"				46.1					
Claystone		12"				41.0					
	weak										
Coal		14"	≤1	119°	89°	34.3					
	strong										
Coal		17"	"	"	"	36.6					
	strong										
Coal		14"	"	"	"	39.1 / 39.3					

Page 1 of 2

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Shale /

HEIGHT MEASUREMETNS HERE

Coal
Shale
Shale
Claystone
Coal
Coal
Coal

Floor Material Type/Strength: Coal /

Data Collection Sheet for Coal Pillar Ribs

Rib deterioration index

1 Sloughage of 3 in (7.5 cm) or less damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby

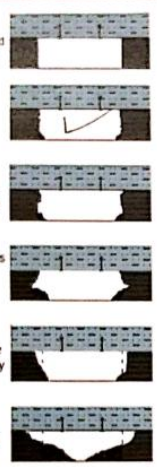
2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib



What causes most of your typical rib problems?

Other Notable Conditions:

Nature of rib spalling/sloughing

None	Friable
Brow	Slabby
Slabby/Blocky	Blocky
Blocky/Columnar	Columnar

Characteristics of rib spalling

Average block Size (in) : 2"

Previously cleaned up : Yes/No

RIB SUPPORT SIDE VIEW: Sketch Here

Roof line

Same as Site #2

Support	Specifications	Support 1	Support 2
Bolt	Type	Steel / Fiber	Steel / Fiber
	Length (ft)		
	Diameter (in)		
	Grade (ksi)		
	Anchor type	Grouted/ Mechanical	Grouted/ Mechanical
	Installation method	Straight/Angled	Straight/Angled
Plate	Type		
	Dimensions (in)		
Mesh	Type	Plastic/Steel	Plastic/Steel
	Dimensions (ft)		
Prop	Type		
	Size (in)		
	Height (ft)		
Other			

Rib support additional information

Development method: Place Change/Full Face

Support 1 is part of roof bolting cycle: Yes/ No

Support 2 is part of roof bolting cycle: Yes/ No

Page 2 of 2

Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: 11/30/2022	Mining Method (R&P/LW): R&P	Overburden (ft): 1025	Entry width (ft): 18
Mine Name:	Date mined: mid /2020	Rib height (ft): 8	Entry azimuth (°): N 20° W
Site #: 1	Mining stage (Dev/Ret): Dev	Pillar size (ft): 72 (72)	Cross-cut azimuth (°): N 65° E

Rib Data

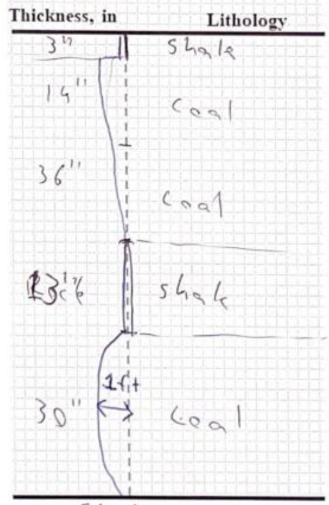
Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	3			
C Strong / Weak				
2 Coal / Rock	14	25.2		
C Strong / Weak				
3 Coal / Rock	36	10.5	10.2	
C Strong / Weak				
4 Coal / Rock	13	28.9	36.1	X
C Strong / Weak		22.7	31.2	
5 Coal / Rock	30	17.8	14.0	
C Strong / Weak				
6 Coal / Rock				
C Strong / Weak				
7 Coal / Rock				
C Strong / Weak				
8 Coal / Rock				
Floor C: Str. / Weak				

Rib Profile

Roof Material: Lithology/Strength

Shale / Strong

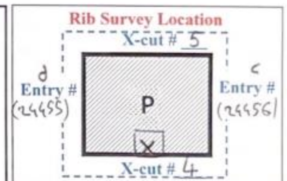
Thickness, in **Lithology**



Shale / Strong

Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

Spacing ("): < 1"

Strike / Dip (°): N40W / 90°

Notable Conditions

CMRR :

Roof: Good

Floor: Good

Other: Corners have large damages (~40 inches failed)

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

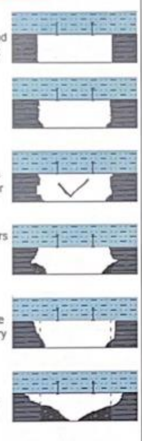
2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

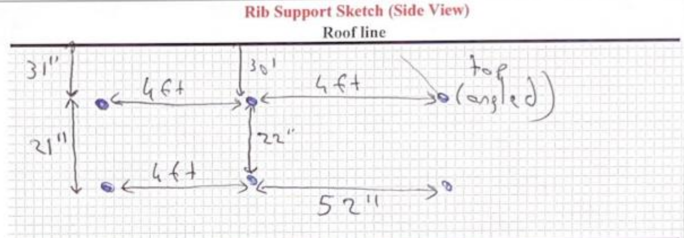
4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



Rib Support Sketch (Side View)



Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
top Support 1	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled
Support 2 Bottom	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
top Support 1	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		
Support 2 Bottom	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None

Brow

Slabby/ Blocky

Blocky/ Columnar

Friable

Slabby

Blocky

Columnar

Characteristics of Spalling

Avg. block size (in): 1-2

Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face

Support 1 is part of roof bolting cycle: Yes / No

Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems?__________

Other notable conditions:__________

Data Collection Sheet for Coal Pillar Ribs

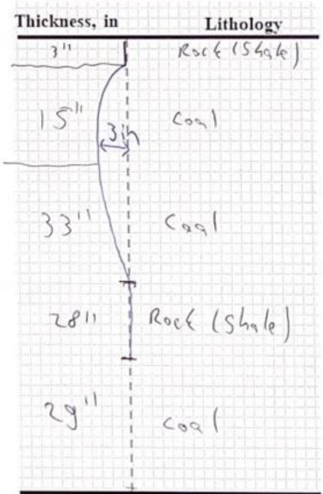
Rib Survey Date: 11/30/22	Mining Method (R&P/LW): R&P	Overburden (ft): 1025	Entry width (ft): 18
Mine Name:	Date mined: mid /2020	Rib height (ft): 9	Entry azimuth (°): N 20° W
Site #: 2	Mining stage (Dev/Ret): Dev	Pillar size (ft): 89	Cross-cut azimuth (°): N 65° E

Rib Data

Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	3			
C Strong / Weak				
2 Coal / Rock	15			X
C Strong / Weak				
3 Coal / Rock	33	14.3	12.2	
C Strong / Weak				
4 Coal / Rock	28	25.7	25.9	
C Strong / Weak				
5 Coal / Rock	29	18.5	27.2	
C Strong / Weak		19.7		
6 Coal / Rock				
C Strong / Weak				
7 Coal / Rock				
C Strong / Weak				
8 Coal / Rock				
Floor C: Str. / Weak				

