Preliminary Rib Support Requirements for Solid Coal Ribs Using A Coal Pillar Rib Rating

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ABSTRACT

Researchers from the National Institute for Occupational Safety and Health (NIOSH) are developing a coal pillar rib rating (CPRR) technique to measure the integrity of coal ribs. The CPRR characterizes the rib composition and evaluates its impact on the inherent stability of the coal ribs. The CPRR utilizes four parameters: rib homogeneity, bedding condition, face cleat orientation with respect to entry direction, and rib height. All these parameters are measurable in the field. A rib data collecting procedure and a simple sheet to calculate the CPRR were developed.

The developed CPRR can be used as a rib quality mapping tool in underground coal mines and to determine the potential of local rib instabilities and support requirements associated with overburden depth. CPRR calculations were conducted for 22 surveyed solid coal ribs, mainly composed of coal units. Based on this study, the rib performance was classified into four performance levels: poor, fair, good, and very good. A preliminary minimum primary rib support density (PRSD) line was obtained from these surveyed cases. Two sample cases are presented that illustrate the data collection form and CPRR calculations.

INTRODUCTION

Over the past decade, falls of rib or face have resulted in 16 fatalities, representing more than 50% of the ground-fall fatalities in U.S. underground coal mines. More recently, within the past five years, this proportion has increased to 80% of the ground-fall related fatalities in these mines. In 2018 and 2019, 100% of the three ground-fall related fatalities in U.S. underground coal mines were attributed to falls of rib or face (MSHA, 2019). These statistics clearly indicate that, over time, falls of rib or face are contributing more to mineworker fatalities than any other ground-fall fatality cause. It is commonly understood that coal mines today are facing ever increasing challenges in the form of increased overburden depth, multiple-seam interactions, thinner coal beds, and thicker in-seam partings. While it is difficult to quantify how much each of these factors contribute to the relative stability of the roof and ribs, the consensus is that these are factors so important that they must be considered in modern mine design. To eliminate injuries and fatalities caused by falls of rib in underground coal mines, National Institute for Occupational Safety and Health (NIOSH) researchers are currently working on the development of engineering-based rib control methods.

Currently, mine operators' decisions concerning rib control and support guidelines are based on the roof control plan approval handbook (MSHA, 2013). Appendix O in the roof control plan approval handbook provided information on the conditions that contribute to rib-fall hazards and the available methods for protecting miners from rib falls. Two significant geologic conditions that contribute to hazards related to falls of ribs were identified: (1) seam height and (2) depth of cover. The appendix contains statistics indicating that of 23 rib-fall fatalities that occurred between 1996 and 2010, 22 (96%) occurred where the mining height was at least 7 ft, and 18 (76%) occurred where the depth of cover was at least 700 ft.

Like any static structure, rib stability can be determined by the load applied on the rib and the strength of the rib. The depth of cover is a good indication of the load on the rib for primary support design. On the other hand, the rib (seam) height may affect rib performance, but there are other important parameters that affect rib strength, such as rib homogeneity, bedding condition, face cleat orientation with respect to entry direction, and so forth. The coal pillar rib rating (CPRR) was developed to help quantify the integrity of coal pillar ribs. All these parameters are measurable in the field. The CPRR was generated because none of the current rock mass classification systems can be readily adaptable to coal ribs for at least one of the following reasons: (1) coal mass properties, such as cleat density and orientation in addition to coal pillar rib heterogeneity, were not incorporated in any rock mass classification system; and (2) almost all classification systems are originally based on case histories not relevant to coal pillar rib performance. Consequently, the direct application of a current classification system would, generally, yield an unrealistic result.

The goal of the CPRR is to aid in the early selection of coal pillar rib support based on the rib composition, mining height, and the expected loading conditions. The CPRR was developed using a hybrid numerical-empirical approach. Underground site investigations, calibrated rib models, and the findings presented in published papers pertaining to geology and underground coal rib performance were used to develop the CPRR. Through underground coal mine investigations, three main rib categories were observed: (1) solid coal ribs with or without thin partings of thicknesses under 2 in., (2) coal ribs with in-seam thick partings (greater than 6 in.), and (3) coal rib with a roof brow. Only the solid coal rib category is presented in this paper. The other rib categories are still under investigations. Future research is proposed to expand the applicability of the CPRR for conditions where thick in-seam parting and strong coal/rock brows are encountered. This will extend the potential for usage of the CPRR to most coal ribs.

DEFINITION OF COAL PILLAR RIB RATING

CPRR is a technique used for measuring the integrity or stability of coal ribs. CPRR is calculated from the rib factor of safety (RibFOS) (Mohamed, Cheng, and Rashed, 2019) and the ratio of in situ minimum horizontal stress to vertical stress (S_h/S_v). CPRR can be represented as the scaled area under the relationship between RibFOS and S_h/S_v. The calculated area under this relationship is scaled between 1 and 100. A CPRR of 1 designates the weakest coal rib, and a CPRR of 100 designates the strongest rib. CPRR measures the quality of coal ribs but not the effect of mining-induced stresses, such as development, abutment, or multiple-seam interaction loads on the rib.

The coal mass constitutive model developed by Mohamed et al. 2018 was used to simulate the loading and deformation behaviors of different coal rib lithotypes. In the coal mass model, the response of each coal lithotype is controlled by multiple input parameters. In this paper, each lithotype is referenced by its uniaxial compressive strength (UCS), for example, a UCS of 1,244 psi refers to the behaviors of a bright coal (BC) lithotype and a UCS of 5,075 psi refers to a dull coal (DC) lithotype. Plane strain models (Itasca, 2017) were used to calculate the CPRR of 11-ft-high solid coal ribs with different coal rib lithotypes (Figure 1). The gateroad in these models was oriented parallel to the maximum horizontal stress. The face cleat orientation was assumed to be parallel to the gateroad orientation. The in situ stresses in roof and floor strata were estimated by the model developed by G. S. Esterhuizen (personal communication), and the in situ stresses in coal were estimated by the model developed by Liu et al. (2016). Mohamed et al. (2018) proposed rational mechanical properties for the roof-to-pillar interface and floor-to-pillar interface by calibrating the rib models with a field instrumented case study. The in situ minimum horizontal-stress-to-vertical-stress ratio in these models ranges from 0.06 to 0.53, which corresponds to an overburden depth range of 300–1,050 ft. The end-constrain effects provided by roof and floor strata on the calculated CPRR was eliminated by assuming tall ribs of 11-ft high. Figure 1 shows that the BC rib of highly cleated coal mass resulted in the lowest CPRR of 17 while DC resulted in the highest CPRR of 90.

