Analysis of Rib Bolt Load and Its Impact on Stabilizing Coal Pillar Ribs Using Numerical Simulations

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ABSTRACT

Rib control is a critical component of underground coal mining operations, and comprehensive rib support design is essential for ensuring the safety of miners. However, there is currently no standardized approach for rib support design in the United States. To tackle this issue, the National Institute for Occupational Safety and Health (NIOSH) has developed a standalone application, Design of Rib Support (DORS), for rib stability assessment and rib support design under development load. The rib support design in DORS starts with the rib support density, which is determined from the unsupported rib factor of safety (RibFOS). The relationship between rib support density and unsupported RibFOS was obtained from the collected field data. The objective of this research is to validate DORS rib support design by analyzing the extent to which the proposed design capability was utilized to support the coal ribs using numerical simulations. A series of numerical models with varying overburden depth and rib height were built and the ribs were supported with the DORS-recommended rib support design. The bolt load was analyzed under different conditions and the results show that bolt load varies with the overburden depth, the location of the bolt and bolt length. The load in the bolt(s) increases with the reduction in unsupported RibFOS. The bolt(s) start to yield when the unsupported RibFOS falls below a threshold value of 0.8 and secondary support is necessary.

INTRODUCTION

Coal pillars are intentionally retained during mining to support overlying rock strata and prevent mine roof collapse, and they 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 increasing 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 probably more deformation. The occurrence of rib falls at active mining areas presents severe safety risks, encompassing injuries, fatalities, and equipment damage. According to the Mine Safety and Health Administration (MSHA) statistics during the 10 years 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 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

NIOSH have been working on the development of an engineering-based approach for coal rib stability analysis and bolting design to eliminate the injuries and fatalities resulting 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, 2023). The user interface of the application with an input section and an output section is shown in Figure 1. First of all, 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 calculation is based on the extensive numerical simulations with different rib compositions, overburden depths, and mining heights. In addition, the DORS application can 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 when rib support is recommended. When the unsupported RibFOS is less than 1.5, it is recommended to provide rib support, and the amount of rib support can also be suggested in the form of primary rib support density (PRSD). In the DORS application, the bolt length and number of bolts are determined with the rib height and unsupported RibFOS. The spacing between bolts or bolt spacing is the last parameter to be calculated from PRSD, bolt capacity/grade, and the number of bolts. This is the general process by which the DORS application assesses rib stability and suggests rib support design.
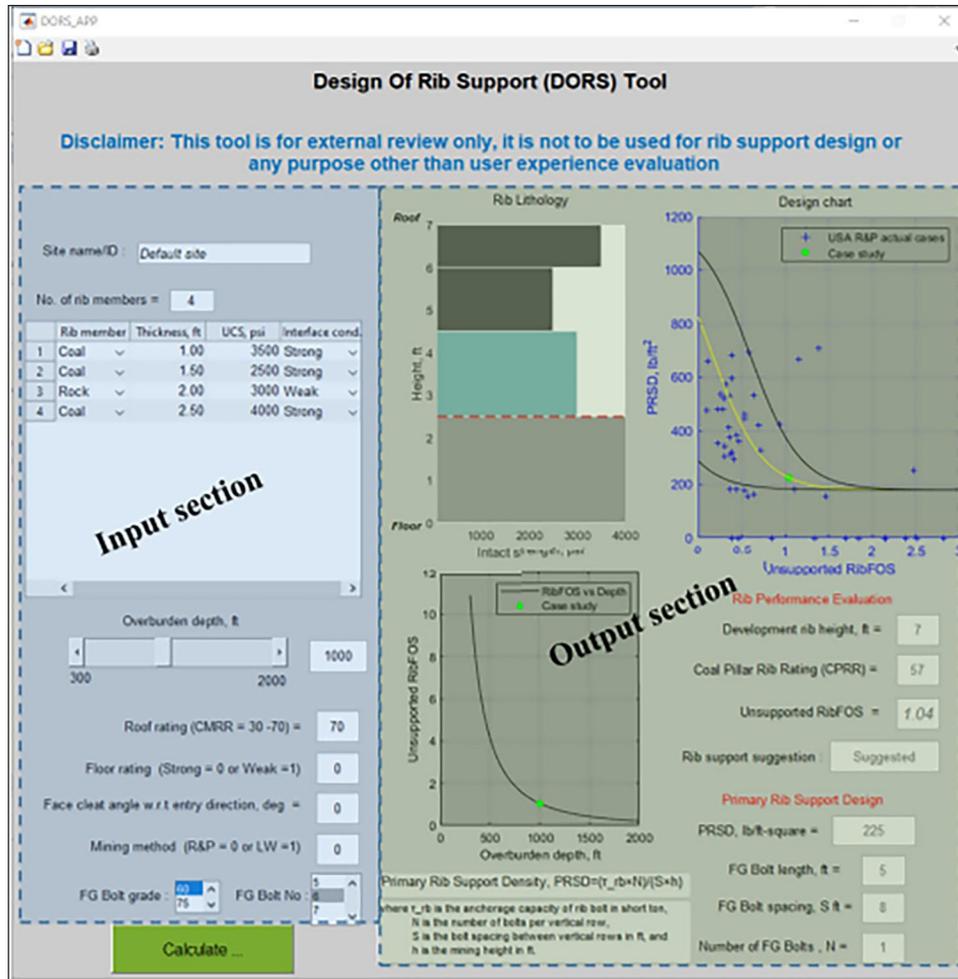
Figure 1. A snapshot of the DORS standalone application