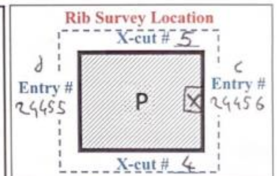
Rib Profile

Roof Material: Lithology/Strength
Shale / Strong



Coal / ~~Strong~~ weak
Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

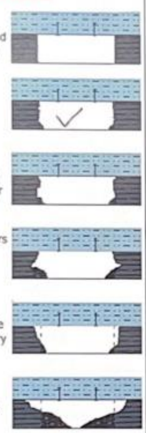
Spacing ('): < 1"
Strike / Dip (°): N40°W / 90°

Notable Conditions

CMRR :
Roof: Good
Floor: Good
Other: —

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index



1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

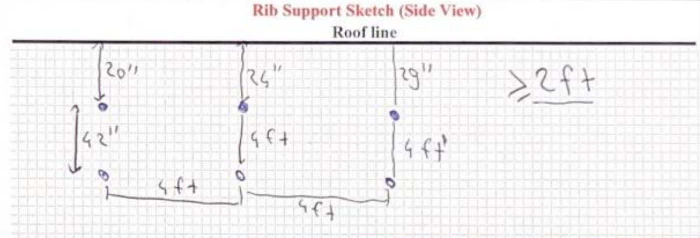
3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Rib Support Sketch (Side View)



Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
top Support 1	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled
Support 2 Bottom	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
top Support 1	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		
Support 2 bottom	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None
Brow
Slabby/ Blocky
Blocky/ Columnar
Friable
Slabby
Blocky
Columnar

Characteristics of Spalling

Avg. block size (in): < 1"
Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face
Support 1 is part of roof bolting cycle: Yes / No
Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems?

Other notable conditions:

Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: 11 /30/2022	Mining Method (R&P/LW): R&P	Overburden (ft): 1025	Entry width (ft): 18'
Mine Name:	Date mined: mid /2020	Rib height (ft): 7 ft	Entry azimuth (°): N 20° W
Site #: 3	Mining stage (Dev/Ret): Dev	Pillar size (ft): 72'	Cross-cut azimuth (°): N 65° E

Rib Data

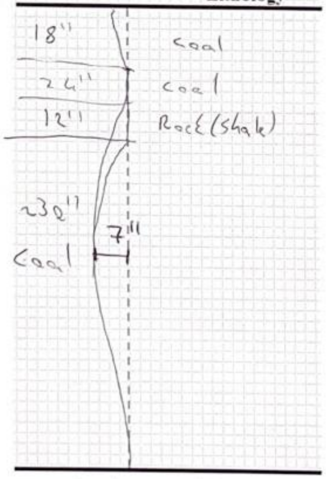
Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	18			
C *Strong / Weak*				
2 Coal / Rock	24	26.9	15.1	
C *Strong / Weak*			13.0	
3 Coal / Rock	12	18.5		
C *Strong / Weak*				
4 Coal / Rock	39			X
C *Strong / Weak*				
5 Coal / Rock				
C *Strong / Weak*				
6 Coal / Rock				
C *Strong / Weak*				
7 Coal / Rock				
C *Strong / Weak*				
8 Coal / Rock				
Floor C: Str. / Weak				

Rib Profile

Roof Material: Lithology/Strength

Shale / strong

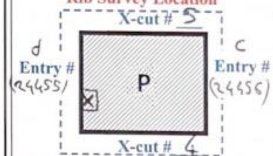
Thickness, in **Lithology**



Coal / weak

Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

Spacing ('): < 1"

Strike / Dip (°): N40W / 90°

Notable Conditions

CMRR :

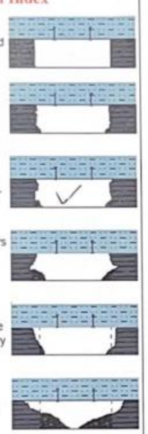
Roof: Good

Floor: Good

Other: ~

Data Collection Sheet for Coal Pillar Ribs

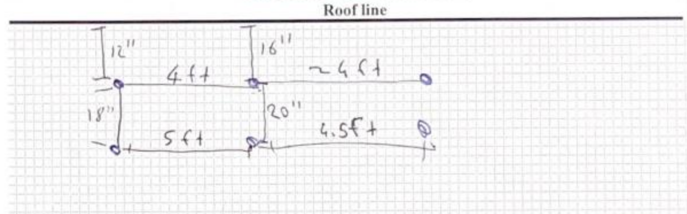
Rib Deterioration Index



1. Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.
2. Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor
3. Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.
4. Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.
5. Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.
6. Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.

Rib Support Sketch (Side View)

Roof line



Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
top Support 1	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled
Support 2 bottom	Steel / Fiber	5	3/4	60	Grouted / Mechanical	Straight / Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
top Support 1	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		
Support 2 bottom	Plastic/Steel	12x12	Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None
Brow
Slabby/ Blocky
Blocky/ Columnar
Eriable
Slabby
Blocky
Columnar

Characteristics of Spalling

Avg. block size (in): < 1"

Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face

Support 1 is part of roof bolting cycle: Yes / No

Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems?

Other notable conditions:

Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: 12 / 1 / 2022	Mining Method (R&P/LW): R&P	Overburden (ft): 1100	Entry width (ft): 18'
Mine Name:	Date mined: October / 2022	Rib height (ft): 6' 1''	Entry azimuth (°): N55°E
Site #:	Mining stage (Dev/Ret): Dev	Pillar size (ft): 49'	Cross-cut azimuth (°): N 35° W

1

Rib Data

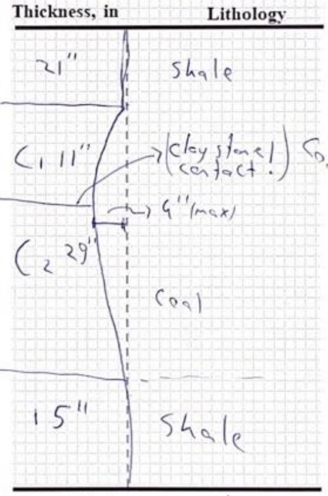
Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	21	36.3	42.2	
C *Strong / Weak*		35.2		
2 Coal / Rock	11	31.0		X
C *Strong / Weak* → claystone		33.3	35.1	
3 Coal / Rock	26	31.5		
C *Strong / Weak*		37.8		
4 Coal / Rock	15			
C *Strong / Weak*				
5 Coal / Rock				
C *Strong / Weak*				
6 Coal / Rock				
C *Strong / Weak*				
7 Coal / Rock				
C *Strong / Weak*				
8 Coal / Rock				
Floor C: Str. / Weak				

Rib Profile

Roof Material: Lithology/Strength

Shale / Strong

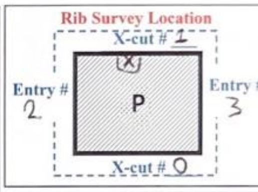
Thickness, in **Lithology**



Shale / Strong

Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

Spacing ('): < 1''

