Investigating the Factors Affecting the Stability of Coal Ribs with In-Seam Rock Partings Through Numerical Simulations

Yuting Xue
Khaled Mohamed
CDC NIOSH Pittsburgh Mining Research Division

ABSTRACT

Researchers from the National Institute for Occupational Safety and Health (NIOSH) have been working on the development of an engineering-based rib control method through the developed coal mass numerical model and strength reduction technique. The Coal Pillar Rib Rating (CPRR) was originally introduced to characterize the quality of solid coal ribs. In this study, the CPRR technique is updated to address coal ribs with in-seam rock partings. The rib factor of safety is a key parameter in calculating the CPRR. Therefore, a parametric study was conducted to determine the factor of safety of ribs with an in-seam rock parting under different mining scenarios and rib conditions. Statistical analysis was carried out on 1,842 cases to investigate the influence of various factors on the stability of coal ribs with in-seam rock partings. The results show that overburden depth, bedding condition, minimum coal strength, coal unit thickness, and parting strength have observable influence on rib stability, while the parting thickness and location were found to have negligible influence on rib stability. The statistical analysis of the data can be helpful for understanding the logic behind the CPRR technique.

INTRODUCTION

The failure of coal ribs is a major hazard in underground coal mines. Over the past decade, rib falls resulted in over 50% of the ground-fall fatalities in U.S. underground coal mines. Extensive studies have been conducted to identify contributing factors, to develop an analysis method and to design effective rib support (Bauer and Dolinar 1999; Colwell 2004; Mark et al. 2009; Pappas and Mark 2012; Jones et al. 2014; Zhang et al. 2017; Mohamed et al. 2019, 2020a; Rashed et al. 2020). However, due to the increasing challenges in the form of increasing overburden depth, multiple-seam interactions, thinner coal beds and thicker in-seam partings, rib falls are contributing more to mineworker fatalities than any other ground fall fatality cause (Mohamed et al. 2020b). To eliminate injury and fatality due to rib falls in underground coal mines, NIOSH researchers are currently developing an engineering-based rib control method based on a large amount of FLAC3D simulations and the calculation of coal rib factor of safety (RibFOS).

A coal mass model was developed to realistically simulate the loading and deformation behaviors of coal ribs (Mohamed et al. 2015). After implementing in FLAC3D, the model was used to simulate a series of triaxial compression tests conducted on coal specimens of different sizes and on large-scale in-situ coal pillars and good agreements were achieved. Zhang et al. (2017) calibrated the coal mass model for scoped rib fractures in a longwall coal mine in the Pittsburgh seam. The results show that the depth of fracture increases with the increasing overburden depth and induced abutment pressure. The coal mass model was also calibrated to predict the rib response during bench mining in a room-and-pillar mine (Sears et al. 2018). The calibrated coal mass model shows good agreement with the field monitoring results in rib displacement and vertical stress in a room-and-pillar mine (Mohamed et al. 2016) and a longwall mine (Rashed et al. 2019).

A strength reduction technique was further proposed to calculate RibFOS of solid coal ribs based on the coal mass model (Mohamed et al. 2019). Different from the conventional methods of reducing the cohesion and tangent of friction angle for Mohr-Coulomb model, the strength reduction with the coal mass model was achieved by varying coal mass scale (CMS). The advantage is that peak strength, residual strength and degradation rate in the post-failure region are all related to CMS through regression analyses, and the variation in CMS leads to the change in these properties of coal mass. A manual procedure written with FISH functions was developed to calculate RibFOS. With the developed strength reduction technique, Mohamed et al. evaluated the stability of solid coal ribs (Mohamed et al. 2019) and developed a Coal Pillar Rib Rating (CPRR) technique to measure the bearing capacity of solid coal ribs (Mohamed et al. 2020b).

There are three main rib categories that could be observed in underground coal mines, as shown in Figure 1, including (a) solid coal

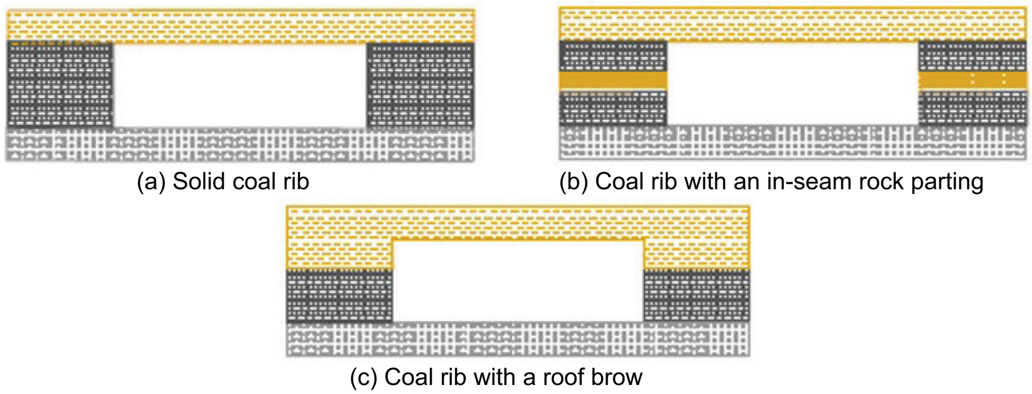

Figure 1. Main rib categories observed in underground coal mines (Mohamed et al. 2019)

rib, (b) coal rib with an in-seam rock parting, and (c) coal rib with a roof brow. The first case has been extensively studied with the development of the CPRR technique for solid coal ribs (Mohamed et al. 2019, 2020b). The present study focuses on evaluating the stability of a coal rib with in-seam rock partings. Although the third case also has rock partings, it may involve the time-dependent deterioration of the coal unit under the rock parting and the formation and failure of the rock parting overhang in the form of a cantilever beam. Thus, the third case with stability analysis of cantilever beam is excluded from this study. For the second case, it was expected to use the proposed strength reduction technique to determine the RibFOS for coal ribs with an in-seam rock parting and further extend the CPRR technique to cover the ribs with in-seam partings.

