

Analyzing the effect of bolt spacing on coal rib stability through numerical simulation

Xue, Y. and Mohamed, K.M.

National Institute for Occupational Safety and Health, Pittsburgh, PA, USA

Copyright 2024 ARMA, American Rock Mechanics Association

This paper was prepared for presentation at the 58th US Rock Mechanics/Geomechanics Symposium held in Golden, Colorado, USA, 23-26 June 2024. This paper was selected for presentation at the symposium by an ARMA Technical Program Committee based on a technical and critical review of the paper by a minimum of two technical reviewers. The material, as presented, does not necessarily reflect any position of ARMA, its officers, or members. Electronic reproduction, distribution, or storage of any part of this paper for commercial purposes without the written consent of ARMA is prohibited. Permission to reproduce in print is restricted to an abstract of not more than 200 words; illustrations may not be copied. The abstract must contain conspicuous acknowledgement of where and by whom the paper was presented.

ABSTRACT: Rib falls pose a major safety risk in underground coal mines, and there is currently no standardized approach for rib support design in the U.S. coal mines. To tackle this issue, a standalone application, Design of Rib Support (DORS), was developed for rib stability assessment and rib support design under development load. The last step of the rib support design in DORS was to calculate the bolt spacing from the recommended rib support density, bolt grade and number of bolts. Notably, the change of bolt grade and the number of bolts significantly affects bolt spacing, but it remains unclear how varying bolt spacing impacts the supported rib factor of safety (RibFOS). In this study, numerical simulations were conducted to analyze the influence of bolt spacing on coal rib stability. Initially, plane-strain 3DEC models were used to estimate the RibFOS of unsupported solid coal ribs, serving as a baseline for rib stability evaluation. Subsequently, 3D models were conducted for supported solid coal pillar ribs. A parametric study was conducted to investigate the influence of bolt spacing on the supported RibFOS under different conditions, such as varying overburden depths and bolt lengths. The simulation results show a general trend of reduced supported RibFOS with the increase in bolt spacing, and the trend can be further affected by varying conditions. The variation of supported RibFOS with bolt spacing can be quantified by normalizing the supported RibFOS to its values with a bolt spacing of 0.3 m. Finally, when the rib support density was maintained by varying bolt grade and bolt spacing, the influence of bolt spacing can still be observed in the results. Thus, it is essential to consider this bolt spacing effect in rib support design.

1. INTRODUCTION

Coal pillars are intentionally retained during mining to support overlying rock strata and prevent mine roof collapse and play a crucial role in maintaining the structural integrity of underground coal mines. When coal is extracted from a seam, the overburden load and/or abutment load tend to transfer and redistribute to the remaining pillars, leading to excessive pillar load. Coal ribs are the walls of coal pillars with free surfaces. Without rib support, the coal mass has low or no confinement, leading to lower strength and less constraint for deformation. The occurrence of rib falls presents severe safety risks, encompassing injuries, fatalities, and equipment damage. According to the Mine Safety and Health Administration (MSHA), statistics during the 10-year period between 2010 and 2019, rib-fall accidents contributed to 45.2% of the ground-fall fatalities (Rashed et al. 2022). Thus, rib falls pose a major safety hazard in U.S. underground coal mines.

Due to the versatility, effectiveness, and relatively straightforward installation process, rib bolting systems have been widely used to enhance the rib stability and prevent hazardous collapse in underground coal mines. The effectiveness of the rib bolting systems mainly depends on the rib support design, which can be affected by coal rib composition, local geological condition, and

load applied onto the ribs. Inadequate support design could result in insufficient reinforcement and subsequent instability. However, the rib bolting design in U.S. underground coal mines currently relies on a trial-and-error approach, which falls short of adequately mitigating the risk of injuries and fatalities caused by rib falls. Researchers from the National Institute for Occupational Safety and Health (NIOSH) have been working on the development of an engineering-based approach for coal rib stability analysis and bolting design with the purpose of eliminating the injuries and fatalities resulted from rib falls.