Current rib support design practices are mainly based on the rib support density, which shows the average support capability that can be applied onto the unit rib area through bolting (Stone 2016; Mohamed et al. 2021). The support capability is calculated from the strength of bolt and grout, which shows the full capability of the bolting system. However, after installation, the load that the bolts are truly bearing cannot be determined without a specific monitoring study. It is unknown how much of the designed support capability is activated to reinforce the coal ribs, especially when the rib support is over-designed. In addition, there are unknowns in the surveyed data. There were no rib-fall accidents at the sites where the surveyed data were collected, and thus, it is assumed that the rib support designs in the database are successful. The rib support density was theoretically calculated from the support design at surveyed sites. However, the true support density that is activated to reinforce the rib is unknown because it is not practical to conduct a large number of bolt load tests in the field. It is possible that the rib support was overdesigned and was included in the database. Thus, it is necessary to investigate the design and true rib support density under different conditions.

Instead of field tests, numerical simulations can be carried out to assess bolt load. Instead of the trial-and-error approach in the industry, numerical simulations offer a platform for optimizing bolting design, including the number of bolts, bolt spacing, etc. After calibration, the model can be run with different bolting designs and the optimum bolt design can be selected by comparing the rib performance after support. Another notable advantage of numerical simulation is its capability to determine the bolt load without specific bolt load monitoring study in the field or in the laboratory. A series of numerical simulations have been conducted to validate the rib support design by DORS. In this paper, the analysis of bolt load and its impact on coal rib stability through numerical simulation is presented.

SIMULATION METHODOLOGY

Model Setup

The model, gridded block, and the boundary conditions that were used in the numerical study are illustrated in Figure 2. The symmetry axes and the left boundaries of the model were fixed in the x-direction, and a fixed boundary condition was applied to the bottom horizontal boundary to prevent movements and rotations along z-direction. A stress boundary condition was applied at the top of the model to achieve the desired simulated depth. When considering the influence of bolt spacing, the model in Figure 2 was extended to different thicknesses along the out-of-plane (Y-axis) direction to simulate varying bolt spacing, and a symmetric
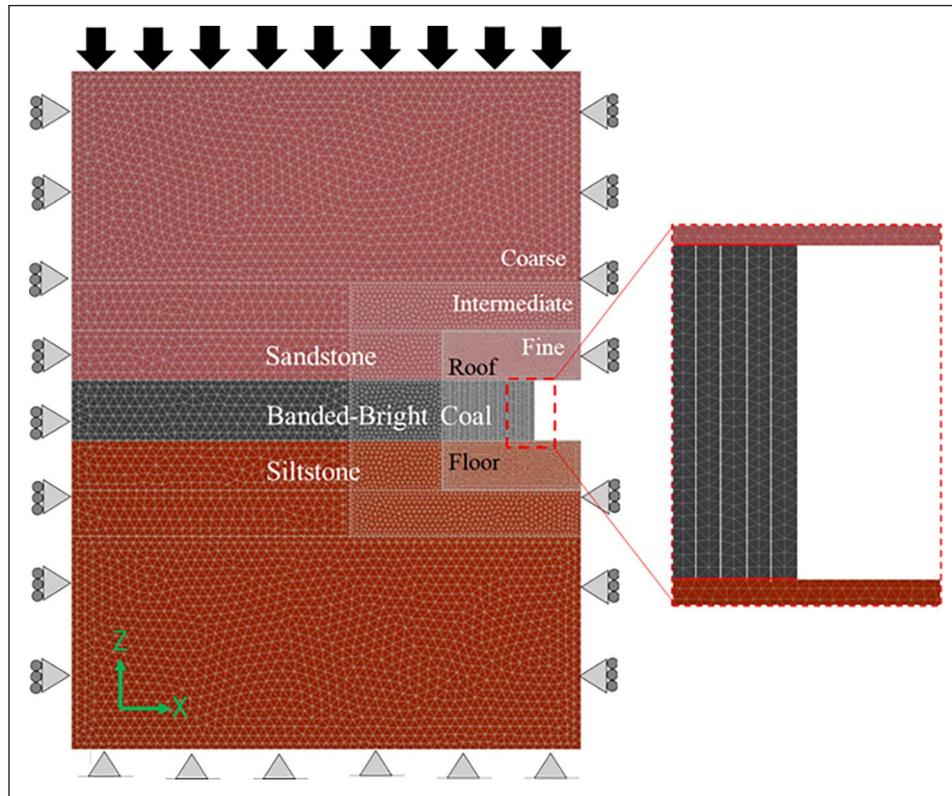
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Figure 2. Model setup and geometry configuration