The coal mass model was carefully calibrated to simulate the mechanical behaviors of rock partings. The laboratory test data of shale, siltstone, and mudstone, the common rock partings observed in underground coal mines were collected. The coal mass model was calibrated for the laboratory data to determine the intact rock parameters. In addition, the scale/size effect incorporated in the coal mass model was calibrated for rock partings. Within the coal mass model, the scale effect was used to obtain the field parameters from the laboratory data. The scale effect of coal was determined through the regression analysis of test data with coal specimens of different sizes, which is not available for shale rocks. Instead, the results of plate-bearing tests with different plate sizes on coal and shale rocks were collected to establish a relationship between peak strength and bearing size for shale rocks. The detailed calibration process can be found in another paper (Xue and Mohamed 2021) and the calibrated properties for rock partings can be found in next section. With the calibrated coal mass model and the strength reduction technique, a detailed numerical study could be conducted to investigate the stability of coal ribs with an in-seam parting under various conditions.

In summary, the calibrated coal mass model for coal and rock partings and the strength reduction technique were used to study the factors affecting the stability of coal ribs with an in-seam parting. The setup of the model, model parameters, and mining scenarios were introduced first. After obtaining all the RibFOS, the influence of various factors, such as overburden depth, mining height, and bedding condition, on the stability of coal ribs with an in-seam parting were analyzed. The statistical analysis of the data can be helpful for understanding the logic behind the updated CPRR technique.

NUMERICAL SIMULATION METHODOLOGY

The methodology of the numerical simulation is detailed in this section. Plane strain models were used for the simulated coal ribs. The setup of the model is shown in Figure 2. It is assumed that the gateroad in the model is orientated parallel to the maximum horizontal stress and the face cleat orientation is parallel to the gateroad orientation. The in-situ stress was estimated with the equations developed by G.S. Esterhuizen (personal communication) and Liu et al. (2016).

The roof and floor are elastic. The coal seam, including the rock parting, is represented by the coal mass model. Interfaces were inserted between roof and coal seam and between floor and coal seam. No interface was used within the ribs. The bedding condition can be either weak or strong when there is change in lithotype. For a weak bedding, a thin layer of soft clay with a thickness of 0.05 m (2 inches) was used in the numerical simulations, and relative displacement can easily occur across the bedding. On the contrary, the strong bedding condition represents the rough contact between the beddings and there is no infilling. Under such condition, the relative displacement across the bedding is highly restricted.

The parametric study considers the practical variation in overburden depth, mining height, coal lithotype and bedding condition. The strength, thickness, and location of the rock partings within the coal ribs were also taken into consideration for the coal ribs with an in-seam rock parting. When the rock parting is located at the bottom of the rib, there are two units, one coal unit and one rock unit. There are three units, one rock unit and two coal units, when the rock parting is located at the center of the rib. For a three-unit rib, the lithotype of the two coal units can be the same or different. The rock parting was not placed at the top of the rib, which is the third rib category in Figure 1 (c). A detailed plan for the parametric study can be found in Table 1. During the simulations, different conditions/parameters in Table 1 were combined to reproduce different combinations of rib composition and mining condition.

Three coal lithotypes, namely Bright Coal (BC), Banded Bright Coal (BBC) and Dull Coal (DC), were used in the simulations, and there were two types of rock partings, namely Rock-18.1 parting and Rock-38.4 parting, which have intact rock strength of 18.1 MPa and 38.4 MPa, respectively. The mechanical properties of the coal,

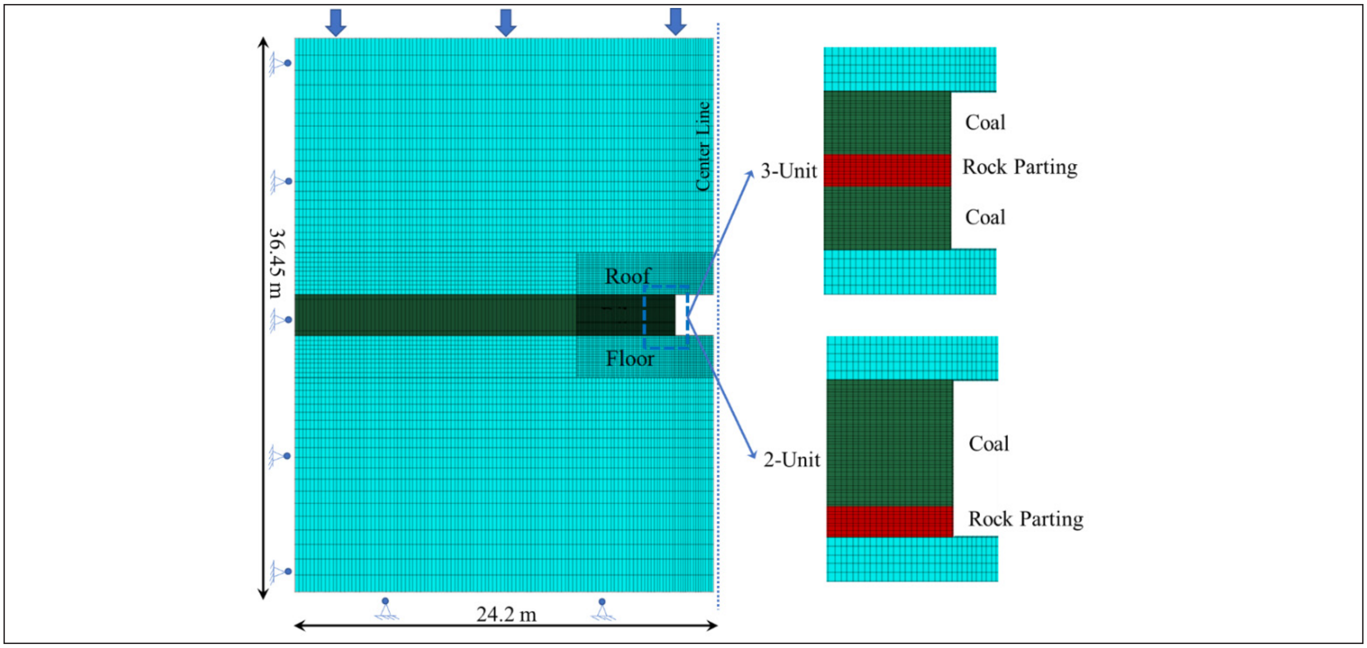

Figure 2. Setup of the plane strain model

Table 1. Detailed numerical simulation plan

Parameter	Condition/Value
Overburden Depth (m)	90, 135, 180, 225, 270, and 315
Mining Height (m)	1.5, 2.1, 2.7, and 3.3
Coal Lithotype	BC, BBC and DC
Rock Parting Strength	Rock-18.1 and Rock-38.4
Rock Parting Location	Bottom and Center
Rock Parting Thickness	20%, 35%, and 50% of the mining height
Bedding Condition	Weak and Strong

NOTE: Some special cases with one coal unit consisting of two coal lithotypes were run to study the stability of ribs with rock partings and heterogeneous coal unit.

rock parting, interfaces, roof, and floor used in the simulations are summarized in Table 2.