Based on the extensive numerical simulations and field studies, a standalone application called Design of Rib Support (DORS) was developed for rib stability analysis and primary rib support design (Mohamed et al. 2021). The user interface of the application with an input section and an output section is shown in Fig.1. The DORS application can assess the stability of unsupported ribs at the middle of coal pillars subjected to development loading by calculating the unsupported RibFOS with some basic parameters. The DORS application can also suggest rib support designs based on rib surveys conducted in eastern U.S. coal mines. The collected data and calculated unsupported RibFOS suggest an unsupported RibFOS value of 1.5 to delineate whether rib support is recommended. When the unsupported RibFOS

rib subject to elevated vertical stress conditions (Colwell and Frith 2021). If not controlled, the vertical stress-driven column behavior can lead to excessive deformation, failure, and eventual collapse. Therefore, the slender columns should be representatively accounted for in the numerical study for rib stability assessment and associated ground support design. According to field observations, the average fractured zone depth along the rib is typically in the range of 0.5–2.0 m, and therefore, the first 4 m of the coal pillar at its rib side was modeled using face-cleat sets to allow the formation of slender columns in the rib.

Regarding the study of bolt spacing effect, there are mainly two approaches with numerical simulation. The first one is to scale the bolt properties based on the spacing. This is the common method that has been used for 2D or plane-strain models, for example the UDEC program. In general, the UDEC model represents a one-unit section, and if the bolts are spaced other than one unit, the input (stiffness, moduli, and strength) and results (force and stress) are scaled to represent the spacing internally in UDEC (Itasca Consulting Group 2010). If the one-unit section is 1-m thickness and the bolts are spaced every 3 m, only 1/3 of a bolt is considered to be used in each one-unit section in UDEC. The problem with this method is that the bolt is equally applied onto these unit sections. The second method is to build three-dimensional models and install the bolts with desired spacing. The model is symmetric along the vertical plane at the center between two bolts and the simulated model in this study is the slice between two vertical planes. Starting from the model in Fig.2, it can be extended to different thicknesses along the out-of-plane (Y-axis) direction to simulate varying bolt spacing. The bolt is assumed to be installed at the center along the out-of-plane direction and a symmetric boundary condition can be applied onto the boundaries along the Y direction. This is more realistic than the first approach. Since the running time is still acceptable, the second method with the model in Fig.2 was extended to different thicknesses and was used for the parametric study.

The model was initially brought to equilibrium under the in-situ stress conditions before mining. Once the model was excavated, the reaction force around the boundary was measured and the same force was applied to the boundaries. This reaction force was then nonlinearly reduced to simulate the realistic softening response of the excavation boundary. During this unloading/relaxation process, the state of the elements in the coal ribs was monitored, and the rib supports were installed once the elements started to yield. Furthermore, the RibFOS was calculated with the previously proposed strength reduction method, where the coal mass scale of the coal mass model was varied to obtain the critical stability condition (Guner et al. 2023). A displacement-based

stability criteria was used to define rib stability, and it was established by defining a displacement threshold based on the realistic rib deformation limits in the field. A mobilized zone was defined with 5-mm lateral deformation, and if the depth of the mobilized zone exceeds 25 cm, the rib was classified to be unstable. During the strength reduction modeling, the coal mass scale was varied to make the mobilized zone to be 25-cm deep.

2.2 Cable Structural Elements in 3DEC

Cable structural elements were used to simulate the rib bolts in the study (Kirmaci et al. 2023). The main objective of rib bolting was to reinforce the spalling rib by constraining the buckling of the slender columns, and thus, the axially directed frictional interaction between bolts and the surrounding coal mass plays the key role. Under this circumstance, the tensile capability of the bolts, rather than the bending moment, is important.

As shown in Fig.3, each cable structural element is defined by its geometric, material, and grout properties. A cable element is assumed to be a straight segment of uniform cross-sectional and material properties lying between two nodal points. The cable element behaves as an elastic, perfectly plastic material that can yield in tension and compression but cannot resist a bending moment or shearing across the elements. A bolt can be grouted to the surrounding coal mass such that force develops along its length in response to relative motion between the bolt and the surrounding coal mass. The grout can fail in shear with excessive difference in the displacement between the bolt and the surrounding rock/coal mass. The grout behaves as an elastic, perfectly plastic material, with its peak strength being confining stress dependent, and with no loss of strength after failure. Table 1 shows the properties for the cable structural elements that were used in the simulation. They were calibrated with bolt pull-out tests in the ribs and have been used in other studies (Guner et al. 2023).