boundary condition can be applied onto the boundaries along the Y direction.

A previous study demonstrates that slender column behavior is the dominant instability mechanism within a coal mine 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 up to the range of 0.5–2.0 m with varying overburden depth and rib height, and therefore, the first 4 m of the coal pillar at its rib side was modeled using face-cleat sets with a spacing of 25 cm, which allows the formation of slender columns in the rib with acceptable requirement of computational resources.

The model was initially brought to equilibrium under the in-situ stress conditions before mining. Once the opening was excavated, the reaction force around the boundary was determined 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 were 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 deformation-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, rather than the fracture zone, was defined with 5-mm lateral deformation, and if the depth of the mobilized zone exceeded 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.

Cable Structural Elements in 3DEC
Cable structural elements were used to simulate the rib bolts in the study. The main objective of rib bolting is 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 capacity of the bolts, rather than the bending moment, is important.

As shown in Figure 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 no loss of strength after failure, and with its peak strength being confining
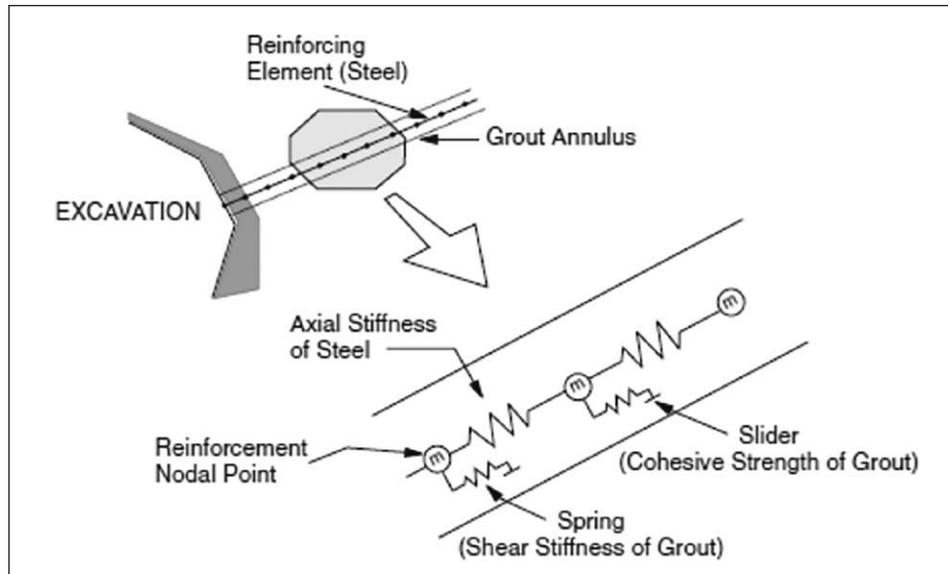
Figure 3. The representation of bolt with cable structural elements in 3DEC

stress dependent. 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).