RESULTS AND DISCUSSION

The developed CPRR is a technique to measure the bearing capacity of coal ribs. The CPRR is calculated as the scaled area under the relationship between RibFOS and the ratio of in-situ horizontal stress to vertical stress. Any factors that can affect RibFOS and in-situ stress potentially affect the CPRR value. Based on the simulation plan in Table 1, a total of 1,842 models were run with the strength reduction technique to determine the RibFOS under different mining scenarios and rib conditions. A statistical analysis was then conducted to investigate the influence of various factors on RibFOS. The significance of the influence of one factor on RibFOS was potentially reflected on CPRR calculation. More points are added/deducted for more important factors. The statistical analysis will be helpful for understanding the logic behind the CPRR technique.

Overburden Depth

Overburden depth is identified as one of the significant geologic factors that contribute to hazards related to rib falls in the Roof Control Plan Approval and Review Procedures Handbook (MSHA 2013). The statistical analysis of the 23 rib-fall fatalities that occurred between 1996 and 2010 shows that 18 (76%) occurred with overburden depth above 700 ft (Mohamed et al. 2020b). Like any static structure, the stability of coal ribs is mainly determined by two factors: the stress applied onto the rib and the strength of the rib (Peng et al. 2019). CPRR is an approach to quantify the quality of the coal ribs, which demonstrates the bearing capacity or strength, while overburden depth is the main factor affecting the in-situ stress and thus is a good indication of the load. Abutment pressure can be another factor affecting the load (Zhang et al. 2017), which is out of the scope of this study. Six overburden depths were used in the numerical study and the box plots of RibFOS at different overburden depths are presented in Figure 3.

The box plots of RibFOS at different overburden depths show that, in general, RibFOS gradually reduces with the increase in overburden depth. It can be seen from the trend of median and mean values with overburden depth that the mean value reduces from 2.97 at 90 m (300 ft) to 0.90 at 270 m (900 ft). Therefore, overburden depth is one key factor affecting rib stability. At the same time, Figure 3 shows that the influence of overburden depth gradually decreases with increasing overburden depth. This is because the reduction in the median and mean values of RibFOS decrease with increasing overburden depth. Due to the difference in various conditions, like bedding condition, coal lithotype, rock parting, and rib height, there is high variation in RibFOS in Figure 3; however, the general trend of reducing RibFOS with increasing overburden depth is clear.

Table 2. Mechanical properties used in the simulations

Coal and Parting Properties					
Property	**BC**	**BBC**	**DC**	**Rock-18.1**	**Rock-38.4**
Bulk modulus (GPa)	0.55	1.70	2.34	2.78	3.89
Shear modulus (GPa)	0.33	1.02	1.41	2.08	2.92
Intact compressive strength (MPa)	8.58	19.70	35.00	24.00	24.00
Coal Mass Scale	20	20	20	20	20
Exponent *a*	0.5	0.5	0.5	0.42	0.42
Critical shear plastic strain	0.06	0.055	0.055	0.01	0.01
Critical tensile plastic strain	0.0033	0.001	0.001	0.001	0.001
Joint friction angle (degree)	25	25	25	10	10
Coal Seam/Roof and Coal Seam/Floor Interface Properties					
Friction angle (degree)	30	Shear Stiffness (MPa)	26	Cohesion (MPa)	0.57
Tension (MPa)	0.11	Residual cohesion (MPa)	0.35	Residual friction (degree)	14
Normal stiffness (GPa/m)	78	Residual tension (MPa)	0.07		
Roof and Floor Properties					
Property	Roof	Floor			
Young's modulus (GPa)	15	8			
Poisson's ratio	0.26	0.26			

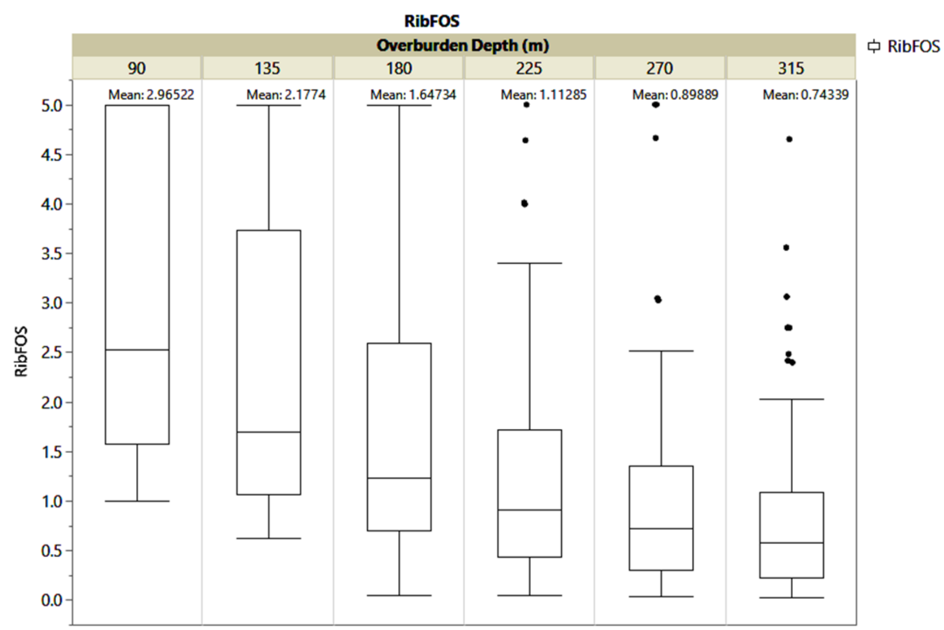

Figure 3. Box plot of RibFOS at different overburden depths

Bedding Condition

Figure 4 shows that the bedding condition has significant influence on the stability of coal ribs. There is a 0.5-point reduction in the mean value of RibFOS without extracting the influence of any other factors, such as overburden depth and rib height. Generally, a stable coal rib has a RibFOS value above 1.0. The 0.5-point difference may lead to completely different rib performances. In order to understand the influence of bedding condition, two models were compared where the only difference between them is the presence of weak bedding condition between coal and rock in one model. The rib height is 3.35 m (11 ft) with an overburden depth of 91 m (300 ft). They are three-unit ribs with BC (0.84 m),