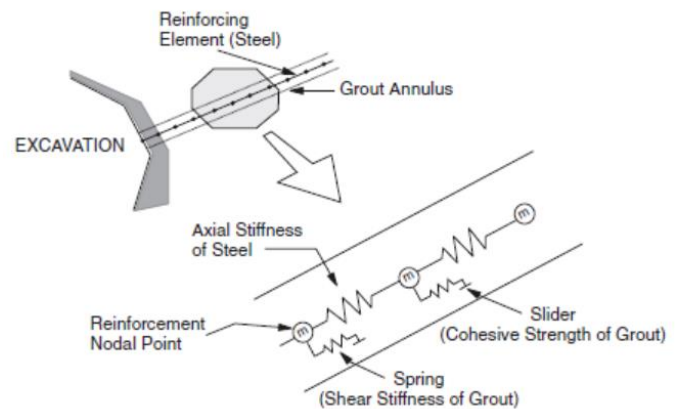


Fig.3. The representation of a bolt with cable structural elements in 3DEC.

Table 1. Physical and mechanical support properties for coal ribs (Mohamed et al. 2020)

Bolt Length (m)	1.5, 1.8
Bolt Type	Fully Grouted
Bolt Diameter (mm)	16, 19
Young's modulus of steel (GPa)	200
Yield load (KN)	90, 118
Grout stiffness (MN/m/m)	16.55
Grout cohesion (KN/m)*	45
Grout Friction angle	25
Young's modulus of faceplate (GPa)	200
Faceplate thickness (mm)	9
Coupling stiffness normal & shear (GPa)	10

*This parameter was taken from Zipf's study (2006).

3. SIMULATION RESULTS AND DISCUSSIONS

3.1 Rib Bolting in Numerical Simulation

The plane-strain model shown in Fig.2 was used to visualize the influence of bolting on rib stability in numerical simulation. The bolting mechanism in numerical simulation is shown in Fig.4. Mining excavation releases the confinement that originally holds the coal ribs, leading to the deformation of the coal rib. It can be imagined that rib deformation would concentrate at the surface of the rib at middle height and less deformation would occur deeper into the rib. The deforming coal mass tries to pull the bolt outward because of two reasons: 1) the bolt is bonded with the surrounding coal mass; 2) the presence of the face plate, which constrains, not completely prevents, the deformation of coal mass and further transfers the pulling load to the connected bolt. However, the bolt is anchored all the way deep into the rib where there is small deformation. It can be found from Fig.4 that, at the section close to the bolt head, the deformation in the surrounding coal mass is larger than that of the bolt and the bolt is pulled outward. While at the other side of the bolt, the deformation in the surrounding coal mass is smaller than that of the bolt, and the surrounding coal mass holds the bolt. During this process, axial tensile load can generate in the bolt. At the same time, the bolt load works as reaction forces to reinforce the deforming rib.