Strike / Dip (°): N 40° E / 90°

Notable Conditions

CMRR :

Roof: good

Floor: good

Other:

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

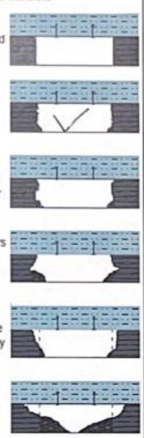
2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft (15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

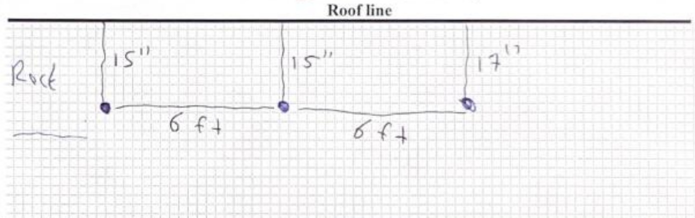
5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



Rib Support Sketch (Side View)

Roof line



Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
Support 1	Steel / Fiber	5	3/4	60	Grouted/ Mechanical	Straight/ Angled
~~Support 2~~	Steel / Fiber				Grouted/ Mechanical	Straight/Angled

	Plate Type	Plate Dimensions (in)	Mesh Type	Mesh Dimensions (ft)	Standing support Type	Size (in)	Height (ft)
Support 1	Plastic/ Steel	Pizza pan (17x17)	Plastic/Steel		Timber/steel		
~~Support 2~~	Plastic/Steel	regular (8x8)	Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None

Brow Potential

Slabby/ Blocky

Blocky/ Columnar

Friable

Slabby

Blocky

Columnar

Characteristics of Spalling

Avg. block size (in): < 1''

Previously cleaned up: Yes/ No

Rib support additional information

Development method: Place change / Full face

Support 1 is part of roof bolting cycle: Yes / No

Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems?

Other notable conditions: Bolt Practice : if top rock thickness exceeds 2 ft angled (5ft) bolt applied (around midpoint of the Rock)

Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: 12 / 1 / 2022	Mining Method (R&P/LW):	Overburden (ft): 1100	Entry width (ft): 19
Mine Name:	Date mined: /	Rib height (ft): 7'	Entry azimuth (°): N55°E
Site #:	Mining stage (Dev/Ret):	Pillar size (ft): 58'	Cross-cut azimuth (°): N35°W

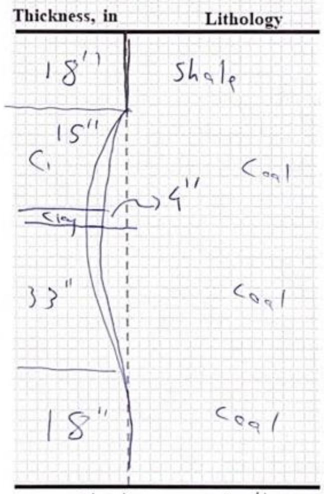
(2)

Rib Data

Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	18	47.3		X
C *Strong / Weak*		33.1		
2 Coal / Rock	15	31.3	31.4	
C *Strong / Weak*		42.5		
3 Coal / Rock	33	43.1		X
C *Strong / Weak*		40.9		
4 Coal / Rock	18	39.3		
C *Strong / Weak*		40.3		
5 Coal / Rock				
C *Strong / Weak*				
6 Coal / Rock				
C *Strong / Weak*				
7 Coal / Rock				
C *Strong / Weak*				
8 Coal / Rock				
Floor C: Str / Weak				

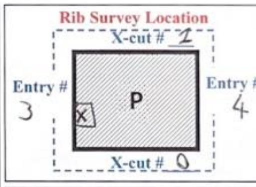
Rib Profile

Roof Material: Lithology/Strength
Shale / strong



Shale / Schmidt: 33.8 / 30.5
Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

Spacing ('): < 1''
Strike / Dip (°): N40°E / 90°

Notable Conditions

CMRR :
Roof: Good

Floor: Good

Other: Weak clay between coal members around 2'' thick (Moisture Sensitive)

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

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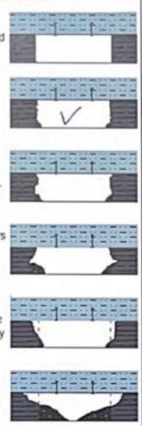


Rib Support Sketch (Side View)

Roof line

spot Bolting
x where top rock > 2 ft
(Brow control)

Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
Support 1	Steel / Fiber	5	3/4	60	Grouted/ Mechanical	Straight/Angled
Support 2	Steel / Fiber				Grouted/ Mechanical	Straight/Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
Support 1	Plastic/Steel		Plastic/Steel		Timber/steel		
Support 2	Plastic/Steel		Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None
Brow ✓
Slabby/ Blocky
Blocky/ Columnar
Friable
Slabby
Blocky
Columnar

Characteristics of Spalling

Avg. block size (in): < 1''
Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face
Support 1 is part of roof bolting cycle: Yes / No
Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

What causes most of your typical rib problems? Brow

Other notable conditions: This site has around 170 ft below from previously mined seam!!

Data Collection Sheet for Coal Pillar Ribs

Rib Survey Date: 12 / 1 / 2022
Mine Name:
Site #: (2)

Mining Method (R&P/LW): R&P
Date mined: August / 2022
Mining stage (Dev/Ret): Dev

Overburden (ft): 900
Rib height (ft): 6 ft
Pillar size (ft): 43 ft

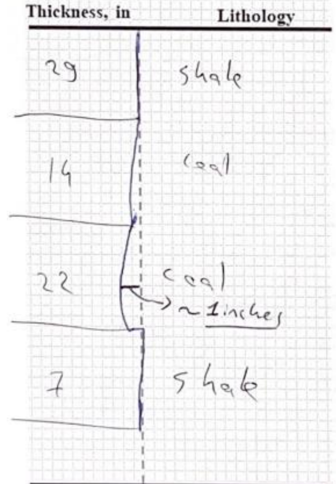
Entry width (ft): 20 ft
Entry azimuth (°): S80°W
Cross-cut azimuth (°): N10°W

Rib Data

Rib member & Contact strength	Member Thickness (in)	Schmidt Hammer Reading		Sample ID (if any)
Roof C: Strong / Weak				
1 Coal / Rock	29	36.7		
C Strong / Weak		40.		
2 Coal / Rock	14	41.3		X
C Strong / Weak		35.5		
3 Coal / Rock	22	33.5		
C Strong / Weak		37.5		
4 Coal / Rock	7	43.5		
C Strong / Weak				
5 Coal / Rock				
C Strong / Weak				
6 Coal / Rock				
C Strong / Weak				
7 Coal / Rock				
C Strong / Weak				
8 Coal / Rock				
Floor C: Str. / Weak				

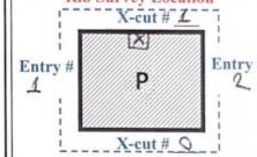
Rib Profile

Roof Material: Lithology/Strength
Shale / strong



Shale / schmidt (43.5)
Floor Material: Lithology/Strength

Rib Survey Location



Face Cleat Properties

Spacing ('): < 1''
Strike / Dip (°): N30°E / 30°

Notable Conditions

CMRR :
Roof:

Floor:

Other: Cleat system not well defined.