PARAMETRIC STUDY TO DEVELOP A CPRR CALCULATION SHEET FOR SOLID COAL RIBS

Calculating the CPRR using the numerical model approach is time consuming and requires expertise in numerical modeling, making it unfavorable in practical application. A more practical alternative
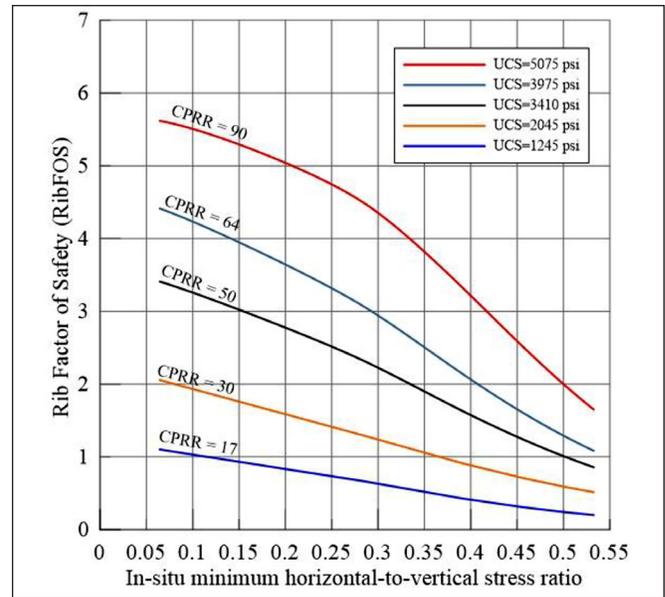

Figure 1. Calculated CPRRs for solid coal ribs with different uniaxial compressive strengths.

is to develop a simplified approach using a system of simple linear equations correlating the CPRR of solid coal ribs with their geological and geometrical parameters. In coal pillar design, the UCS of coal may not be important (Mark and Barton, 1996), but in coal rib design, the UCS of coal ribs was found to be a controlling parameter for rib performance (Colwell, 2006; Seedsman, Gordon, and Aziz, 2009; and Stone, 2015). Colwell (2006) found that for development loading conditions, the most important parameters controlling the rib performance are the overburden depth, cleat orientation with respect to the entry direction, the UCS of coal, and the density of rib support. Seedsman, Gordon, and Aziz (2009) provided a framework for coal pillar rib support. They found that a pattern of rib support is determined by the coal strength index (UCS of coal to the virgin stress ratio). Stone (2015) utilized an empirical database for rib support to determine the minimum rib support density required during roadway development. Initially, Stone assumed that the main factors controlling the rib support densities are the depth of cover and the mining height. Stone later updated the rib support database by including the strength of coal material as one of the parameters controlling the density of rib support. The regression analysis for the rib support database significantly improved by including the UCS of coal.

A parametric study for calculating CPRR based on practical ranges of rib height, UCS of rib units, number of rib units, and the bedding condition, which affect the CPRR, was conducted. A total of 1,206 FLAC3D models were conducted to calculate the CPRRs of 201 different rib compositions. The levels and corresponding value of each parameter are shown in Figure 2. Four levels of rib height were considered in the parametric study: 5 ft, 7 ft, 9 ft, and 11 ft. Except for the 11-ft-high ribs consisting of a single unit, three levels of UCS for the rib units were considered: 1,244 (BC); 2,857 (banded BC); and 5,075 psi (DC). For the 11-ft-high ribs consisting of a single unit, 13 levels of intact UCS were considered: 1,244 (BC); 1,653, 2,045, 2,204, 2,451, 2,567, and 2,857 (banded BC); 3,161, 3,408, 3,973, 4,118, 4,524, and 5,075 psi (DC). Two levels
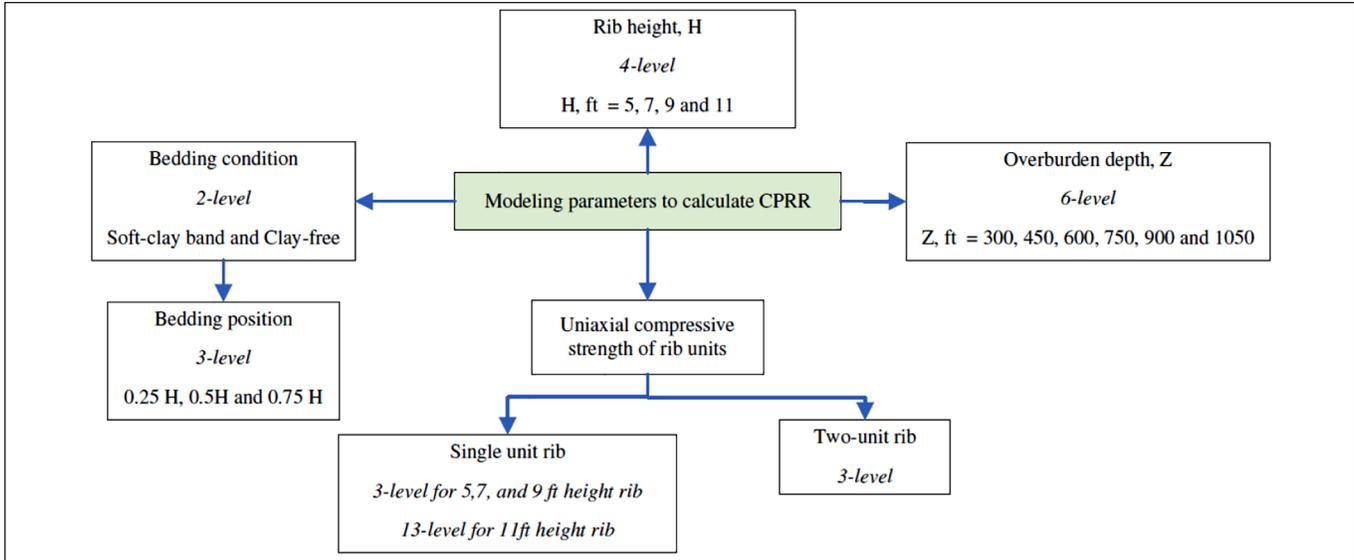
Figure 2. Flow chart for parametric study of calculating CPRR for solid coal ribs.

of bedding conditions, clay-free and soft-clay beddings, were considered for ribs consisting of two units. Three levels of bedding position were considered at quarter height, mid-height, and three-quarter height of the rib. To ensure a good resolution for calculating the CPRR, six levels of overburden depth were considered: 300, 450, 600, 750, 900, and 1,050 ft. The face cleat orientation was assumed to be parallel to the entry orientation in the CPRR calculations. The effect of face cleat orientation with respect to entry orientation on the CPRR was determined empirically. The roof and floor were assumed to be elastic in all models.