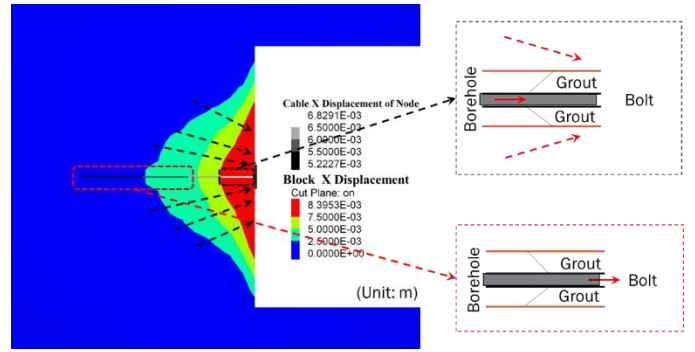
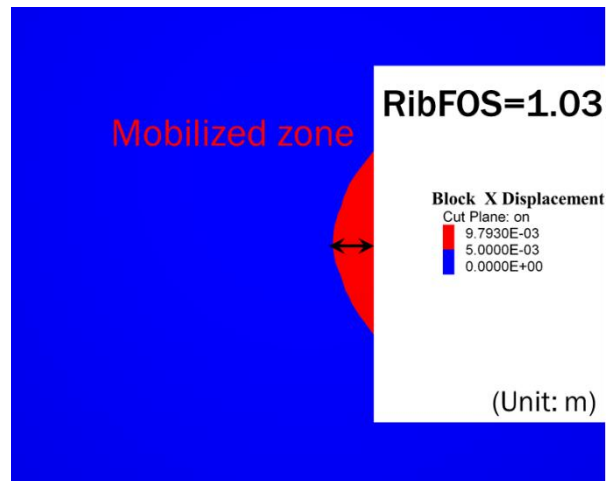
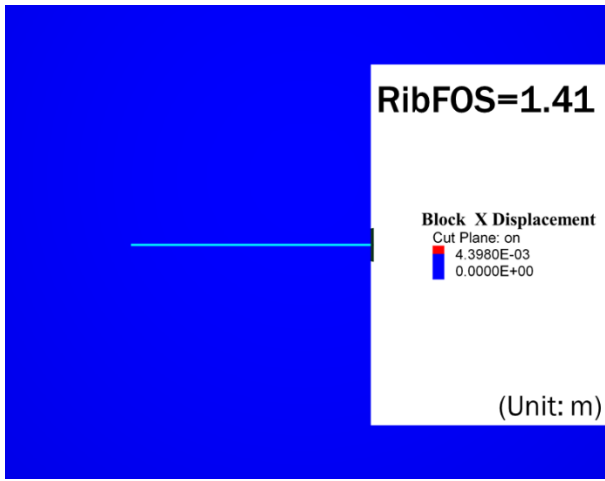


Fig.4. Illustration of bolting mechanism in numerical simulation.

It can be expected from the bolting mechanism in Fig.4 that the rib deformation can be significantly affected by the bolt. Since the stability criterion for RibFOS calculation in numerical simulation is displacement-based, the effect of bolting on rib deformation can then be reflected in the improvement of RibFOS. Fig.5 shows the influence of rib bolting on RibFOS. The same model was run two times, one without support and the other one with support. The overburden depth was 270 m, the rib height was 2.7 m, and the coal was banded-bright coal. Without the rib bolt, there is a mobilized zone with a lateral displacement limit of 5 mm in the rib. Based on the proposed strength reduction method, a RibFOS of 1.03 was obtained for the case without bolting. If one 1.8-m bolt was installed in the rib, there was no more mobilized zone in the rib, indicating that the rib lateral displacement was smaller than 5mm, and the RibFOS increased to 1.41.



(a) The model without bolting



(b) The model with bolting

Fig.5. Effect of rib bolting under 2D condition.

3.2 Bolt Spacing Effect on Rib Stability

The plane-strain model in Fig.2 was extended to different thicknesses based on the bolt spacing along the out-of-plane direction to get 3D models. Four different values for bolt-spacing or model thicknesses, including 0.3 m, 0.9 m, 1.2 m, and 1.8 m, were used. The bolt was installed at the middle of rib height and the middle of model thickness, as shown in Fig.6. The rib lateral displacement at the bolting horizon with two different spacings are also shown in Fig.6. The comparison of the legend shows that the maximum value increases with the increasing bolt spacing, indicating that more lateral displacement is allowed with increasing bolt spacing and the bolt cannot effectively control the rib displacement. From the distribution of rib lateral displacement, it is observable that the maximum lateral displacement always occurs at the far sides of the plate and bolt. This indicates that the bolt and plate can effectively constrain the rib lateral displacement, but the influence gradually fades with increasing distance from the bolt and plate. It potentially leads to the spalling and fall of rib between bolts with the increase in bolt spacing.

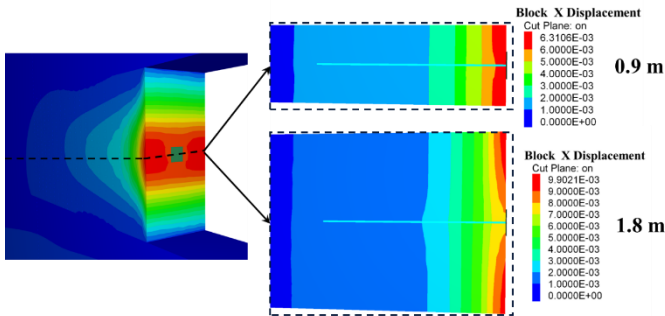


Fig.6. Plot of rib lateral displacement at bolting horizon with varying bolt spacings.