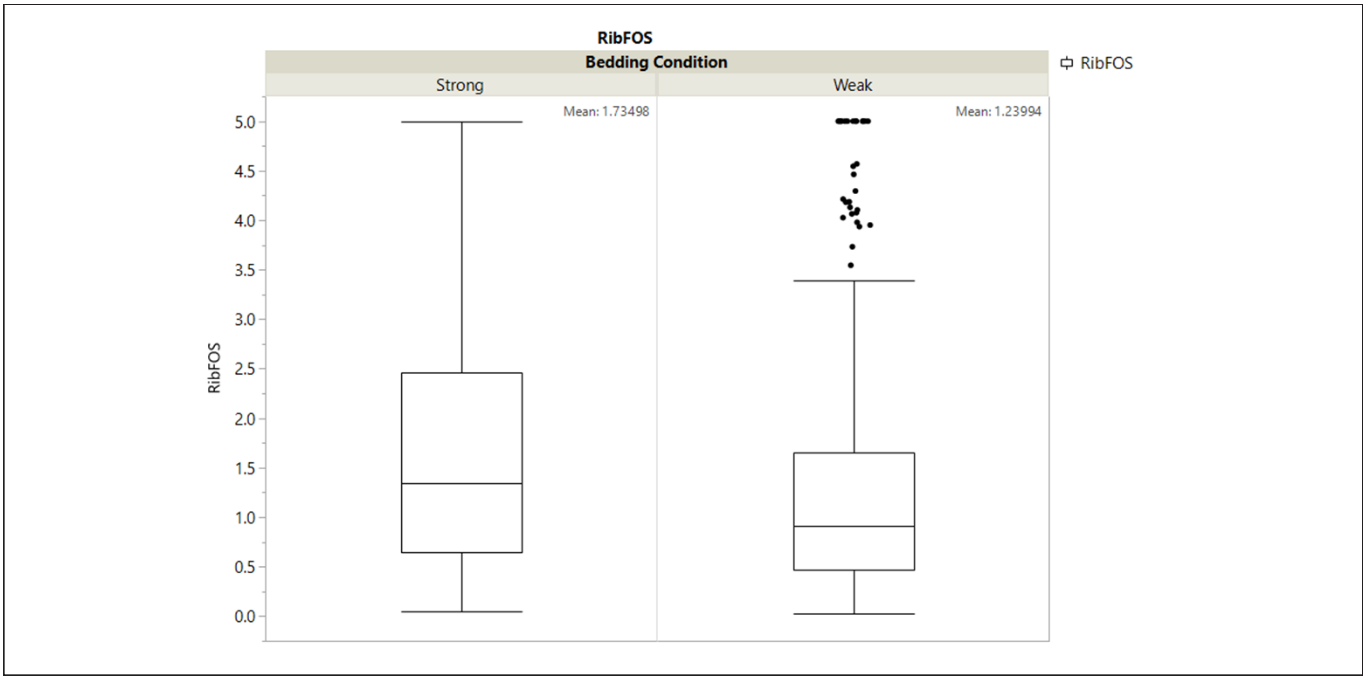

Figure 4. Box plot of RibFOS with different bedding conditions

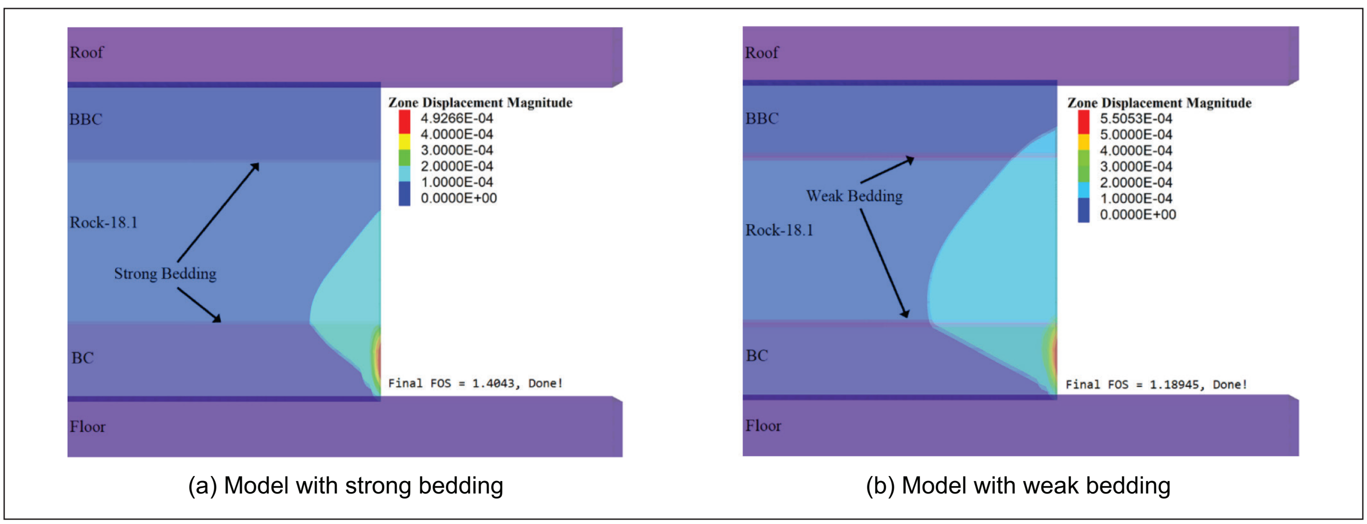

Figure 5. Displacement contour of the models with different bedding conditions with 3.35 m rib height at 91 m depth

rock-18.1 (1.67 m), and BBC (0.84 m) from the bottom to the top. The contour of the model displacement magnitude is presented in Figure 5.