By conducting the proposed parametric study (Figure 2) and studying the effect of each parameter on the calculated CPRR, a simplified method to calculate the CPRR was developed (see Appendix A). A single-page calculation sheet for the calculations of the CPRR of solid coal ribs was developed (Figure 3). The top portion of the CPRR calculation sheet contains the basic rib information such as mine name, site identification, and description of the rib lithotypes (coal brightness, thickness, and UCS). The UCS of rib units can be measured by direct and/or indirect methods as explained in the following sections. The weighted average compressive strength and the total rib height are recorded in the top portion of the CPRR calculation sheet. The rib homogeneity index, explained in Appendix A, is calculated and recorded. The orientation of the face cleat with respect to entry direction and bedding condition (no bedding, bedding with no-clay, and bedding filled with soft clay) are also recorded. The calculations of the CPRR are conducted in two steps.

Step 1: Calculation of the Basic Coal Pillar Rib Rating (CPRR$_{Basic}$)

The basic coal pillar rib rating (CPRR$_{Basic}$) is calculated by adding the ratings of the geological parameters (homogeneity and bedding conditions) of solid coal ribs. Using the mine rib data in the top portion of the CPRR calculation sheet, the CPRR$_{Basic}$ in the top part of Figure 3 is calculated assuming a rib of 11 ft in height and face cleat orientation parallel to the entry direction. Rib homogeneity rating is defined using the calculated rib homogeneity index (r) and weighted average compressive strength (s_c). The

homogeneity rating for solid coal ribs ranges between 0 and 45 (top part of Figure 3). Despite the coal lithotype, heterogenous ribs ($r \leq 0.25$) have a zero-rib homogeneity rating. The highest rib homogeneity rating of 45 is assigned for homogeneous coal ribs ($r = 1$) dominated by strong dull coal units.

The rating of the bedding conditions in solid coal ribs ranges between 4 and 46 (Figure 3A). The minimum rating of bedding condition was assigned for ribs dominated by weak BC and contain bedding(s) filled with soft clay. The maximum rating of bedding condition was assigned for single-unit rib of strong dull coal.

Step 2: Adjustment of the CPRR

The CPRR$_{Basic}$ in Step 1 was calculated for 11-ft-high ribs and face cleat orientation parallel to the entry direction. Therefore, the CPRR$_{Basic}$ will be adjusted for the geometrical parameters (face cleat orientation and rib height) of the solid coal ribs. Documented research and field observations concluded that face cleat adjustment is only applicable for face cleat angles equal to or greater than 20 degrees with respect to entry direction (Whittles, 2000). Similar to the rock mass rating (Bieniawski, 1976), a maximum adjustment of 7 was assigned to the face cleat orientation in ribs dominated by strong dull coal units. On the other hand, no adjustment was assigned for ribs dominated by weak BC.

The CPRR of shorter ribs (less than 9 ft) was adjusted depending on the rib homogeneity, bedding condition, and the calculated weighted average UCS. The adjustment of the CPRR for the rib height in solid coal ribs ranges between 0 and 12 (bottom part of Figure 3). A maximum adjustment of 12 was assigned for 5-ft-high heterogenous ribs, while an adjustment of 4 was assigned for the same rib height of homogeneous ribs with a weighted average uniaxial strength of less than or equal to 2,500 psi.

The CPRR for solid coal ribs is obtained by the summation of the adjustment factors and the CPRR$_{Basic}$. The validity of the simplified CPRR calculation method was proven by testing it against the complex numerical modeling approach. Figure 4 shows the

CPRR calculated by the simplified method in comparison with the $\text{CPRR}_{\text{Model}}$ calculated by numerical modeling. The CPRR calculation sheet (Figure 3) uses simple linear relationships between the CPRR and the most significant parameters (see Appendix A); therefore, some level of deviation in CPRR calculations should be expected between the simplified method and the numerical method. Figure 4 shows a good correlation between the simplified method and the numerical modeling method, where the R-squared is 0.90. Therefore, it can be concluded that the simplified method is a good approximation for the highly complicated numerical modeling approach for calculating the CPRR of solid coal ribs.

CLASSIFICATION OF EXPECTED RIB PERFORMANCE FOR SOLID COAL RIBS

A regression model for correlating the RibFOS with CPRR and the overburden depth was developed (Equation 1) using the results of the numerical model parametric studies.

$$\text{RibFOS} = 19.76 \times \frac{\text{CPRR}}{\text{Depth, ft}} \qquad \text{(Equation 1)}$$

The R-squared of regression of the RibFOS model is 0.963. Figure 5 shows the graphical representation of the RibFOS model. The RibFOS model was extrapolated to the depth of cover of
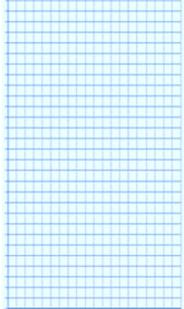