Fig.7 shows the relationship between RibFOS and bolt spacing for one model with a single 1.5-m bolt. It can be found that the unsupported RibFOS keeps constant while the supported RibFOS decreases with the increase in bolt

spacing. The rib lateral displacement in Fig.6 has shown that the reinforcement effect of the bolt gradually decreases with the increasing bolt spacing, and more lateral displacement leads to reducing RibFOS. However, the reduction in RibFOS with increasing spacing is not linear and gradually decreases. When the bolting spacing is extended to a certain value, there is minor influence of bolting spacing on the RibFOS.

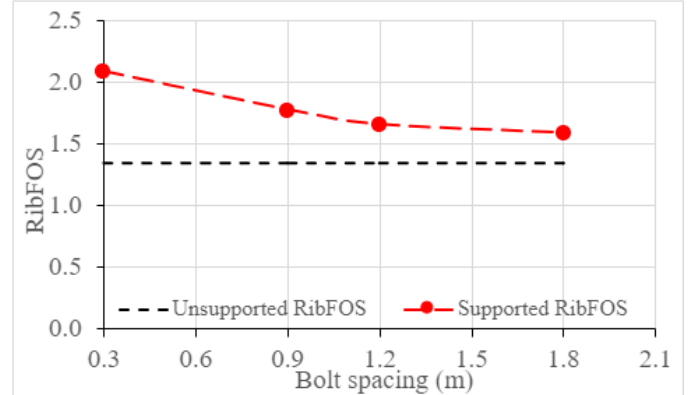


Fig.7. Plot of RibFOS with varying bolt spacing.

In addition, the variation of the bolt spacing effect under different conditions, like overburden depth and bolt length, was investigated in the study. Fig.8 shows the influence of overburden depth. The influence of bolt spacing gradually decreases with the increase in overburden depth. Under shallower overburden, the supported RibFOS is higher when bolt spacing is small, but there is more significant reduction in the RibFOS. The supported RibFOS is low, and the reduction becomes insignificant with high overburden depth. Fig.9 shows the influence of bolt length. When the spacing between bolts is small, higher supported RibFOS can be obtained with longer bolts. However, the difference gradually decreases with increasing bolt spacing. It indicates that the RibFOS for the model with longer bolt and higher supported RibFOS decreases more than the one with smaller RibFOS. These two figures show a similar trend, where more significant reduction can be observed when the supported RibFOS is higher with small bolt spacing.

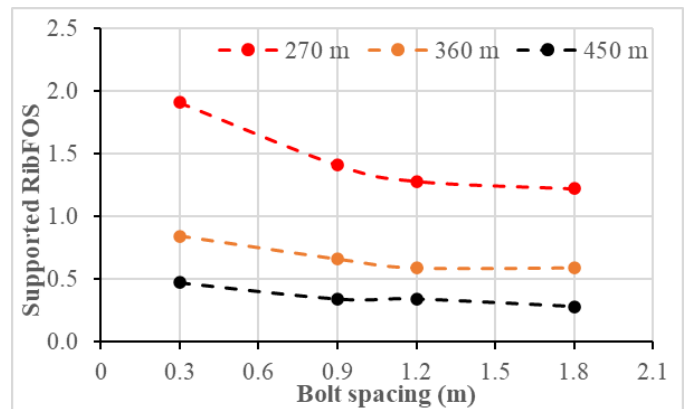


Fig.8. The variation of bolt spacing with overburden depth.

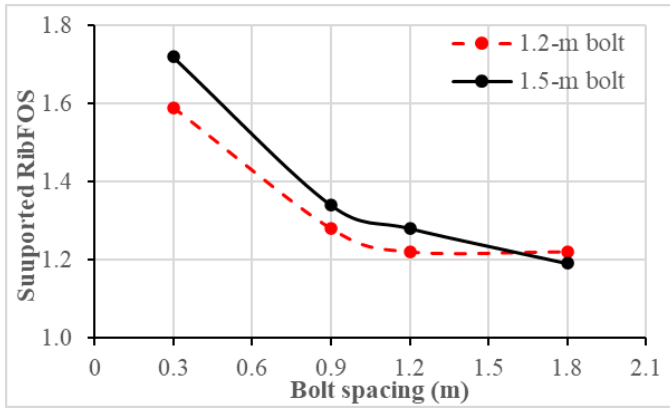


Fig.9. The variation of bolt spacing with bolt length with 315-m overburden depth.