For both cases, the bottom BC unit is the weakest within the heterogeneous rib, and large displacement concentrates within the BC unit in the form of rib spalling. Failure could further develop into the BC unit, deteriorating the stability of the whole rib. Figure 5 shows that, starting from the BC unit, the displacement within the rock parting and BBC unit are mobilized. However, differences in the distribution of rib displacement can be observed with the presence of weak beddings. An in-seam rock parting breaks the coal ribs into two shorter coal ribs. The behavior of these two shorter coal ribs is affected by the rock parting and the bedding condition. When the bedding is rough and strong, the relative displacement across the bedding is restricted. The stiffer rock parting restricts the displacement of the softer BC unit, and less maximum displacement is achieved. From this point of view, the presence of rock parting improves the stability of the coal rib. In contrast, the weak bedding condition reduces the restriction across the bedding and the rock parting, located between weak beddings at the center of the rib, is easy to deform. As shown in Figure 5(b), the displacement within the rock parting further affects the coal units. For the model with weak beddings, a larger area is mobilized within the ribs and larger maximum displacement magnitude is achieved within the BC unit. The RibFOS drops from 1.40 to 1.19 when the bedding condition varies from strong to weak. Therefore, weak bedding condition plays an important and adverse role in controlling rib spalling and stability. This makes the bedding condition an important factor in the CPRR calculation.

Minimum Coal Unit Strength

Coal strength was found to be important in determining rib performance (Colwell 2006; Seedsman et al. 2009; Stone 2015; Mohamed et al. 2020b). When developing CPRR for solid coal ribs, the weighted-average strength was found to be highly correlated with CPRR and was used to assign the Basic CPRR value (Mohamed et al. 2020b). Generally, the rib with higher weighted-average strength has higher CPRR value, indicating that the rib has higher bearing capacity. Within the studied range of parting thicknesses, however, the parting thickness is found to have neglectable influence on determining RibFOS, which will be discussed in Section 3.6. The presence of a rock parting within the coal seam affects the rib height and further affects the weight-average strength of the whole rib. Thus, the updated CPRR technique will focus on each coal unit separated by the rock parting, and each coal unit is treated as a shorter solid coal rib. The CPRR value for each coal unit is calculated separately and compared to find the minimum value, which is used to represent the CPRR value of the whole rib. This is based on the phenomenon observed when updating the algorithm for CPRR calculation to cover coal ribs with in-seam rock partings. When the minimum coal strength in the rib is BC, the maximum CPRR value that can be obtained is 40. When the coal unit with minimum coal strength is homogeneous BBC or DC, the CPRR value can be above 90. This indicates that the stability of the whole rib is highly dependent on the weakest coal unit. Thus, statistical analysis was conducted to determine the influence of minimum coal unit strength on rib stability. The box plots of RibFOS with different ranges of minimum coal strength are shown in Figure 6. It should be noted that when there is more than one coal lithotype, the coal unit strength is represented by the weighted-average coal strength in Figure 6.

Figure 6 shows that there is significant influence of minimum coal unit strength on the stability of coal ribs. When the minimum coal unit strength is less than 8.6 MPa, the mean value of RibFOS is 0.71 with most of the data (3/4) located below 1.0, regardless of the overburden depth. For the other two strength ranges, the mean values of RibFOS are 1.78 and 2.83, respectively, with most data located above 1.0. It indicates stable rib condition for most cases when the weakest coal unit is BBC or DC. Although RibFOS can be affected by other factors, like overburden depth and bedding condition, Figure 6 shows a clear trend that coal rib stability is highly dependent on the weakest coal unit and thus, the reinforcement of the weakest coal unit is the key for rib support.

Rib Height and Coal Unit Thickness

Rib height is another significant geologic condition that contributes to rib fall hazards in underground coal mines in the Roof Control Plan Approval and Review Procedures Handbook (MSHA 2013). The statistical analysis of the 23 rib-fall fatalities that occurred between 1996 and 2010 shows that 22 (96%) occurred with at least 7-ft rib height (Mohamed et al. 2020b). Four rib heights were used in the numerical study, and the box plots of RibFOS with different rib heights are shown in Figure 7. It should be noted that the rib heights are the sum of thickness of coal unit(s) and rock parting.

The analysis of the influence of bedding plane on rib stability in Section 3.2 already demonstrates that the weak bedding condition affects the rib displacement distribution and potentially affects the influence of rib height on rib stability. When the bedding condition varies, different trends are observed in the box plots of RibFOS with different rib heights in Figure 7. The box plots of RibFOS with strong bedding condition show that the median and mean values gradually decrease with the increase in rib height from 1.5 m (5 ft) to 2.7 m (9 ft). Above 2.7 m (9 ft), there is no observable change in RibFOS with increasing rib height. This coincides with the result of solid coal ribs where 2.7 m (9 ft) was used as the limit to conduct rib height adjustment for CPRR (Mohamed et al. 2020b). From the