Figure 3. CPRR calculation sheet and adjustment factors for solid coal ribs.
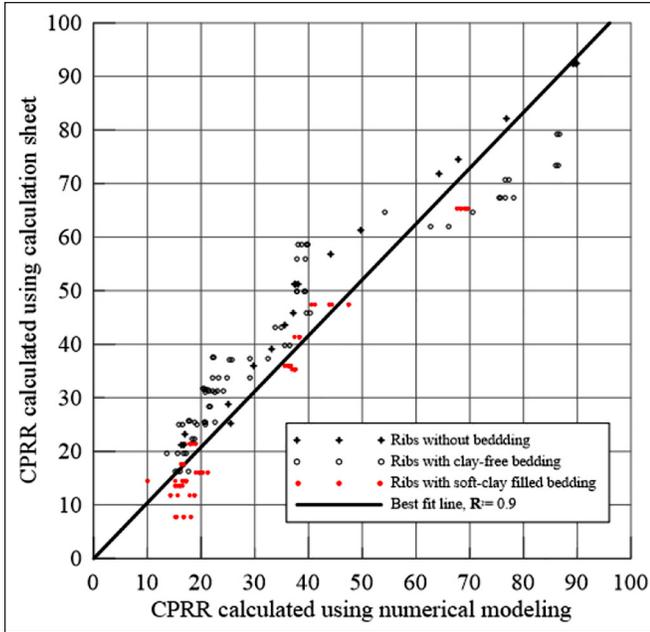
Figure 4. CPRR calculated by simplified method in comparison with CPRR calculated by numerical modeling.
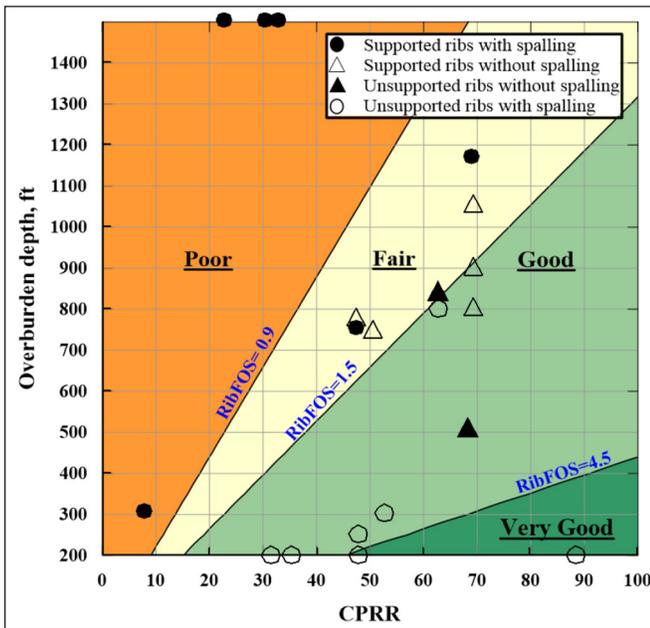

Figure 5. Classification of solid coal ribs based on CPRR and overburden depth. Boundaries between rib classes are defined by the RibFOS.

1,500 ft, beyond the range of the parametric study (1,050 ft), to make it applicable to the surveyed rib cases.

CPRR calculations were conducted for 22 surveyed solid coal ribs using the CPRR calculation sheet. The surveyed ribs were collected from room-and-pillar and longwall mines. All surveyed ribs were subjected to the development conditions with no multiple-seam

interactions. The 22 cases were classified into four categories based upon in-mine observation and data collection: (1) unsupported ribs with spalling, (2) unsupported ribs without spalling, (3) supported ribs with spalling, and (4) supported ribs without spalling. Field observations have shown that the unsupported ribs without spalling have the best rib performance as described in Figure 5.

Figure 5 shows the calculated CPRR for the 22 cases projected on the RibFOS model. It shows that the CPRR and overburden depth can be used to classify the performance of surveyed ribs. Four performance levels of solid ribs were identified: poor, fair, good, and very good, as follows:

- Poor rib performance category (RibFOS ≤ 0.90). All cases in this category are identified as supported ribs with spalling. All cases recorded in this category have very low CPRR (less than 30) and the majority have high overburden depth (1,500 ft). Despite rib support applied in this category, the ribs showed some level of spalling.
- Fair rib performance category (0.9 ≤ RibFOS < 1.5). Most of the cases in this category are identified as supported ribs without spalling. The decision of rib support in these cases was adequate to eliminate rib spalling, except for two cases that showed rib spalling despite rib support.
- Good rib performance category (1.5 ≤ RibFOS < 4.50). All cases in this category are identified as unsupported ribs without spalling.
- Very good rib performance category (RibFOS ≥ 4.50). The two cases in this category are identified as unsupported ribs without spalling and with shallow depths.

APPLYING RIBFOS TO ASSESS EXPECTED RIB SUPPORT REQUIREMENTS

Rib support requirements can be calculated empirically by establishing a relationship between the RibFOS of surveyed ribs and the applied rib support densities in these surveyed cases. Table 1 summarizes the bolt specifications of the rib support cases. Mechanical bolts and fully grouted resin bolts were used in these cases. The primary rib support density index (PRSD) was calculated using Equation 2.

$$\text{PRSD} = \frac{\text{Cap} \times L \times N}{S \times H} \qquad \text{(Equation 2)}$$

where Cap is the anchorage capacity in pounds, L is the length of the bolt in feet, N is the number of bolts per vertical rib bolt row, S is the bolt spacing in ft, and H is the rib height in feet.

Figure 6 shows the relationship between the PRSD and RibFOS for all surveyed cases (supported and unsupported). The unsupported cases have zero PRSD. Figure 6 shows that no rib support was required in the surveyed cases for solid coal ribs of RibFOS greater than 1.5 (Good and Very good ribs). The scatter of the calculated PRSD among the surveyed cases is attributed to the lack of standard rib support requirements. All the adopted rib support designs of the surveyed cases were assumed successful even for cases with rib spalls because it was not necessary for the coal operator to change/ modify the rib support plans. A preliminary minimum PRSD line is proposed in Figure 6 by fitting all cases with minimum PRSD. Additional mine observations and data collection would enhance and refine the understanding of the rib performance categories and rib support design line.

Table 1. Rib bolt specifications and supported rib performance (spalling and RibFOS.