Figs. 8 and 9 show that the bolt spacing effect varies under different conditions, and it is not easy to quantify the variation. However, the results show a general trend that the reduction in supported RibFOS is highly dependent on the values with small spacing. What if all the supported RibFOS values with varying overburden depths, rib heights, bolt lengths and bolt spacings are normalized with the values with 0.3-m bolt spacing? Fig.10 shows the results of all the simulated cases. All the supported RibFOS was normalized to its own value with 0.3-m spacing, and therefore, all the curves start from one. It can be found that, after normalization, the curves follow the same trend. One curve was used to fit the data and a good R square value was obtained. It means that such an equation can be used to quantify the bolt spacing effect on supported RibFOS. If the bolt spacing is going to change from 1.2 m to 1.8 m when designing rib support, a higher rib support density is necessary to account for the reduction in RibFOS resulted from the bolt spacing effect.

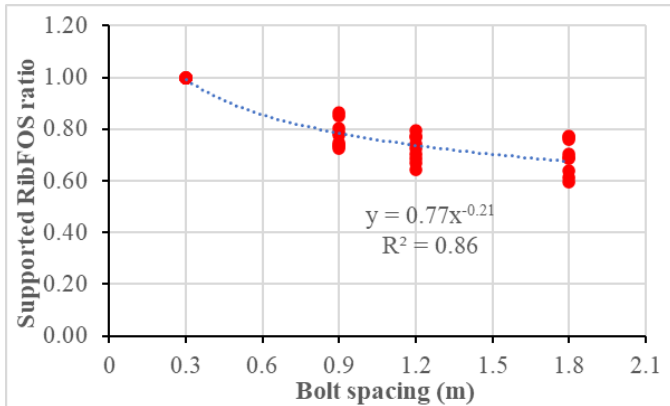


Fig.10. The relationship between supported RibFOS ratio and bolt spacing.

3.3 Bolting Design with Different Bolt Spacings

In the previous section, the influence of bolting spacing on supported RibFOS was investigated through numerical simulation. However, the same bolt properties were used for all the simulations. The increase in bolt spacing led to the reduction in support density. Thus, it would expect the decrease in supported RibFOS with the same bolt

properties and increasing bolt spacing. When the DORS application is used for rib support design at the primary stage, this situation should not occur because the support density was calculated from the unsupported RibFOS based on the regression analysis on field data (Mohamed et al. 2023). Instead, the situation that could occur is that the bolts with different steel grade or bolt diameter are used and the spacing is adjusted to make the same support density.

Three ribs were simulated with varying bolt designs and the results are presented in Fig.11. The spacing between the bolts to support the first two ribs varied from 1.8 m to 2.4 m when bolt capacity increased from 90 KN to 118 KN. For the third rib, one was supported with 2 bolts and the spacing was 2.4 m, while the other one had only one bolt with a spacing of 1.2 m. The same bolt properties were used for the two scenarios of the third rib. From the supported RibFOS ratio, we can see that, even with the same support density, there is still reduction in the supported RibFOS with the increase in bolt spacing. The relationship between supported RibFOS ratio and bolt spacing follows a similar trend as shown in Fig.10, indicating that it is still possible to use the fitted equation to estimate the decrease in RibFOS with increasing bolt spacing.

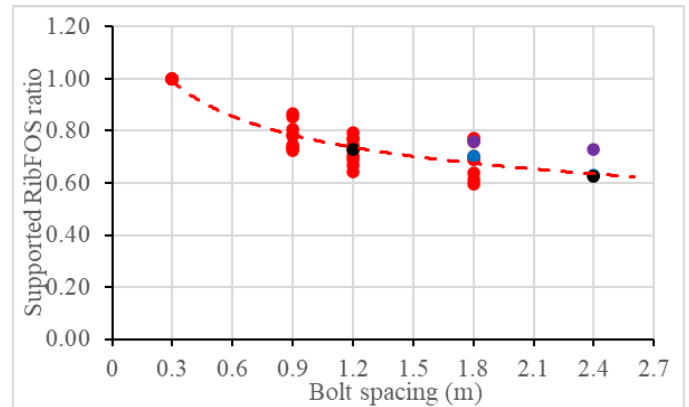


Fig.11. The results for the cases with varying bolt spacing and same support density.