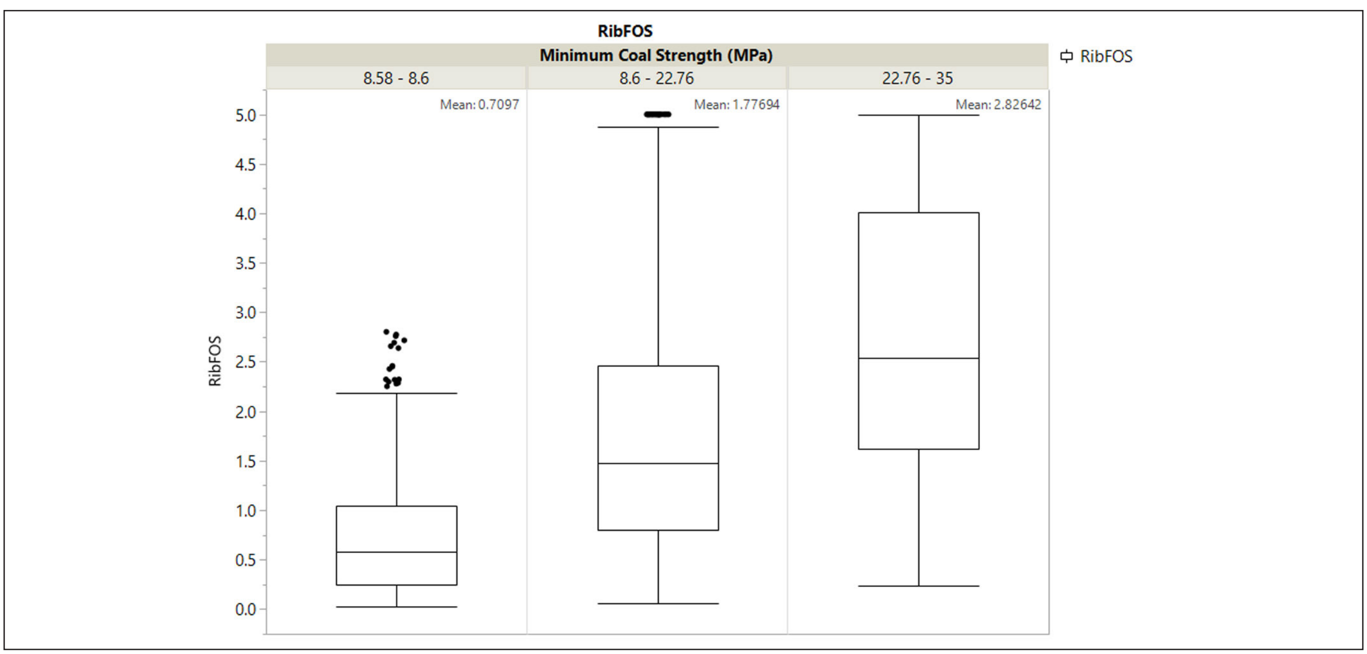

Figure 6. Box plot of RibFOS with different minimum coal unit strengths

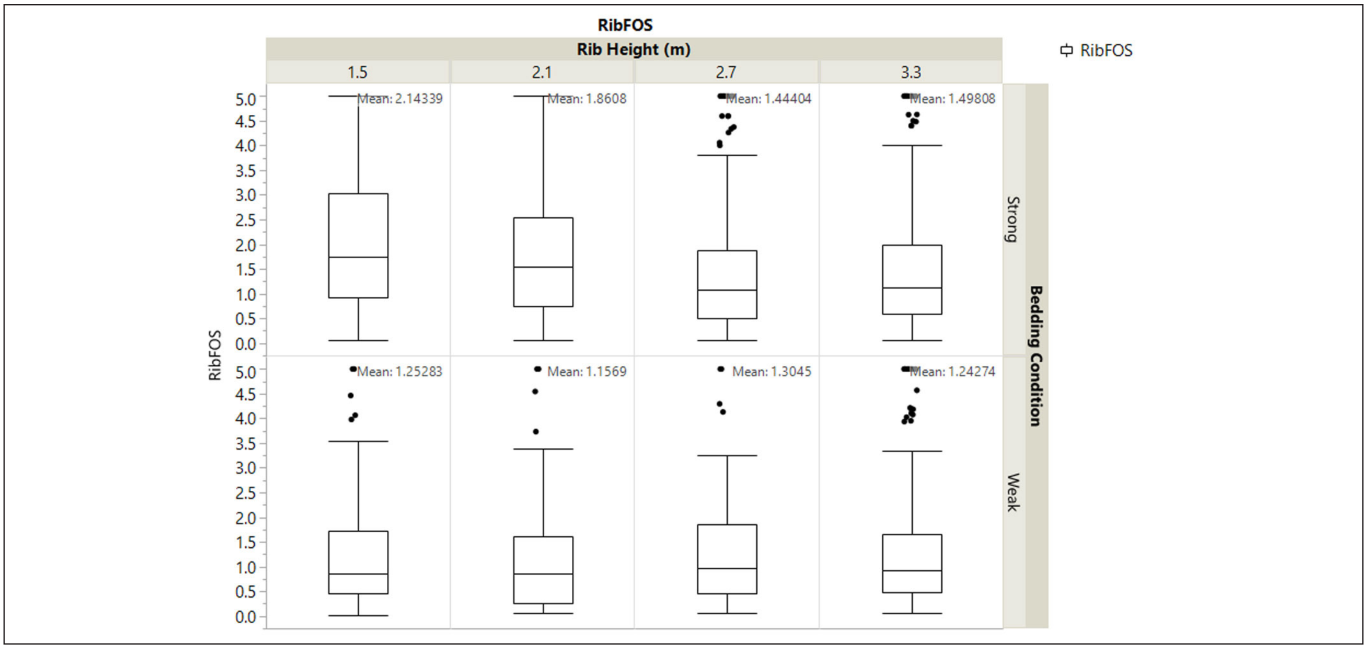

Figure 7. Box plot of RibFOS with different rib heights

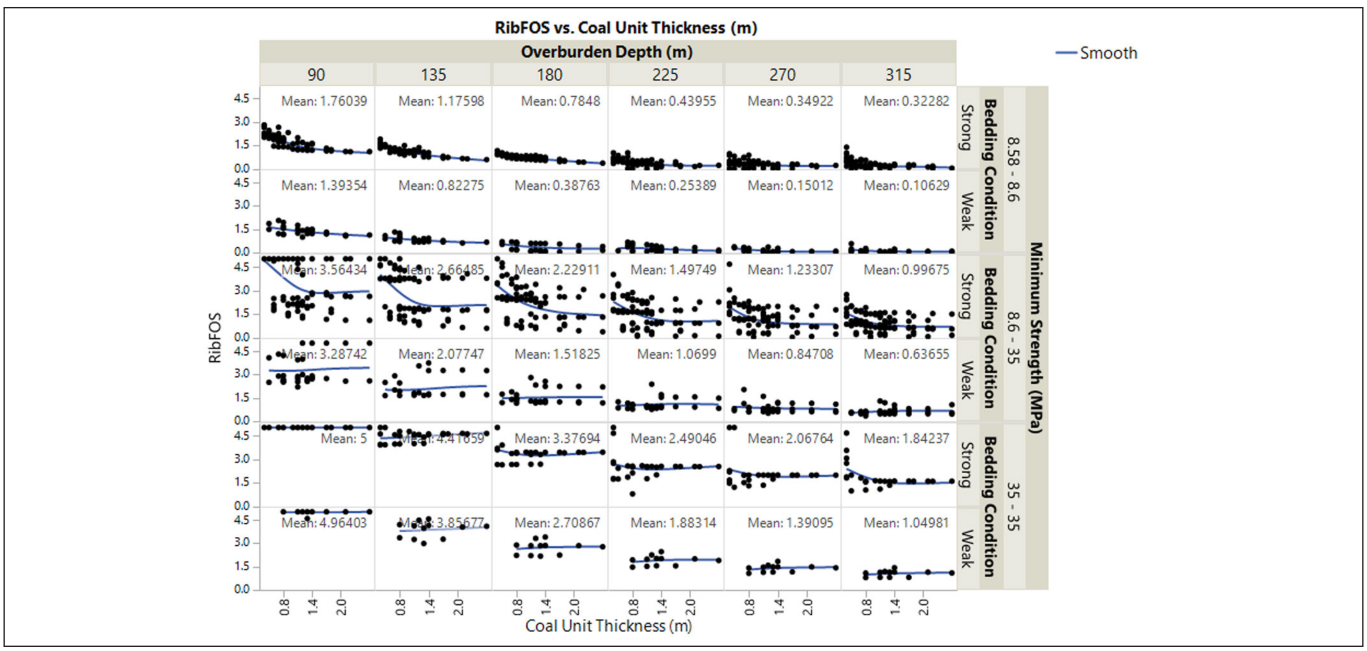

Figure 8. The relationship between RibFOS and coal unit thickness under different conditions

box plots of RibFOS with weak bedding condition, the results show that there is no clear influence of rib height on RibFOS, indicating that the influence of rib height on RibFOS is reduced or eliminated by the presence of soft clay.

However, the parting thickness is found to have negligible influence on RibFOS in Section 3.6; at the same time, the presence of rock parting within the coal seam affects the rib height. This makes it impractical to include the influence of rib height into the updated CPRR calculation. Since the updated CPRR technique will treat each coal unit as a shorter solid coal rib, it is rational to analyze the relationship between RibFOS and coal unit thickness, which is presented in Figure 8. It should be noted that, when there are more than one coal unit and the coal unit strengths are different, the thickness of the unit with minimum coal unit strength is used. This is the reason the minimum coal strength is used to categorize the data in Figure 8.

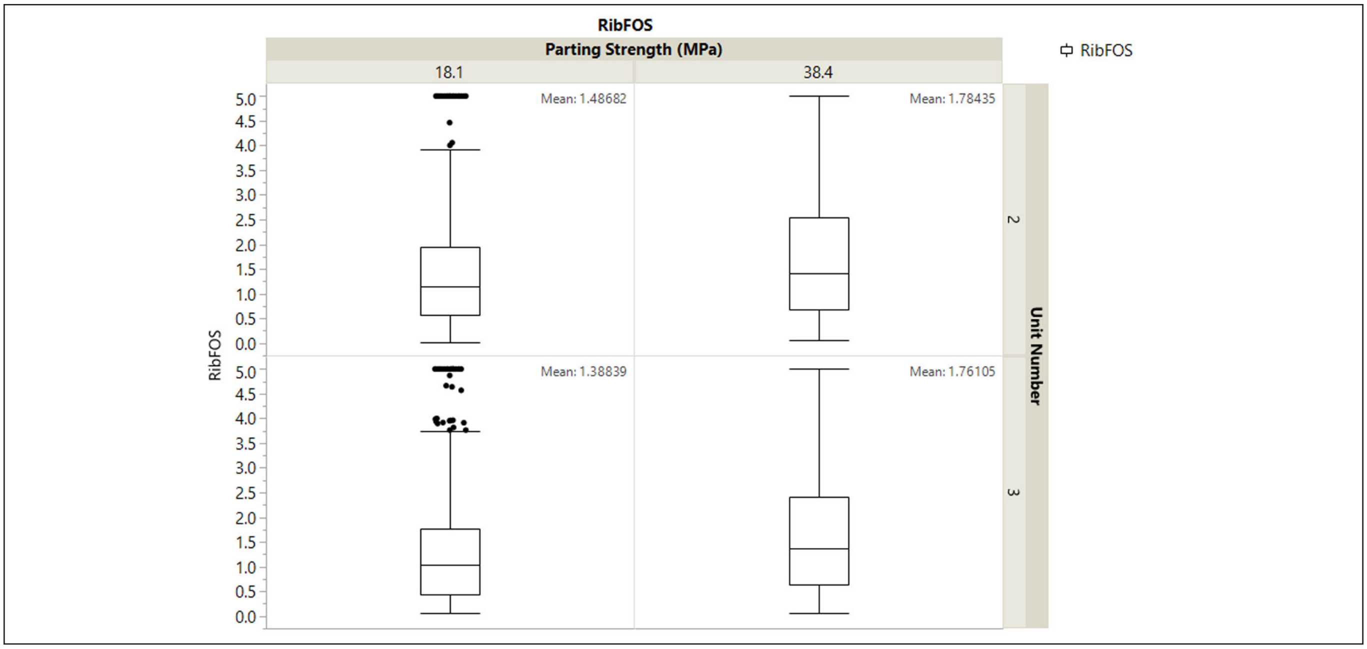

Figure 9. Box plot of RibFOS with different rock parting strengths and locations