| ID	Type	Diameter, in.	Grade, kpsi	Cap, lb	*L*, ft	*S*, ft	*H*, ft	*N*	PRSD, ton/ft	Depth, ft	CPRR	RibFOS	Spall
1	Grout	0.75	60	26,507	4	6	9.0	2	1.96	780	48	1.20	N
2	Grout	0.75	60	26,507	5	12	7.0	2	1.58	780	48	1.20	N
3	Mech	0.625	75	13,500	4	5	10.6	2	1.02	805	70	1.71	N
4	Mech	0.625	75	13,500	4	8	9.7	1	0.35	1,165	70	1.18	Y
5	Mech	0.625	75	13,500	4	8	8.8	1	0.39	1,055	70	1.30	N
6	Mech	0.625	75	13,500	4	8	9.3	1	0.36	900	70	1.53	N
7	Grout	0.63	60	18,408	6	4	8.0	1	1.74	1,650	23	0.28	Y
8	Grout	0.63	60	18,408	6	4	8.5	1	1.62	1,500	23	0.27	Y
9	Grout	0.63	60	18,408	6	4	11.0	2	2.51	1,500	31	0.37	Y
10	Grout	0.63	60	18,408	6	3	11.1	2	3.32	1,500	33	0.39	Y
11	Mech	0.75	60	18,000	5	6	10.3	2	1.46	750	48	1.26	Y
12	Mech	0.75	60	18,000	5	6	10.3	2	1.46	750	51	1.34	N
13	Grout	0.63	55	16,874	3	4	10.0	1	0.63	300	8	0.53	Y
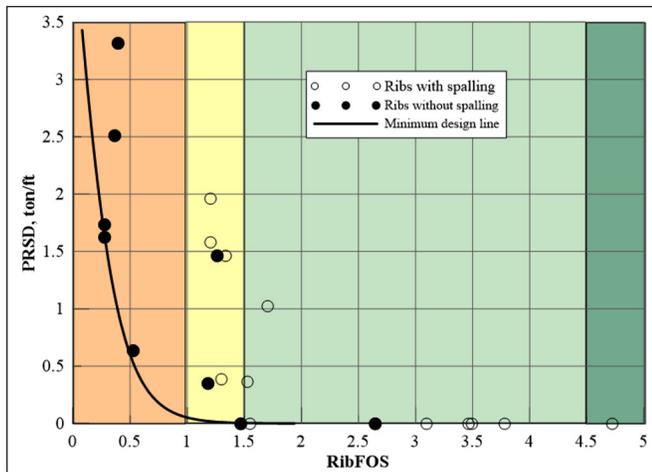
Figure 6. Calculated PRSD versus the RibFOS of surveyed ribs showing preliminary design curves.

PROPOSED PROCEDURE FOR COLLECTING RIB DATA

When conducting a rib performance survey, it is vitally important to check the stability of the roof and ribs at the site before work is to be conducted. If loose rock or coal cannot be scaled safely, then choose an alternate location for accurate data collection. The location should have lithology members in the rib without cracks or separations in the rock or coal with minimal rock dust so that the lithology is easily discernible.

The first sheet of the collecting rib data procedure (see Appendix B) is the general data about the mining conditions and rib geology, including location, entry dimensions, and the rib composition. In the Rib Profile Section (Sheet 1), enter the average block size of the coal that spalls into the entry and note the nature of the coal blocks. The coal brightness profile (Rusnak, 2017) is a quick determination of the brightness and the relative strength of the individual coal units within a rib profile (Figure 7). Most coals will fall under the banded bright or banded dull categories, and the corresponding category is the code that should be written on the sketch of the rib profile. The rib profile is the area to label the type of lithologies present in the rib. Identifying lithologies other than coal, such as sandstone, limestone, shale, and clay, is very important for understanding the strength of the rib and getting a more realistic CPRR value. The Geologic Features section of Appendix B (Sheet 1) is used for noting any geologic feature that is not part of the typical rib section. These anomalies include, but are not limited to, unusually thick parting, sandstone or shale channels, and slips or slicks.

The second sheet (Appendix B) is used to characterize the properties of the lithologic units composing the rib. Depending on the number of units in the rib, additional pages could be required. Lithologic units are only considered if their thickness is greater than 6 in. If the lithologic unit is less than 6 in., then it will be included with the next lithologic unit that is greater than 6 in.

After identifying the lithologic rib units (coal or rock), determine the joint spacing of the rock units as well as the cleat spacing and orientation for coal units. Additional measurements will be needed for coal units, including cleat persistence, strike and dip of the cleat, if water is present, and if the cleating is closed or open. Indicate if samples were collected for UCS testing or if testing has been done.

The final step for lithologic unit characterization is determining the UCS of the rib units. The lithologic strength determination is divided into three possible categories. The categories are listed in order of most to least accurate and include unconfined UCS, Schmitt hammer test or point load test, and lithotype identification (or cleat density if it is coal). If UCS testing is not available, testing with a low-energy Schmidt hammer using a large-area plunger can provide reasonable estimates on lithology strength. Each lithologic unit of coal and rock should be tested at least 10 times and averaged for the rebound number obtained on the Schmidt hammer test for each individual lithologic unit, excluding the lowest and highest set of numbers.
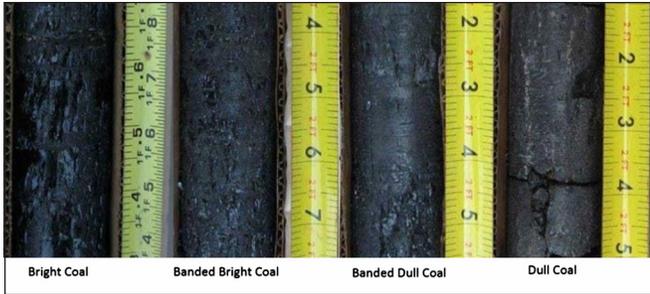
Figure 7. Coal brightness profile (after Rusnak 2017).

Rashed et al. (2018) compared the point load tests and the in situ Schmidt hammer test with the unconfined compressive strength of coal, and the results are expressed in Equations 3 and 4.

UCS, in psi = 20.0 * PLI$_{(50)}$ Equation 3)

UCS, in psi = 215.7 * Schmidt$_{rebound_{number}}$ – 3779   (Equation 4)

where the PLI$_{(50)}$ is the point load strength index for standard size sample (50 mm).

Rusnak (2017) provided a correlation between the UCS and the brightness profile of coal. The megascopic lithotype of coal was divided into four groups: BC, banded BC, banded DC, and DC. The brighter the coal, the higher the cleat density and, hence, the weaker the coal. In contrast, DC typically has a lower cleat density, resulting in a higher strength. Hence, from visual observation an estimate of the intact strength could be obtained. Determination of the intact strength of coal based on coal lithotype is the least accurate method and should be used only if the strength of coal is not available from either direct or indirect methods. The third sheet (Appendix B) is used to report the applicable rib support: type, pattern, and bolt specifications (size, length, and grade). It also contains notes about causes of rib instability and the face advance method. The fourth sheet (Appendix B) is used to classify the observed rib condition by rib deterioration index (RDI). The RDI classifies the observable rib condition into six categories ranked from 1 to 6. The RDI of 1 represents ribs of less than 2 in. of skin spalling, which have vertical rib profiles with intact rock dust. The RDI of 2 represents ribs of 2 to 6 in. of skin spalling, hence, small blocks of sloughed ribs will be observable next to the rib. The RDI of 3 represents ribs of 6- to 12-in. spalling, hence, large blocks of sloughed ribs will be observable next to the rib. Obvious rib damage characterizes ribs of an RDI of 4, in which damage to the pillar could extend from 1 to 2 ft. Positioning next to ribs of an RDI of 5 could be difficult where significant pillar damage could extend from 2 to 4 ft. The last rib category has the highest RDI of 6, in which positioning next to the rib could be impossible.