4. CONCLUSIONS

Rib bolting systems have been widely used in underground coal mines to improve rib stability. The effectiveness of the system is mainly dependent on the rib support design. In this study, numerical simulations were conducted to analyze the influence of a bolting design parameter, bolt spacing, on coal rib stability.

Plane-strain 3DEC models were initially used to demonstrate the bolting effect of rib bolts on rib lateral displacement. The results show that there is a significant influence of bolts on rib displacement, leading to the increase in RibFOS when the displacement-based criterion is used to calculate the RibFOS.

Subsequently, 3D simulations were conducted to investigate the influence of bolt spacing. The rib lateral displacement shows that bolting provides local support where the effect gradually fades with increasing distance from the bolt, potentially leading to the spalling and fall of ribs between bolts with increasing bolt spacing. Also, a general trend of reduction in supported RibFOS with the increase in bolt spacing is observed. However, the trend can be further affected by varying conditions, such as overburden depth and bolt length. In order to quantify the variation of supported RibFOS with bolt spacing, the supported RibFOS was normalized to its values with a spacing of 0.3 m, and an equation was fitted to represent the relationship between supported RibFOS ratio and bolt spacing. When different bolt designs with the same support density were simulated and analyzed, the influence of bolt spacing can still be observed in the supported RibFOS and estimated with the fitted equation.

5. LIMITATIONS

In this study, numerical simulations have been conducted to investigate the influence of bolt spacing on rib stability based on the previously calibrated bolt properties. The simulated ribs are homogeneous with solid banded-bright coal and with varying rib height (1.5 m–2.7 m) and overburden depth (180 m–450 m). Grade 60 rebar with varying length (0.9 m–1.8 m), row number (1–3) and diameter (16 mm–19 mm) were simulated to reinforce the ribs. It is important to note that the simulated rib supports are under ideal conditions without considering any deficiency in installation. The findings and conclusions stated in this publication is specific for the evaluated scenarios and are presented to understand the relationship between bolt spacing and RibFOS under several common conditions.

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), Centers for Disease Control and Prevention (CDC).

REFERENCES

1. Colwell, M., & Frith, R. (2021). Utilising the scientific method to demonstrate that slender beam/column behaviour is the dominant behavioural mechanism leading to roof/rib failure. *International Journal of Mining Science and Technology*, 31(5), 867–887.
2. 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 Using

- Coal Mass Constitutive Model. *Mining, Metallurgy and Exploration*, 40(5), 1535–1546.
3. Itasca Consulting Group. (2010). UDEC (6.0).
4. Kirmaci, A., Guner, D., Karadeniz, K. & Sherizadeh T (2023). Distinct element analysis of various structural element responses for coal rib support simulation. *Proceedings of the 57th US Rock Mechanics/Geomechanics Symposium*, American Rock Mechanics Association.
5. Mohamed, K. M., Kimutis, R., Xue, Y., & Rashed, G. (2020). Rib Support Optimization for a Room-and-Pillar Mine. *39th International Conference on Ground Control in Mining*, August, 247–256.
6. Mohamed, K., Sears, M., Gunner, D., Nowak, S., Kirmaci, A., & Sherizadeh, T. (2023). Coal Pillar Rib Stability: A Regression Model Based on Distinct Element Method. *42nd International Conference on Ground Control in Mining*.
7. Mohamed, K., Xue, Y., Rashed, G., & Kimutis, R. (2021). Analyzing rib stability and support using a coal pillar rib rating. *40th International Conference on Ground Control in Mining*.
8. Rashed, G., Sears, M., Khademian, Z., & Xue, Y. (2022). Ground-Fall Accident Trends in Mining: 2010 to 2019. *Proceedings of the 41st International Conference on Ground Control in Mining*.
9. Zipf, R. K. (2006). Numerical modeling procedures for practical coal mine design. *Proceedings of the 41st U.S. Rock Mechanics Symposium*.