SIMULATION RESULTS AND DISCUSSIONS

Bolting mechanism and bolt load in numerical simulation

Based on the field monitoring, Heritage (2019) summarized the mechanisms of rib bolts, including controlling kinematic failure, providing confinement, controlling the progressive rib deformation into the rib, and controlling time-dependent deterioration of coal. First of all, kinematic failure involves the coal blocks formed from discontinuities and/or mining-induced fractures, and rib bolts can be effective in controlling the kinematic failure if the bolts are installed at the correct location. Meshing is a generic and effective way to control kinematic failure without knowing the failure location. Secondly, the confinement provided by rib bolts can help increase the strength of intact coal and the residual strength of failed coal. This will help further control kinematic failure and the progressive rib deformation into the rib. Thirdly, if the rib skin deformation and failure in the form of kinematic failure and inadequate confinement is not controlled, the rib line will gradually change as the rib spalls off. The control of kinematic failure and the increase in confinement through a rib bolt is critical in controlling the progressive rib deformation into the rib. Finally, the rib can deteriorate with time and coal falls away from the ribs, which can be controlled through rib support. However, it is difficult to simulate all the mechanisms or effects of rib bolts. Different simulation methods/techniques should be used. Time-dependent constitutive models are essential for the simulation of coal deterioration over time and the coal blocks need to be explicitly generated in the coal ribs for the purpose of simulating the kinematic failure. The rib bolting mechanism(s) that can be achieved through the simulation methodology used in this study were analyzed.

The plane-strain model shown in Figure 2 was used to visualize the influence of bolting on rib stability in numerical simulation. The

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

Bolt Length (m)	0.9, 1.2, 1.5, 1.8
Bolt Type	Fully Grouted
Bolt Diameter (mm)	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).

bolting mechanism in numerical simulation is shown in Figure 4. Mining excavation releases the confinement that originally holds the coal ribs, leading to the deformation of the coal rib. Rib deformation would concentrate at the surface of the rib and less deformation would occur deeper into the rib. The deforming coal mass pulls the bolt outward because of two reasons: 1) the bolt is bonded with the surrounding coal mass through grout; 2) the presence of the faceplate, which constrains but not completely prevents, the deformation of coal mass and further transfers the pulling load to the connected bolt. However, the bolt has a much larger stiffness than the surrounding coal mass and it is anchored all the way deep into the rib where there is minimal deformation. It can be found from Figure 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. As a result, there
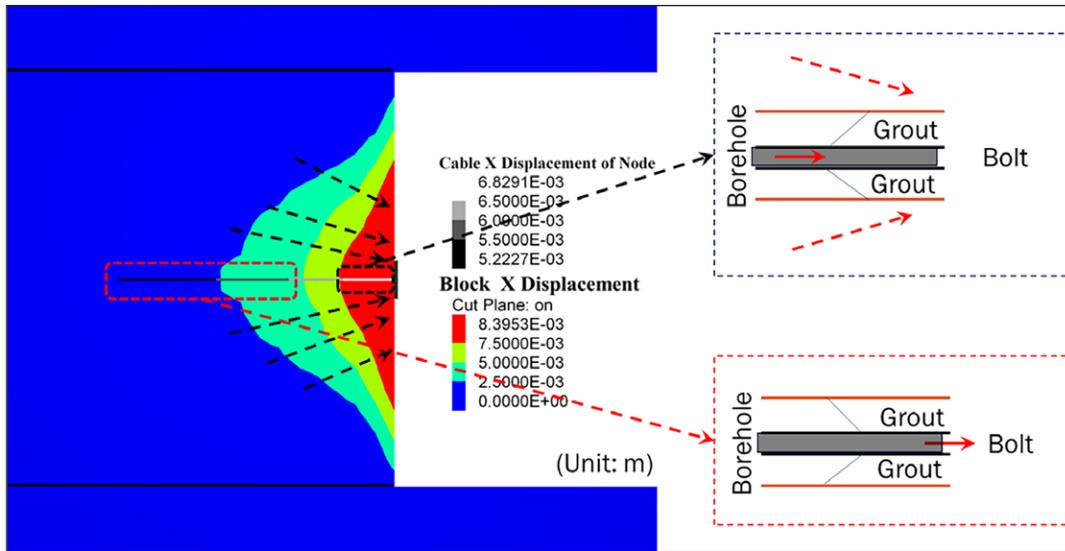
Figure 4. Illustration of bolting mechanism in numerical simulation

is a relative displacement between the bolt and surrounding coal mass, leading to shear load in the grout and tensile load in the bolt. The axial load in the bolt works as reaction forces to reinforce the deforming rib. When the bolt is connected to a faceplate, the reaction force confines a larger area than that without a faceplate. This will further improve the reinforcement of bolts (Guner et al. 2023).