SAMPLE CASES FOR THE APPLICATION OF THE COAL PILLAR RIB RATING

Two sample cases in a room-and-pillar mine were used to demonstrate the applicability of the proposed rib data collection procedure and the calculations of the CPRR. The mined coal is between 55- and 60-in. thick at depths ranging from 250 to 350 ft. For a few cases, the coal seam could be as high as 10-ft thick. The coal seam is immediately overlain by black shale with intermittent thin layers of sandy streaks. The immediate floor consists of

approximately 2.5 ft of claystone. The selected sample cases in the surveyed mine were at an overburden depth of 300 ft.

Sample case 1 (site ID M1-S4) was for a 10-ft-high rib. Three coal units were identified in this rib. The top unit is defined as banded BC, and the middle and bottom units are BC separated by a clay band. Two types of rib bolts were used at this site: a Hilti screw anchor type and fully grouted 2- to 3-ft-long, no. 5, grade 55 rebar. All rib bolts were anchored in coal and have 17-in.-square pizza pans incorporated for additional skin control. The data collection sheet for sample case 1 is illustrated in Appendix B. The calculation of the CPRR for sample case 1 is provided in Appendix C (case 1). The calculated CPRR of sample case 1 is 9. Despite the shallow overburden depth at sample case 1, it was located at the border between the poor and fair classes (Figure 5). The rib classification agrees with the observed RDI of 3 in Appendix B.

Sample case 2 (site ID M1-S1) was for a 6-ft-high rib. The rib is composed of a single banded bright unit. Rib bolting was not in use at sample case 2 and no rib sloughing was observed. Therefore, a RDI of 1 was selected for sample case 2. The calculation of the CPRR for sample case 2 was illustrated in Appendix C (case 2). The calculated CPRR for sample case 2 is 52. This corresponds to a rib classification of "very good," which agrees with the observed RDI.

CONCLUSIONS

This paper presents the development of a CPRR for solid coal ribs. CPRR is calculated based on in-mine testing, rib surveys, and observations. It provides a useful and practical approach for classifying the performance of solid ribs. The parameters controlling the CPRR are rib homogeneity, bedding condition, face cleat orientation with respect to entry direction, and rib height. Given this new method of classification, mine operators and engineers will be better positioned to make engineering-based decisions concerning coal mine rib control.

The performance of solid coal ribs based on the calculated CPRR and depth of cover was classified into four categories: poor, fair, good, and very good. A survey of solid coal ribs showed that "good" and "very good" ribs do not require primary rib support.

Preliminary rib support design lines to estimate the PRSD for poor and fair rib categories were deduced from the surveyed cases. Additional mine observations and data collection would enhance and refine the understanding of the rib performance categories and rib support design lines.

Future research is proposed to expand the applicability of the CPRR for conditions where thick in-seam parting and solid rock brows are encountered. This will extend the potential for usage of the CPRR to most coal ribs. Application of this analysis technique, in combination with sound engineering-based rib control strategies, should reduce the potential for rib-fall-related injuries and fatalities.

DISCLAIMER

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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APPENDIX A. CALCULATIONS OF CPRR OF SOLID COAL RIBS

The calculation of the CPRR for solid coal ribs is conducted in the following two steps.

Step 1: Calculation of the Basic Coal Pillar Rib Rating (CPRR$_{Basic}$)

The basic coal pillar rib rating CPRR$_{Basic}$ quantifies the effects of rib composition (homogeneity and bedding condition) on the bearing capacity of 11-ft-high rib with face cleat orientation parallel to the entry orientation. The CPRR$_{Basic}$ is calculated using Equation A-1.

$$\text{CPRR}_{Basic} = \alpha_{Homo} + \alpha_{bedding} \qquad \text{(Equation A-1)}$$

Solid coal ribs are usually heterogeneous, that is, composed of coal units with different lithotypes. The rating for rib homogeneity is calculated as follows

$$\alpha_{Homo} = 3.72 \times \left(\frac{\alpha_c}{\alpha_{BC}}\right) \times \left[4 - \frac{1}{r}\right] \qquad \text{(Equation A-2)}$$

$$r = \min\left[\frac{\sigma_k}{\sigma_{k-1}}, \frac{\sigma_k}{\sigma_{k+1}}\right] \text{ and } \sigma_{BC} = 1,250 \text{ psi} \qquad \text{(Equation A-3)}$$

where σ_c, is the weighted average of the uniaxial compressive strength of all units composing the rib, σ_{BC} is the uniaxial compressive strength of bright coal (BC) (σ_{BC} = 1250 psi), r is the rib homogeneity index, σ_k, σ_{k+1}, and σ_{k-1} are the uniaxial compressive strengths of weakest coal unit (k), coal unit ($k + 1$), and unit ($k - 1$) in the rib, respectively. The minimum rib homogeneity index is 0.25.

There are three bedding conditions that could be encountered for solid coal ribs: (1) no bedding, (2) clay-free bedding, and (3) bedding filled with soft clay. The rating for bedding condition is calculated as follows

$$\alpha_{Bedding} = 11.94 \times \frac{\sigma_c}{\sigma_{BC}} - 1.85, \text{ for no bedding}$$

$$\alpha_{Bedding} = 11.45 \times \frac{\sigma_c}{\sigma_{BC}} - 3.85, \text{ for clay-free, or} \qquad \text{(Equation A-4)}$$

$$\alpha_{Bedding} = 5.44 \times \frac{\sigma_c}{\sigma_{BC}} - 1.85, \text{ for no bedding filled with soft-clay}$$

If the rib contains more than one type of bedding condition, then the rating of bedding condition will be assessed based on the minimum rating of those types.