Data Collection Sheet for Coal Pillar Ribs

Rib Deterioration Index

1 Sloughage of 3 in (7.5 cm) or less. damage is only on skin of the pillar and rock dust is mostly intact in areas that are outby.

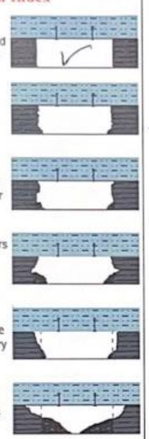
2 Wide spread skin damage 3 to 6 in (7.5 to 15 cm). Small blocks of sloughage appear on floor

3 Ribs are beyond slight skin damage and is observed from 6 in to 1 ft(15 to 30 cm) from the original rib line, larger blocks of sloughage appear on floor.

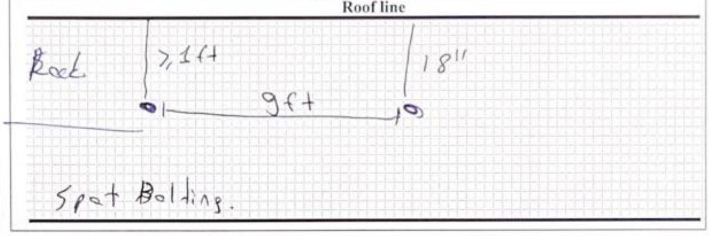
4 Obvious rib damage. Damage to pillars extends 1 to 2 ft (0.3 to 0.6 m) on average from the original pillar line.

5 Significant rib damage. Damage extends 2 to 4 ft (0.6 to 1.2 m) into the pillar from the original rib. travel is very difficult due to sloughage covering most of the floor.

6 Severe rib sloughage. Rib damage extends beyond 4 ft (1.2 m). Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite rib.



Rib Support Sketch (Side View)



Rib bolt

	Type	Length (ft)	Diameter (in)	Grade (ksi)	Anchor type	Installation method
Support 1	Steel / Fiber	5 ft	3/4	60	Grouted/ Mechanical	Straight/Angled
~~Support 2~~	Steel / Fiber				Grouted/ Mechanical	Straight/Angled

	Plate		Mesh		Standing support		
	Type	Dimensions (in)	Type	Dimensions (ft)	Type	Size (in)	Height (ft)
Support 1	Plastic/Steel	17 x 17	Plastic/Steel		Timber/steel		
Support 2	Plastic/Steel	Pizza pan.	Plastic/Steel		Timber/steel		

Spalling/ Sloughing

None
Brow
Slabby/ Blocky
Blocky/ Columnar
Friable
Slabby
Blocky
Columnar

Characteristics of Spalling

Avg. block size (in): < 1''
Previously cleaned up: Yes / No

Rib support additional information

Development method: Place change / Full face
Support 1 is part of roof bolting cycle: Yes / No
Support 2 is part of roof bolting cycle: Yes / No

Notable Conditions

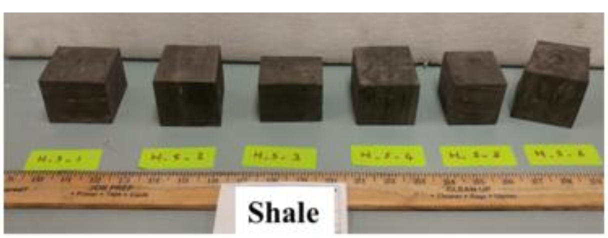
What causes most of your typical rib problems?

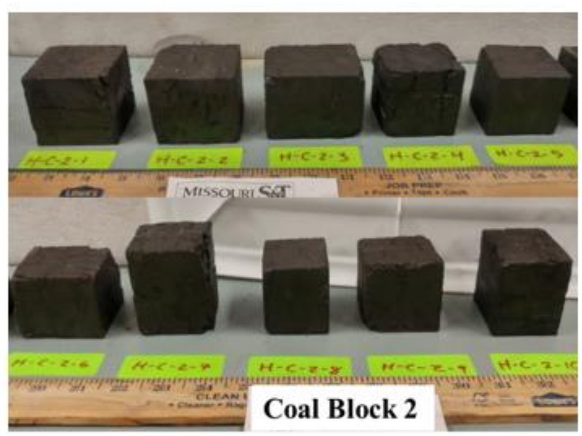
Other notable conditions:

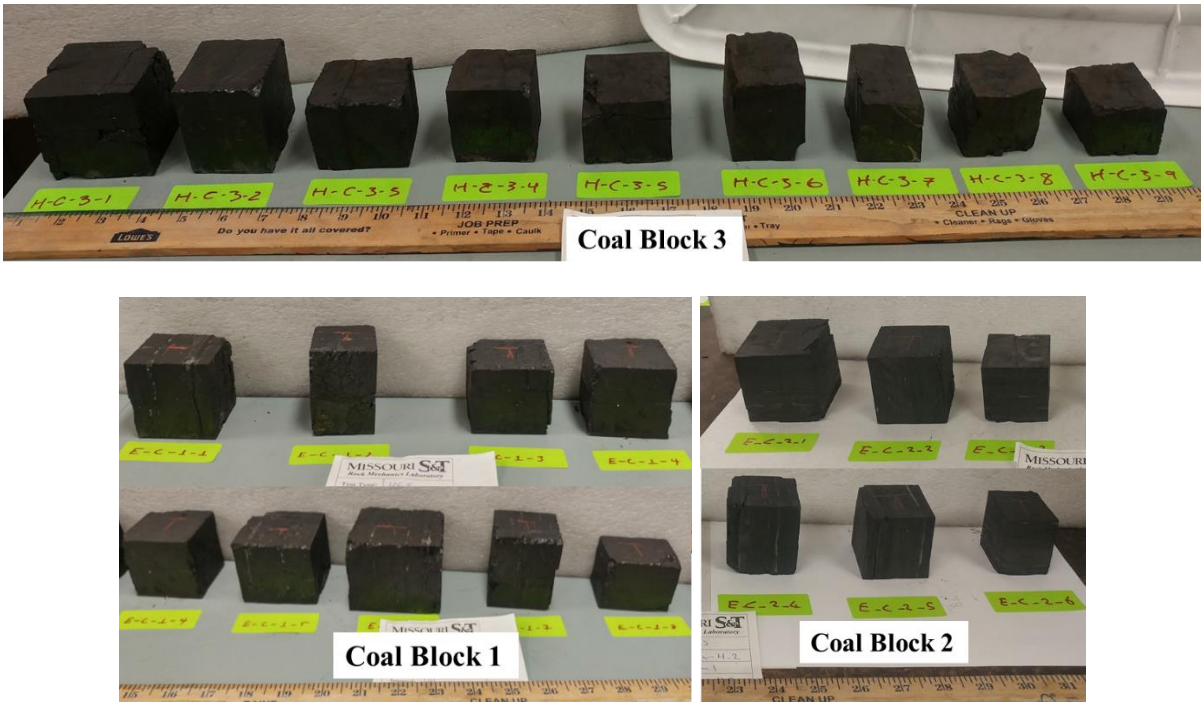
9.2 Laboratory efforts and rock mechanics test results