Bolt Load Analysis

The bolting mechanism shown in Figure 4 demonstrates that, without pre-tension, the rib bolting is a passive support method, and the bolt load is generated when the rib starts to deform. It indicates that more bolt load can be expected at the location where larger deformation occurs in the rib. Also, other parameters, like overburden depth and rib height, could affect the rib deformation and are potential factors affecting bolt load. Furthermore, the pillars can be further loaded with abutment pressure during retreat (Rashed et al. 2020). The extra load can lead to more rib deformation, and thus, it is rationale to expect that rib bolts are going to bear more load with abutment load. However, the current DORS application is mainly for primary rib support design and does not account for the

influence of the abutment load. Thus, the influence of retreating is not considered in this study.

Since overburden depth is one of the key factors affecting rib stability and rib deformation, a series of simulations were conducted to investigate its influence on bolt load. The model had a rib height of 2.7 m and was supported by 1.8-m long bolt(s). The overburden depth varied from 225 m (750 ft) to 450 m (1,500 ft). For this specific rib condition, a threshold value of 1.0 is used to determine the row number of rib bolts in DORS rib support design (Mohamed et al. 2023). The first two cases have unsupported RibFOS larger than 1.0 and only 1 row of bolt is used. While the other three cases have larger overburden depth and smaller unsupported RibFOS than 1.0, two rows of rib bolts are recommended. The results are summarized in Figure 5. Since the unsupported RibFOS would decrease with increasing overburden depth, the unsupported RibFOS is shown as labels in Figure 5.

The data in Figure 5 can be separated into two groups based on the number of bolts per row. A general trend for both groups of data
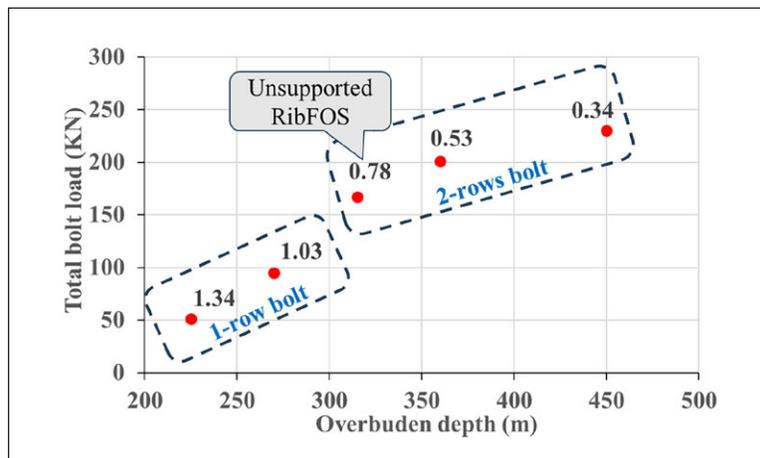

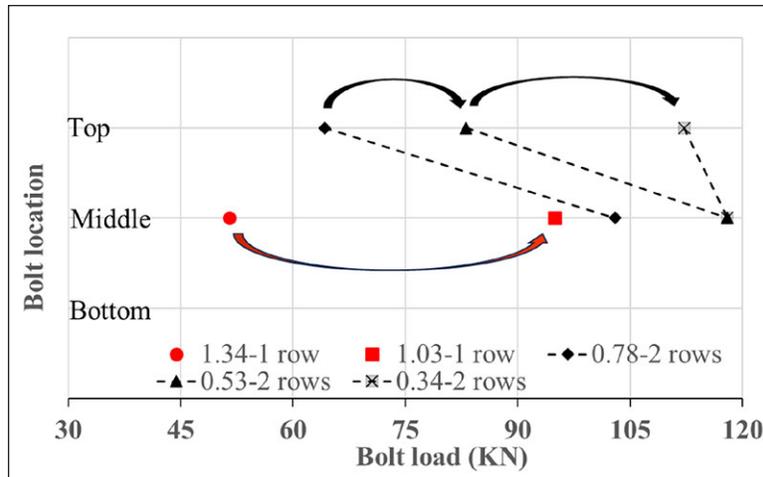**Figure 5. The relationship between overburden depth and total bolt load**