Step 2: Calculate the CPRR adjustments

1. Adjustment of the CPRR for face cleat angle (α_{cleat}) Face cleat adjustment is only applicable for face cleat angles equal to or greater than 20 degrees with respect to entry direction. The CPRR adjustment for cleat orientation is calculated as follows

$$\alpha_{cleat} = 5.0 \times \left[\frac{\left(\frac{\sigma_c}{\sigma_{BC}}\right) - 1}{2.25}\right] \qquad \text{(Equation A-5)}$$

2. Adjustment of the CPRR for rib height (α_H. Rib height adjustment for solid ribs of less than 9 ft is calculated using Equation A-6.

   $\alpha_H = 9 - H$, for homogeneous solid ribs with $\alpha_c \leq 2500$psi

   $\alpha_H = 3 \times (9 - H)$, for heterogeneous solid ribs, or (Equation A-6)

   $\alpha_H = 0$, for solid rib with soft-clay bedding

where H is the rib height in feet.

The coal pillar rib rating for solid coal ribs (CPRR) is obtained by the summation of the adjustment factors to the basic CPRR$_{Basic}$ as follows:

$$\text{CPRR} = \text{CPRR}_{Basic} + \alpha_{cleat} + \alpha_H \qquad \text{(Equation A-7)}$$

APPENDIX B. DATA COLLECTION SHEETS FOR SAMPLE CASE 1

Sheet 2.

Rock units — unit-1 from the roof

			Schmidt hammer (Coal/Rock)
Rock units			
joint spacing	water sensitivity		
> 6 ft	yes/no		
2 – 6 ft			
8 in - 24 in			
2.5 in – 8 in			
< 2.5 in			
	Samples collected		
	Yes/ No	Average rebound number	30.5

Collected from site M1-S1

Coal units — unit-1 from the roof

face cleat	Butt cleat	
spacing (in)	spacing (in)	
persistence	persistence	
Yes/No	Yes/No	
strike (degree)	strike (degree)	
dip (degree)	dip (degree)	
condition	condition	
closed / opened	closed / opened	
Samples collected Yes/ No		

Rock units — unit-2 from the roof

			Schmidt hammer (Coal/Rock)
Rock units			
joint spacing	water sensitivity		
> 6 ft	yes/no		
2 – 6 ft			
8 in - 24 in			
2.5 in – 8 in			
< 2.5 in			
	Samples collected		
	Yes/ No	Average rebound number	23.3

Coal units — unit-2 from the roof

face cleat	Butt cleat	
spacing (in)	spacing (in)	
persistence	persistence	
Yes/No	Yes/No	
strike (degree)	strike (degree)	
dip (degree)	dip (degree)	
condition	condition	
closed / opened	closed / opened	
Samples collected Yes/ No		

same as below (unit-3)

Rock units — unit-3 from the roof

			Schmidt hammer (Coal/Rock)
Rock units			
joint spacing	water sensitivity		
> 6 ft	yes/no		
2 – 6 ft			
8 in - 24 in			
2.5 in – 8 in			
< 2.5 in			
	Samples collected		
	Yes/ No	Average rebound number	23.3

Coal units — unit-3 from the roof

face cleat	Butt cleat	
spacing (in) 4–5	spacing (in) 2–3	
persistence Yes/No	persistence Yes/No	
strike (degree) N65 E	strike (degree) N15 W	
dip (degree) 90	dip (degree) 90	
condition closed / opened	condition closed / opened	
Samples collected Yes/ No		

Sheet 1.

MINE NAME: WKY - 1
SITE #: M1 - S4
Date: 04 - 10 - 2019

General Data

Entry Height:	10 ft	Pillar size (ft):	70 x 70 (c-c)
Entry width:	19 ft	Overburden (ft):	300
Entry Azimuth (deg):	330	Date mined:	Jan, 2017
XCut Azimuth (deg):	30		

Rib Spalling Characteristics

Average Block Size: 6 – 8
Previously cleaned up : Yes / No

Spalling/ sloughing	None	Blocky / Columnar
	Slabby	Columnar
Nature	Slabby / Blocky	Friable
	Blocky	Brow

Coal Brightness Guide

Bright Coal	Banded Bright Coal	Banded Dull Coal	Dull Coal
BC	BBC	BDC	DC

Geologic Features;

Sandstone / Shale Channel	Yes / No
Clay Vein	Yes / No
Slips / Slicks	Yes / No
Soft parting	Yes / No

Ground water condition
- Dry / Damp/ light drip/ Heavy drip/ flowing

SKETCH RIB PROFILE HERE

Roof Material Type / Strength: Black shale / Weak

Rib profile markings (top to bottom):
- Banded Bright Coal (0–1)
- Bright Coal (1–2)
- Soft parting (3)
- Bright Coal (4–6)

HEIGHT MEASUREMETNS HERE, ft (0 to 10)

Floor Material Type/Strength: Claystone / weak

Rib survey location
Entry # — X-cut #
Entry # — X-cut #

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Rib Deterioration Index

1   Sloughage of 2 in 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 2 in to 6 in. Small blocks of sloughage appear on floor

3   Ribs are beyond slight skin damage and is observed from 6 in to 12 in from the original rib line, larger blocks of sloughage appear on floor.

4   Obvious rib damage. Damage to pillars extends 1 to 2 ft on average from the original pillar line.

5   Significant rib damage. Damage extends 2 to 4 ft 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 . Travel is extremely difficult or impossible. Rib sloughage extends across the floor joining sloughage from the opposite

Sheet -4

Sheet 4.

Support Characterization for Rib

RIB	Bolt 1	Bolt 2
Type	Steel / Fiber	Steel / Fiber
Length	24 - 36 inch	Screw bolt
Dimtr/Grade	#5 / 55	/
Anchor(s)	FG / PG / M	FG / PG / M /NA
Plate types	Steel	Steel
Plate sizes	5"*5" x 5/32	5"*5" x 5/32
InstalMethd	Straight/Angled	Straight/Angled
Mesh type	Plastic/Steel / NA	Plastic/Steel /NA
Mesh size	NA	NA
Prop Ht/size	NA	NA

RIB SUPPORT SIDE VIEW: Sketch Here

Roofline

Bolt 1 Bolt 2

Floorline
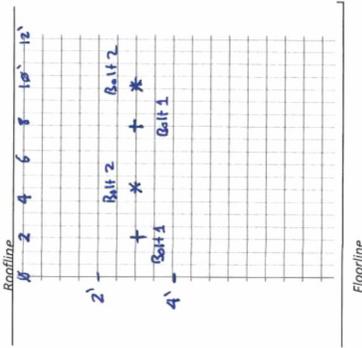
Additional Information Check List

Mining Method: Place Change __X__ Full Face ____ Retreat ____

Roof Bolting Machine: Utilize Mast Tilt for Angle and Rib Drilling: Yes ____ No ____

Time to First Bolt: __NA__ minutes

Rib Bolting Completed as Part of Roof Bolting Cycle: Yes _NA_ No _NA_

Time to Complete Roof and Rib Drilling per Cut: _NA_ minutes

What causes most of your typical rib problems? _Rib instability is primary experienced in the upper portions of the pillar corners, seems to be related to bedding and joints within the immediate Roof_

Other Notable Conditions:

Sheet 3.