Figure 8 shows that, similar to the influence of rib height on RibFOS, the coal unit thickness has negligible influence on RibFOS when the bedding is weak, regardless of the minimum coal unit strength. However, when the bedding is strong, there is observable influence of coal unit thickness on RibFOS, especially when minimum coal unit strength is BBC. It is found that RibFOS gradually decreases with the increase in coal unit thickness and there is a limit, after which there is no more reduction in RibFOS. It appears that the limits vary with the minimum coal unit strengths, indicating that the influence of coal unit thickness on RibFOS varies depending on the minimum coal unit strength. When the minimum coal unit strength is BBC, the influence is most significant, and the limit is highest.

Strength and Location of Rock Parting

As part of the rib, the strength and location of the rock parting are expected to affect the stability of the whole rib. Based on the collected data for shale rocks (shale, siltstone, and mudstone), the common rock partings observed in underground coal mines, two parting strength categories have been identified to represent the rock partings (Xue and Mohamed 2021). The parting location can be reflected by the unit number in the numerical study. When there are two units, one unit is rock and the other one is rock parting; the rock parting is always located at the bottom of the rib. For one rib with three units, two units are coal and the other one is rock parting; the rock parting is always located at the center of the rib. The box plots of RibFOS with different rock parting strengths and locations are shown in Figure 9.