Figure 6. Bolt load distribution at different locations under different conditions (overburden depth and bolt row number)

is that more bolt load exists with the reduction in unsupported RibFOS. However, there are different mechanisms for the increase in total bolt load. For the cases with only one bolt, the total bolt load is the load within the single bolt. Since they have the same rib support design, the increasing total bolt load indicates that the load in the bolt increases when the overburden depth increases and unsupported RibFOS decreases. However, for the cases with two bolts, the total bolt load is the sum of the load in two bolts and different loading sequences are involved. A detailed display of bolt load is shown in Figure 6. A general trend is that the middle bolt bears more load than the upper one. As shown in Figure 4, the rib deformation varies with the location and maximum lateral displacement occurs at the middle height of the rib where there is the maximum bolt load. It confirms that bolt load can be affected by bolting location. In addition, the rib is stressed more with the increase in overburden depth, and the unsupported RibFOS decreases from 0.78 to 0.53. The load in both bolts increases and the middle bolt starts to yield. After yielding, the middle bolt can deform without holding extra load and more load is generated in the upper bolt.

Furthermore, the relationship between total bolt load and unsupported RibFOS for the simulated cases with DORS recommended rib support design is shown in Figure 7. Compared with the data in Figure 5, there are variety of rib heights, bolt spacings, bolt lengths, and row numbers of bolts in Figure 7. It can be found that, in general, the total bolt load decreases with the increase in unsupported RibFOS. At the same time, the rib support with yielded bolts is marked in Figure 7, and it does not mean that all the bolts yield. The yield case in Figure 7 indicates that at least one bolt yields if there is more than one bolt. The plot shows that the bolt starts to yield when the unsupported RibFOS reduces to a certain level. After yielding, the bolt can further deform without bearing extra load in the simulation, and more rib deformation can be expected with yielded bolts. This indicates that, when the unsupported RibFOS is below the threshold value, the mere installation of bolts cannot effectively reinforce the deforming ribs and secondary support, like strap and mesh, may be essential for the sake of safety. This is similar to the study by Guner et al. (2023) where an unsupported RibFOS of 0.7 was recommended for secondary support
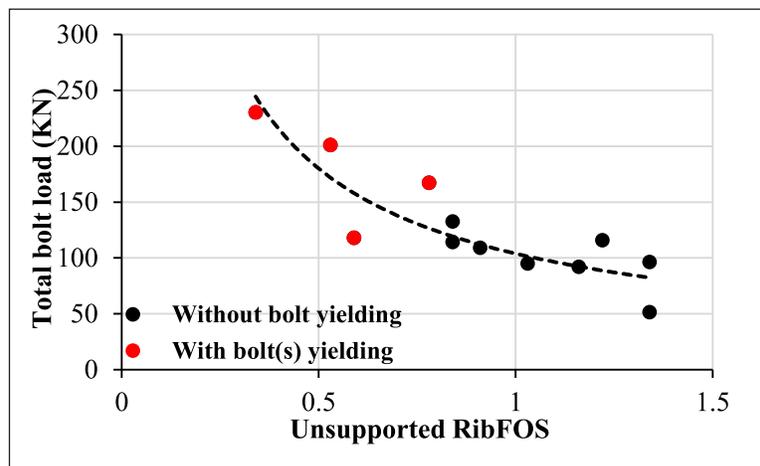

Figure 7. The relationship between total bolt load and unsupported RibFOS
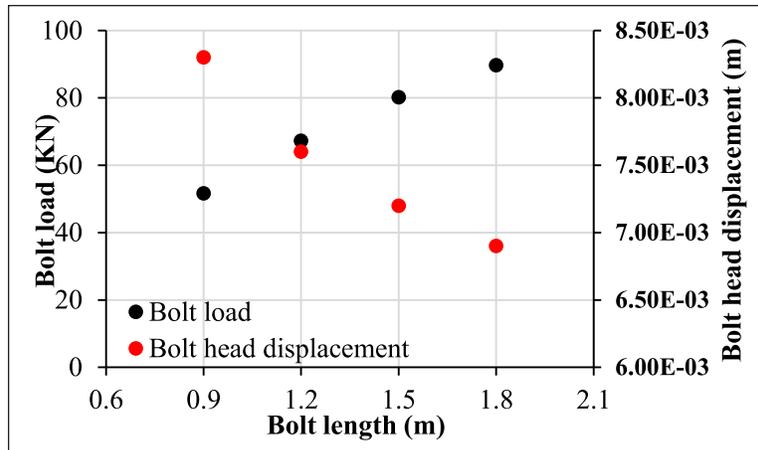
Figure 8. The variation of bolt load and bolt head displacement with bolt length