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APPENDIX C. CPRR CALCULATION SHEETS FOR SAMPLE CASES

Coal Pillar Rib Rating (CPRR) for Solid Coal Rib

Case 1.

Mine name: WKY - 1
Site ID: M1 - 54
Date: 04 - 10 - 2019

SKETCH RIB PROFILE HERE

Rib unit id (roof to floor)	1	2	3	4	5	6	Height, ft = 10
Thickness, ft	1	2	7				
Strength, psi	2800	021	1032				σ_c, psi = 1002

Rib homogeneity index, r = 0.37   Face cleat orientation w.r.t. entry orientation, deg = 70
Bedding condition: No bedding [ ]   Clay-free bedding [ ]   Bedding filled with soft-clay [X]

σ_c is the weighted average compressive strength of coal rib
Rib homogenity index, r = min[$\frac{\sigma_i}{\sigma_{i-1}}$, $\frac{\sigma_i}{\sigma_{i+1}}$], σ_k is the minimum compressive strength of rib unit (k)

Rib parameters ratings and adjustments

Table 1. Rib homogeneity rating (α_{Homo})

		Bright		Banded bright			Banded dull			Dull	Rating
Lithotype	σ_c (psi)	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	
Rib homogeneity index, r	≤0.25	0	0	0	0	0	0	0	0	0	
	0.3	2	3	4	5	6	7	8	9	10	
	0.5	X 7	10	11	15	18	22	24	28	30	5
	0.7	10	13	15	19	24	29	31	36	38	
	0.9	11	14	16	21	27	32	35	40	43	
	1	11	15	17	22	28	33	37	42	45	

Table 2. Bedding condition rating ($\alpha_{bedding}$)

	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	Rating
No bedding	10	14	16	22	28	34	37	43	46	
Clay-free	8	11	14	19	25	30	34	39	42	4
Soft-clay	4	5	6	9	12	14	16	19	20	

$$CPRR_{Basic} = \alpha_{Homo} + \alpha_{bedding}$$ 9

Table 4. Face cleat orientation adjustment, (α_{cleat}) - Applicable for face cleat angles ≥ 20 deg

		Bright		Banded bright			Banded dull			Dull	
Lithotype	σ_c (psi)	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	Ø
Adjustment		0	1	1	2	3	4	5	6	7	

Table 5. Rib height adjustment, (α_H) - Applicable for ribs with No bedding or Clay-free bedding

Height, ft	≤5	6	7	8	≥9	
Homogeneous rib (r = 1 and σ_c ≤ 2500 psi)	4	3	2	1	0	Ø
Heterogeneous rib	12	9	6	3	0	

$$Adjustments = \alpha_{cleat} + \alpha_H$$ Ø

$$CPRR = CPRR_{Basic} + Adjustments$$ 9

Coal Pillar Rib Rating (CPRR) for Solid Coal Rib

Case 2.

Mine name: WKY - 1
Site ID: M1 - 51
Date: 04 - 10 - 2019

SKETCH RIB PROFILE HERE

Rib unit id (roof to floor)	1	2	3	4	5	6	Height, ft = 6
Thickness, ft	6						
Strength, psi	2800						σ_c, psi = 2800

Rib homogeneity index, r = 1   Face cleat orientation w.r.t. entry orientation, deg = 30
Bedding condition: No bedding [X]   Clay-free bedding [ ]   Bedding filled with soft-clay [ ]

σ_c is the weighted average compressive strength of coal rib
Rib homogenity index, r = min[$\frac{\sigma_i}{\sigma_{i-1}}$, $\frac{\sigma_i}{\sigma_{i+1}}$], σ_k is the minimum compressive strength of rib unit (k)

Rib parameters ratings and adjustments

Table 1. Rib homogeneity rating (α_{Homo})

		Bright		Banded bright			Banded dull			Dull	Rating
Lithotype	σ_c (psi)	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	
Rib homogeneity index, r	≤0.25	0	0	0	0	0	0	0	0	0	
	0.3	2	3	4	5	6	7	8	9	10	
	0.5	7	10	11	15	18	22	24	28	30	25
	0.7	10	13	15	19	24	29	31	36	38	
	0.9	11	14	16	21	27	32	35	40	43	
	1	11	15	17	22	X 28	33	37	42	45	

Table 2. Bedding condition rating ($\alpha_{bedding}$)

	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	Rating
No bedding	10	14	16	22	X 28	34	37	43	46	25
Clay-free	8	11	14	19	25	30	34	39	42	
Soft-clay	4	5	6	9	12	14	16	19	20	

$$CPRR_{Basic} = \alpha_{Homo} + \alpha_{bedding}$$ 50

Table 4. Face cleat orientation adjustment, (α_{cleat}) - Applicable for face cleat angles ≥ 20 deg

		Bright		Banded bright			Banded dull			Dull	
Lithotype	σ_c (psi)	≤1,250	1,650	1,900	2,500	3,100	3,750	4,100	4,700	≥5,000	2
Adjustment		0	1	1	2	X 3	4	5	6	7	

Table 5. Rib height adjustment, (α_H) - Applicable for ribs with No bedding or Clay-free bedding

Height, ft	≤5	6	7	8	≥9	
Homogeneous rib (r = 1 and σ_c ≤ 2500 psi)	4	3	2	1	0	Ø
Heterogeneous rib	12	9	6	3	0	

$$Adjustments = \alpha_{cleat} + \alpha_H$$ 2

$$CPRR = CPRR_{Basic} + Adjustments$$ 52