Figure 9 shows that there is noticeable influence of parting strength and negligible influence of parting location on rib stability. There is about a 0.3-point increase in RibFOS when the rock parting strength increases, regardless of the parting location. At the same time, when the rock parting moves from bottom to center of the ribs, the influence on RibFOS is neglectable. Based on these observations, parting strength is included in the updated CPRR technique to cover coal ribs with in-seam rock partings, while the location of rock parting is excluded.

Parting thickness

The box plots of RibFOS in Figure 10 show that there is no clear trend in the influence of parting thickness on rib stability, and as a result, the parting thickness will not be included in the calculation of the updated CPRR technique. The exclusion in the CPRR calculation does not means that the rock parting thickness has no influence on the CPRR calculation. The presence of rock parting separates the whole rib into different coal units. For a certain rib height, the increases in rock parting thickness reduce the thickness of coal units, potentially affecting the CPRR adjustment for coal unit thickness.

To exclude the rock parting thickness, the CPRR calculation will be conducted on each coal unit separated by the rock parting(s). Each coal unit will be treated as a shorter solid coal rib, and CPRR will be calculated based on the weighted-average strength, heterogeneity, bedding condition, and coal unit thickness. The minimum CPRR value of the coal units will be used to represent the CPRR of the whole rib. One advantage is that the approach makes the updated CPRR technique applicable to the ribs with more than one rock parting. During the parametric study, only one in-seam rock parting was studied. It is common to have ribs with multiple rock partings. When CPRR is calculated for each coal unit separated by the rock parting(s), the findings from this study and the updated CPRR technique can be utilized for coal pillar ribs with multiple rock partings.

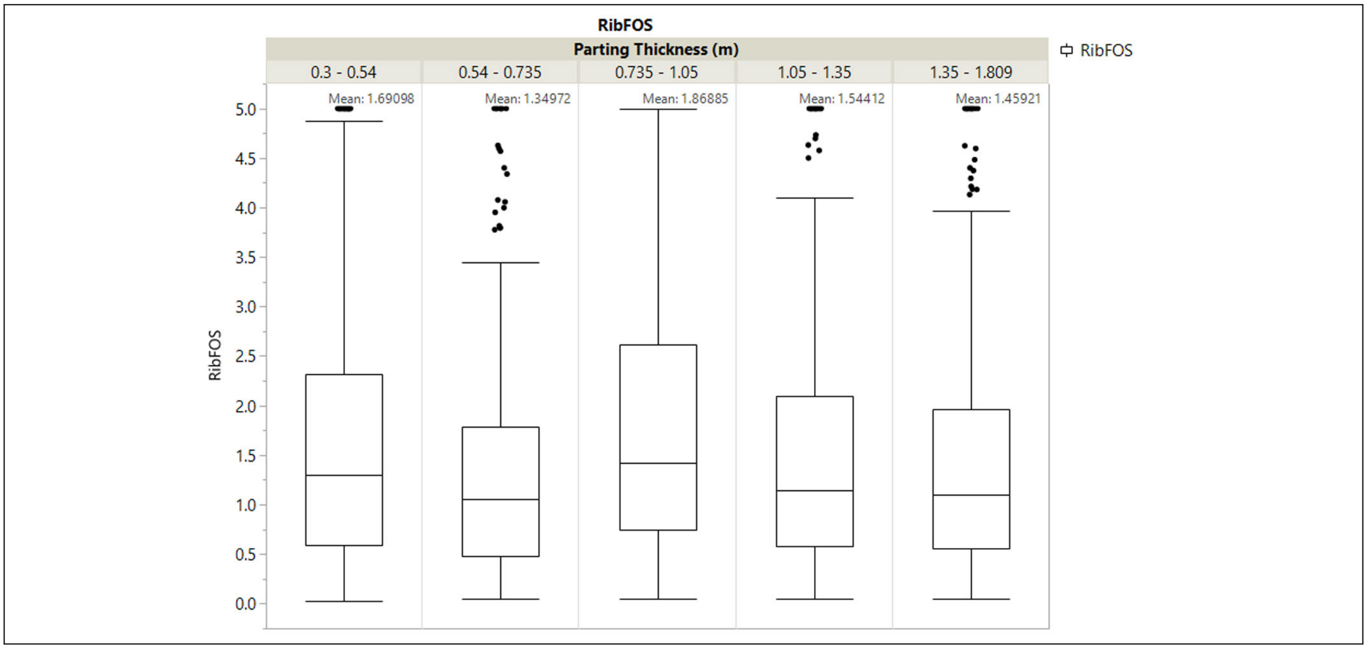

Figure 10. Box plot of RibFOS with different parting thicknesses

CONCLUSIONS

NIOSH researchers have been working on the development of an engineering-based rib control method through the numerical simulations with the developed coal mass model and strength reduction technique. The CPRR technique has been proposed for a solid coal rib. When updating the algorithm for CPRR calculation to cover coal ribs with in-seam rock partings, a parametric study was conducted to determine the RibFOS for coal ribs with in-seam rock partings under different rib compositions and mining conditions.

The statistical analysis of the simulation results shows that overburden depth, bedding condition, minimum coal strength, coal unit thickness and parting strength have observable influence on rib stability. Due to increasing in-situ stress, RibFOS reduces with the increase in overburden depth. The weak bedding condition shows an adverse effect on rib stability and reduces or eliminates the influence of rib height and coal unit thickness by affecting the rib displacement distribution. When the bedding is strong, there is observable influence of coal unit thickness on RibFOS, especially when minimum coal unit strength is BBC. The RibFOS gradually decreases with the increase in coal unit thickness and there is a limit, after which there is no more reduction in RibFOS. In addition, the rib stability is highly dependent upon the minimum coal strength, representing the weakest unit of the rib. The parting strength also shows noticeable influence on rib stability, and RibFOS increases with parting strength. However, parting thickness and location have negligible influence on rib stability and thus are excluded from the CPRR calculation. The findings from this study can be helpful for understanding the influence of various factors on rib stability and the logic behind the CPRR technique.

DISCLAIMER

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

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