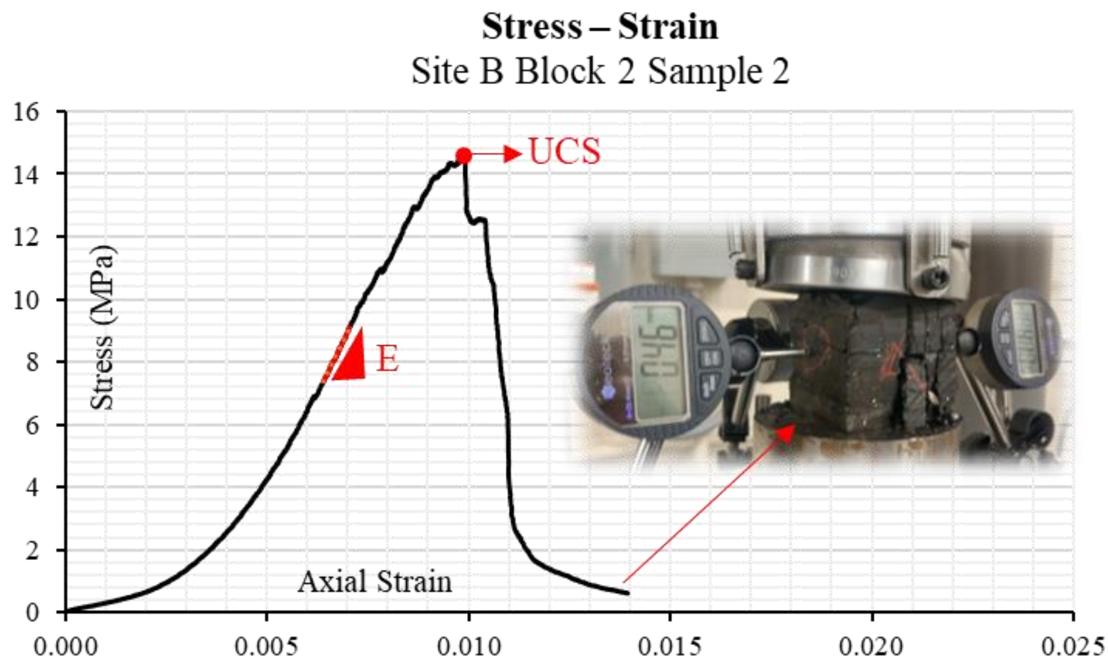
9.2.1 Collected coal lump samples

9.2.2. Prepared samples and representative test curve






Coal Block 3
Coal Block 1
Coal Block 2


Stress – Strain
Site B Block 2 Sample 2
UCS
E
Stress (MPa)
Axial Strain
0
2
4
6
8
10
12
14
16
0.000
0.005
0.010
0.015
0.020
0.025

9.2.3. UCS test results

Site A Block #1							
ID	**H (mm)**	**W1 (mm)**	**W2 (mm)**	**W/H**	**UCS (MPa)**	**Tangent Modulus (GPa)**	**Loading direction with wrt. Bedding plane**
1	57.6	49.8	54.8	0.91	16.10	1.135	Perpendicular
2	60.0	59.5	58.2	0.98	10.04	0.830	Perpendicular
3	61.6	56.3	55.5	0.91	13.51	1.251	Perpendicular
4	49.2	50.3	53.2	1.05	23.03	1.459	Perpendicular
5	50.8	55.4	54.6	1.08	4.91	-	Parallel
6	57.5	49.1	45.5	0.82	6.11	-	Parallel
7	54.1	48.5	52.3	0.93	7.87	0.789	Parallel
8	48.6	53.8	42.6	0.99	12.56	1.201	Perpendicular

Site A Block #2							
ID	**H (mm)**	**W1 (mm)**	**W2 (mm)**	**W/H**	**UCS (MPa)**	**Tangent Modulus (GPa)**	**Loading direction with wrt. Bedding plane**
1	58.80	38.20	56.50	0.81	14.32	0.999	Perpendicular
2	43.18	64.20	56.43	1.40	7.09	0.554	Parallel
3	43.75	44.76	55.08	1.14	17.99	1.127	Perpendicular
4	45.28	39.18	50.02	0.98	10.91	0.972	Perpendicular
5	44.02	43.24	33.80	0.88	15.81	1.035	Perpendicular
6	55.23	44.60	44.09	0.80	11.75	0.657	Parallel
7	52.60	41.32	50.01	0.87	15.25	1.046	Perpendicular
8	41.96	50.42	41.80	1.10	19.04	1.549	Parallel

Site B Block #1							
ID	**H (mm)**	**W1 (mm)**	**W2 (mm)**	**W/H**	**UCS (MPa)**	**Tangent Modulus (GPa)**	**Loading direction with wrt. Bedding plane**
1	55.20	55.04	54.97	1.00	13.64	1.034	Perpendicular
2	59.01	38.77	62.20	0.86	17.43	1.753	Parallel
3	88.77	64.06	61.44	0.71	6.55	0.741	Parallel
4	93.52	78.07	73.01	0.81	6.42	0.657	Parallel
5	52.16	54.29	53.85	1.04	14.85	1.306	Parallel
6	45.12	44.18	43.28	0.97	14.80	1.449	Parallel
7	54.23	44.41	41.56	0.79	6.16	0.628	Parallel
8	44.78	52.29	34.00	0.96	19.42	1.218	Perpendicular
9	55.07	48.20	50.51	0.90	9.85	1.280	Parallel

Site C								
Block	**ID**	**H (mm)**	**W_1 (mm)**	**W_2 (mm)**	**W/H**	**UCS (MPa)**	**Tangent Modulus (GPa)**	**Loading direction with wrt. Bedding**
Shale	1	52.0	56.9	62.8	1.15	44.54	3.647	Perpendicular
Shale	2	55.7	58.6	55.9	1.03	21.53	3.771	Parallel
Shale	3	48.5	62.0	48.6	1.14	24.78	3.544	Parallel
Shale	4	47.2	62.7	60.7	1.31	28.24	3.637	Parallel
Shale	5	50.8	46.7	48.3	0.94	36.15	3.809	Perpendicular
Shale	6	56.5	60.2	53.5	1.01	25.06	3.813	Parallel
Coal Block 1	1	50.11	50.43	55.58	1.06	4.07	0.381	Parallel
Coal Block 1	2	54.40	43.00	62.50	0.97	7.72	0.946	Perpendicular
Coal Block 1	3	60.90	49.55	32.45	0.67	3.64	0.573	Parallel
Coal Block 1	4	51.84	63.88	60.77	1.20	12.54	1.129	Perpendicular
Coal Block 2	1	57.15	58.06	62.46	1.05	16.83	1.383	Perpendicular
Coal Block 2	2	56.33	62.61	64.48	1.13	23.54	1.956	Perpendicular
Coal Block 2	3	54.54	58.10	74.42	1.21	19.94	1.659	Parallel
Coal Block 2	4	55.31	55.24	56.93	1.01	16.85	0.920	Perpendicular
Coal Block 2	5	51.63	53.58	53.66	1.04	17.15	1.671	Parallel
Coal Block 2	6	48.55	54.15	61.02	1.19	21.32	1.857	Perpendicular
Coal Block 2	7	68.27	49.67	52.66	0.75	19.98	1.982	Parallel
Coal Block 2	8	55.30	54.29	46.76	0.91	14.50	1.381	Perpendicular
Coal Block 2	9	52.57	50.99	51.38	0.97	17.31	1.689	Parallel
Coal Block 3	1	66.26	67.05	68.44	1.02	10.35	1.268	Parallel
Coal Block 3	2	66.49	63.76	56.52	0.90	8.07	1.000	Parallel
Coal Block 3	3	51.51	56.69	60.59	1.14	13.71	1.105	Perpendicular
Coal Block 3	4	58.71	50.85	54.77	0.90	23.07	2.134	Perpendicular
Coal Block 3	5	50.06	58.33	58.32	1.17	16.29	1.410	Parallel
Coal Block 3	6	60.93	66.94	47.47	0.94	20.98	2.271	Perpendicular
Coal Block 3	7	48.05	68.27	38.74	1.11	8.04	1.029	Parallel

Site D								
Block	**ID**	**H (mm)**	**W_1 (mm)**	**W_2 (mm)**	**W/H**	**UCS (MPa)**	**Tangent Modulus(GPa)**	**Loading direction with wrt. Bedding**
Coal Block 1	1	57.65	59.08	58.50	1.02	23.44	1.987	Parallel
	2	56.41	47.10	38.20	0.76	11.74	1.112	Parallel
	3	53.40	58.70	60.60	1.12	13.04	0.782	Parallel
	4	56.34	60.70	58.78	1.06	25.83	1.970	Perpendicular
	5	57.50	66.60	65.08	1.15	15.88	1.625	Perpendicular
	6	64.92	68.30	76.70	1.12	26.53	2.097	Perpendicular
	7	66.00	51.98	53.30	0.80	17.84	1.821	Parallel
	8	47.09	46.50	58.50	1.11	18.10	1.620	Perpendicular
Coal Block 2	1	63.03	61.84	60.96	0.97	18.59	1.391	Perpendicular
	2	61.80	55.29	56.70	0.91	14.46	2.634	Parallel
	3	51.95	55.69	52.10	1.04	12.68	1.250	Perpendicular
	4	60.04	50.56	53.59	0.87	12.11	2.095	Parallel
	5	53.13	52.88	48.20	0.95	13.36	2.281	Parallel
	6	48.18	48.40	38.90	0.91	15.10	1.430	Perpendicular

Site E Shale						
ID	**H (mm)**	**W1 (mm)**	**W2 (mm)**	**W/H**	**UCS (MPa)**	**E (GPa)**
1	67.33	65.30	59.28	0.93	26.43	5.312
2	70.45	87.85	68.78	1.11	18.69	3.743
3	65.78	91.50	72.33	1.25	17.60	3.747
4	82.75	68.50	67.33	0.82	19.97	4.577
5	72.55	57.27	60.33	0.81	22.20	4.958
6	70.50	70.20	73.60	1.02	22.11	4.034

Site E Top Coal						
ID	**H (mm)**	**W1 (mm)**	**W2 (mm)**	**W/H**	**UCS (MPa)**	**E (GPa)**
1	52.95	48.30	52.41	0.95	4.48	0.540
2	56.41	47.30	58.60	0.94	3.12	0.246
3	55.19	53.89	58.38	1.02	4.55	0.446
4	61.97	54.58	89.24	1.16	8.26	1.070
5	59.25	52.41	57.29	0.93	3.38	0.378
6	62.38	59.34	70.54	1.04	5.51	0.791
7	52.95	64.38	74.18	1.31	9.26	0.948
8	56.57	46.68	66.24	1.00	4.37	0.433
9	68.21	48.90	74.63	0.91	2.02	0.319
10	68.02	44.45	75.89	0.88	2.61	0.254
11	71.56	69.73	78.46	1.04	11.26	1.502

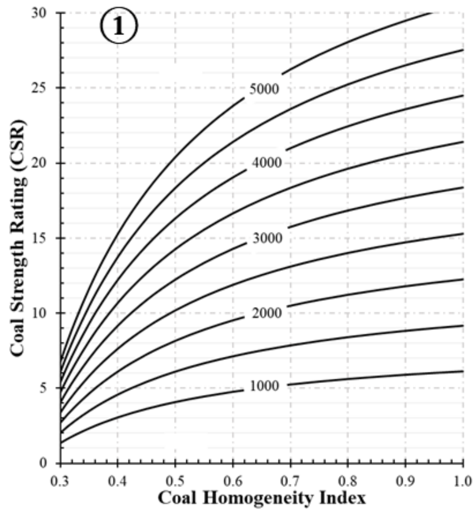
Site E Bottom Coal						
ID	H (mm)	W1 (mm)	W2 (mm)	W/H	UCS (MPa)	E (GPa)
1	82.63	48.15	64.41	0.68	12.40	2.372
2	78.33	51.05	59.89	0.71	2.41	0.334
3	78.68	61.18	87.57	0.95	6.15	0.826
4	70.26	49.92	70.56	0.86	5.95	0.683
5	67.29	55.47	69.55	0.93	19.41	2.814
6	73.96	56.87	77.87	0.91	17.77	2.394
7	78.94	51.15	69.79	0.77	4.32	0.587
8	87.47	68.75	72.31	0.81	3.32	0.360
9	67.84	51.51	63.66	0.85	2.77	0.284
10	83.03	60.43	62.14	0.74	4.65	0.552
11	74.08	59.81	64.22	0.84	6.93	1.146

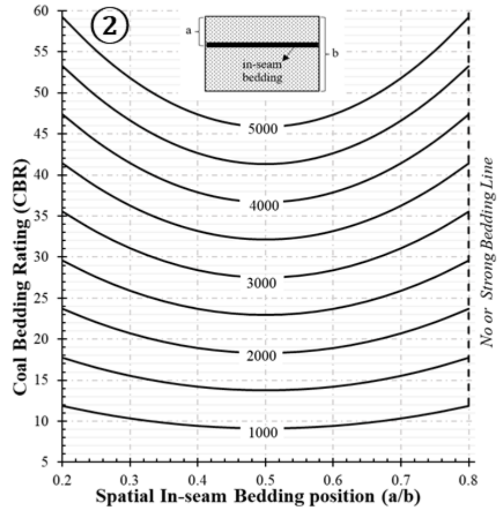
Site F Coal						
ID	H (mm)	W1 (mm)	W2 (mm)	W/H	UCS (MPa)	E (GPa)
1	85.78	54.85	80.20	0.79	4.43	0.765
2	84.93	64.09	64.93	0.76	15.77	2.043
3	86.19	54.73	74.29	0.75	9.29	1.631
4	76.55	70.23	74.15	0.94	3.44	0.657
5	87.18	63.19	66.38	0.74	9.79	1.866
6	88.35	57.98	68.41	0.72	9.94	2.069

Site G Coal						
ID	H (mm)	W1 (mm)	W2 (mm)	W/H	UCS (MPa)	E (GPa)
1	69.81	61.52	85.24	1.05	14.93	1.624
2	68.14	67.29	74.81	1.04	13.99	1.513
3	82.76	69.24	83.51	0.92	4.03	0.579
4	99.28	76.88	91.75	0.85	6.21	1.912
5	82.30	71.81	81.49	0.93	12.52	1.698
6	84.60	82.11	78.76	0.95	12.74	1.358
7	76.23	65.74	76.53	0.93	6.40	0.781
8	82.21	92.04	79.88	1.05	5.08	0.626
9	75.73	71.55	79.92	1.00	9.50	1.363
10	79.41	85.89	82.66	1.06	7.27	1.144

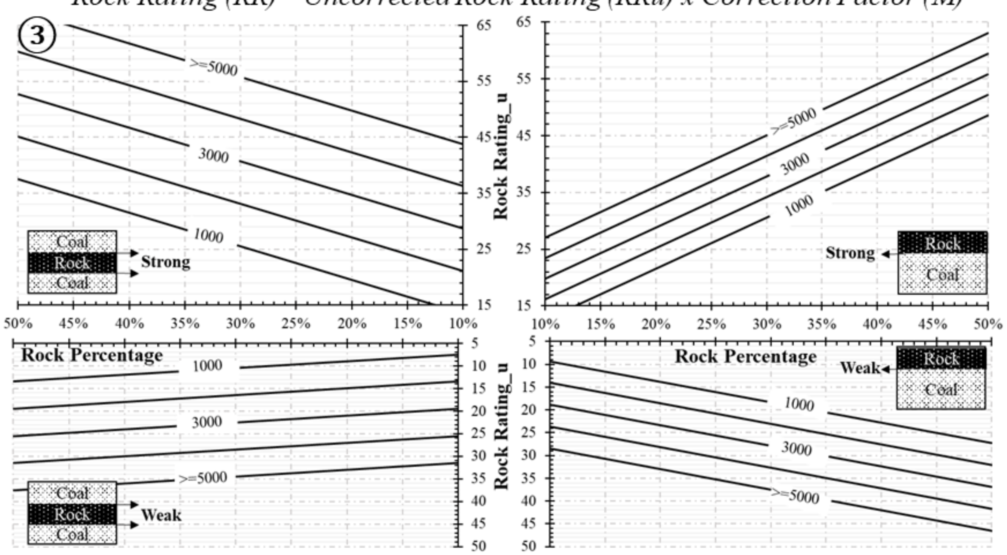
Coal Pillar Rib Rating (CPRR)

Coal Rating (CR) = Strength Rating (SR) + Bedding Rating (BR)





Rock Rating (RR) = Uncorrected Rock Rating (RRu) x Correction Factor (M)



Instructions

1. Find Coal Rating using ① and ②

2. Find uncorrected rock rating from the relevant chart using ③

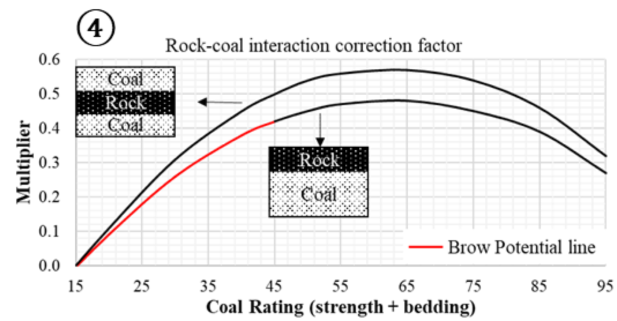
3. Find rock-coal interaction factor from ④

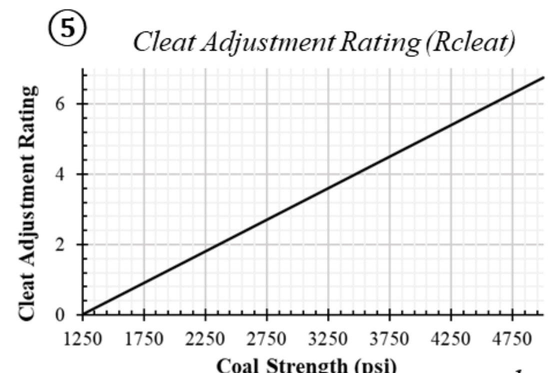
4. Multiply ③ and ④ to find Rock Rating

5. If required find Cleat Adjustment Rating using ⑤

6. Calculate CPRR as follows:

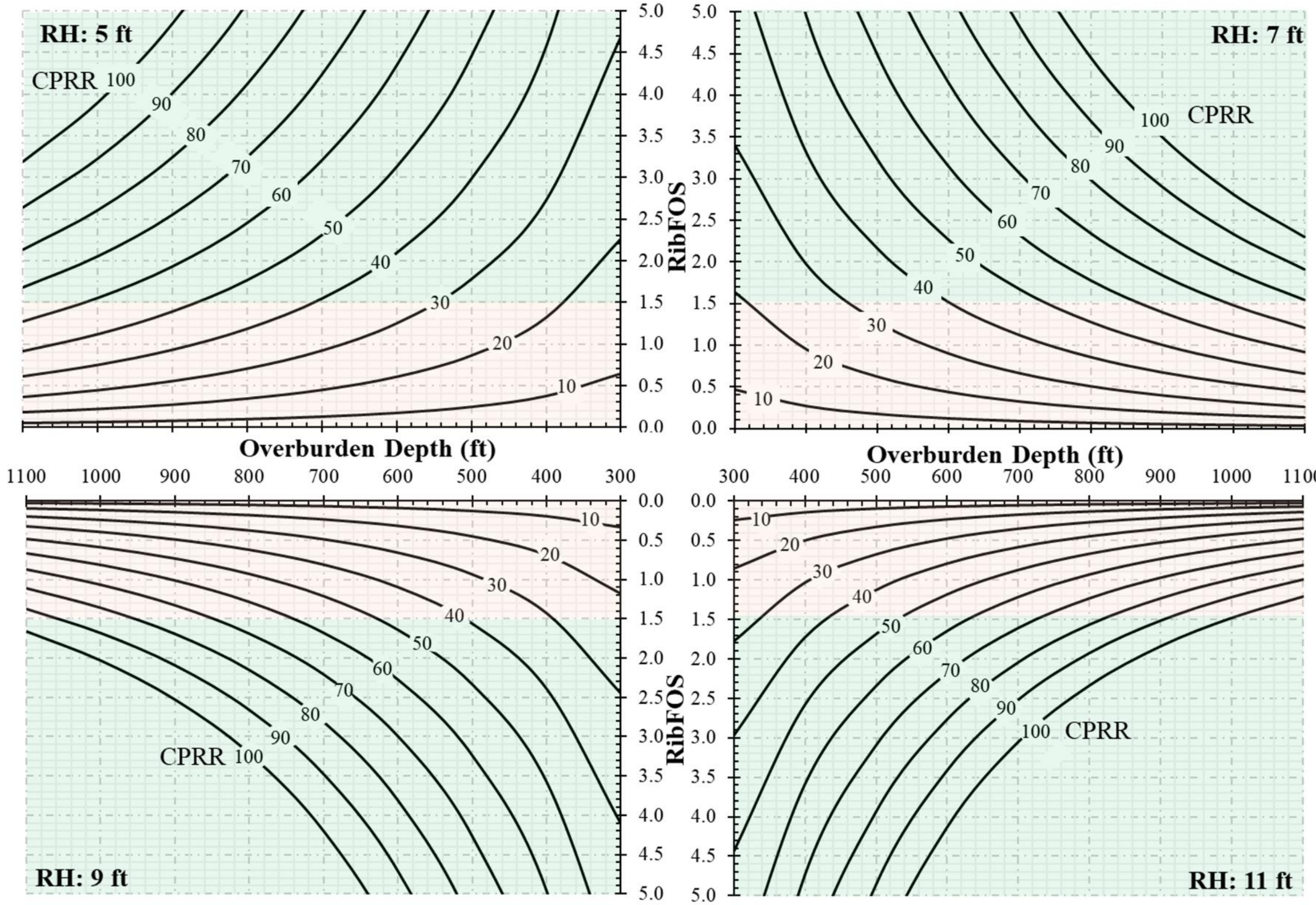
CPRR= CR + (RRu x RC factor) + Rcleat



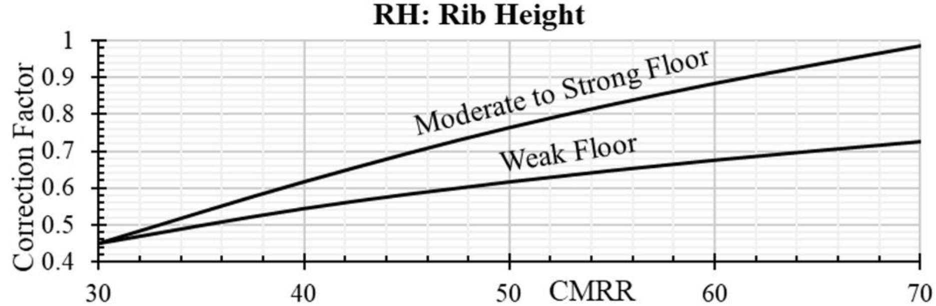


1 of 2

Rib Factor-of-Safety (RibFOS)



RH: Rib Height



Coal Pillar Rib Rating (CPRR)

Step 1: Coal Rating (CR) = Coal Strength Rating (CSR) + Coal Bedding Rating (CBR)

Table 1	*Coal Strength Rating*				
Homogeneity index	**Weighted Coal Strength (psi)**				
	<=1000	*2000*	*3000*	*4000*	*>=5000*
<=0.3	1	3	4	5	7
0.65	5	10	15	20	25
1.00	6	12	18	24	31

Table 2	*Coal Bedding Rating*				
Position	**Weighted Coal Strength (psi)**				
	<=1000	*2000*	*3000*	*4000*	*>=5000*
Close to the coal boundary*	12	24	36	47	59
Upper/lower mid	10	21	31	41	52
Around mid	9	18	28	37	46

* If no or strong bedding, use this row

Step 2: Rock Rating (RR) = Uncorrected Rock Rating (RRu) x Correction Factor (M)

Table 3 Uncorrected Rock Rating

i) Rock parting is overlain and underlain by coal
ii) Rock coal contact is ***strong***

Coal / Rock / Coal → Strong

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	13	21	29	36	44
20%	19	27	35	42	50
30%	25	33	41	48	56
40%	31	39	47	54	62
>=50%	37	45	53	60	68

i) Rock parting is above or below the coal unit
ii) Rock coal Contact is ***strong***

Rock / Coal → Strong

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	13	16	20	23	27
20%	22	25	29	32	36
30%	31	34	38	41	45
40%	40	43	47	50	54
>=50%	49	52	56	59	63

i) Rock parting is overlain and underlain by coal
ii) Rock coal contact is ***weak***

Coal / Rock / Coal → Weak

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	8	13	20	26	32
20%	9	15	21	27	33
30%	11	17	23	29	35
40%	12	18	24	30	36
>=50%	13	20	26	32	38

i) Rock parting is above or below the coal unit
ii) Rock coal Contact is ***weak***

Rock / Coal → Weak

Rock Percentage	**Rock Parting Strength (psi)**				
	<=1000	**2000**	**3000**	**4000**	**>=5000**
<=10%	9	14	19	24	29
20%	14	19	23	28	33
30%	18	23	28	33	38
40%	23	28	32	37	42
>=50%	27	32	37	42	47

Table 4	*Correction Factor (Rock-coal interaction factor)*								
Parting Position	*Coal Rating (coal strength rating + coal bedding rating)*								
	20	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Coal / Rock / Coal	0.11	0.30	0.45	0.53	0.56	0.55	0.50	0.38	0.22
Rock / Coal	0.09	0.26	0.38	0.45	0.47	0.46	0.41	0.32	0.18
	Brow Forming Potential								

Step 3: Cleat Adjustment Rating

Table 5	*Cleat orientation Adjustment Factor*			
Coal Strength (psi)				
<=1250	**2000**	**3000**	**4000**	**>=5000**
0	1	3	5	7