based on the plane-strain simulation results. However, the results in this study show that there is no bolt yielding when the unsupported RibFOS equals to or is larger than 0.84 and the bolt starts to yield with an unsupported RibFOS of 0.78. The unsupported RibFOS of 0.8 could be the potential threshold value for secondary support.

Finally, the influence of bolt length was investigated through numerical simulation. The rib support design in DORS starts with PRSD, which is calculated from unsupported RibFOS. The steel grade and bolt diameter can be manually selected based on availability and are used to calculate the bolt strength. The number of bolts per row is determined from the unsupported RibFOS and rib height, and bolt spacing is then calculated from PRSD, bolt strength, rib height, and number of bolts per row. Bolt length is determined with rib height and is the only parameter that is included in rib support design without affecting rib support density in the design. Thus, a series of simulations were conducted to study the influence of bolt length on bolt load.

One case in the above study was selected for this analysis. The rib is 2.7-m high with an overburden depth of 270 m and was supported with a 1.8-m bolt at 1.8-m spacing based on the DORS recommendation. The bolt length was gradually reduced from 1.8 m to 0.9 m to investigate the influence of bolt length on bolt load. Since the reduction in bolt length does not affect any calculation in rib support design, the designed rib support density is the same for all four cases. Bolt load and bolt head displacement are shown in Figure 8. Different trends are observed for bolt load and bolt head displacement with varying bolt length in the figure. The bolt load increases with increasing bolt length, while the bolt head displacement decreases with the increase in bolt length. For this case, it means that a longer bolt generates more load with less displacement, indicating that the bolting system with a longer bolt is stiffer than that with a short bolt. Under this circumstance, more loads can generate with longer bolt(s) to reinforce the same ribs and as a result, longer bolt(s) is favorable if the bolt(s) does not yield.

Rib Support Density Analysis
Besides the unsupported RibFOS, other varying factors, like rib height and bolt spacing, were included in the analysis of bolt load in Figs. 5 and 7. Since there is no clear trend in the relationship

between rib height or bolt spacing and total bolt load, their influence was not analyzed separately. However, their influence can be included in the analysis of rib support density where the total bolt loads are divided by rib height and bolt spacing to get the averaged support on unit rib area. The data shown in Figure 5 were converted into the relationship between true support density and overburden depth and are shown in Figure 9. The true support density refers to the support density obtained through numerical simulations with calibrated coal mass and bolt properties while the designed support density is the support density calculated from the bolt strength, instead of the true bolt load.

The relationship between overburden depth and true support density in Figure 9 shows that, regardless of the row number of bolts, the true support density increases linearly with overburden depth for the same rib conditions (rib composition and rib height). It indicates that bolting capability is activated to support the deforming ribs with the increase in overburden depth. Since the unsupported RibFOS has a negative linear relationship with overburden depth for the same rib conditions, it is expected that the true support density increases with the reducing unsupported RibFOS linearly. Furthermore, the comparison of the true support density and designed support density shows that not all the bolting capability is activated to support the ribs and there are differences in how much the designed capability is used with varying overburden depth. For each group, the true support density is closer to the designed value when the unsupported RibFOS decreases. For example, the two cases supported with one single bolt have the same designed support density, and for the case with an unsupported RibFOS of 1.03, most of the designed support density has been activated to support the rib, while less than half of the designed support density is activated for the case with an unsupported RibFOS of 1.34. The model was run to an equilibrium condition after excavation and support, and there was no further increase in bolt load because the rib stopped deforming.

In addition, the data in Figure 7 was converted to the relationship between support density and unsupported RibFOS and plotted in Figure 10. The minimum design curve, proposed design curve, and maximum design curve provided in DORS for room-and-pillar mines are plotted in Figure 10 (Mohamed et al. 2023). The current
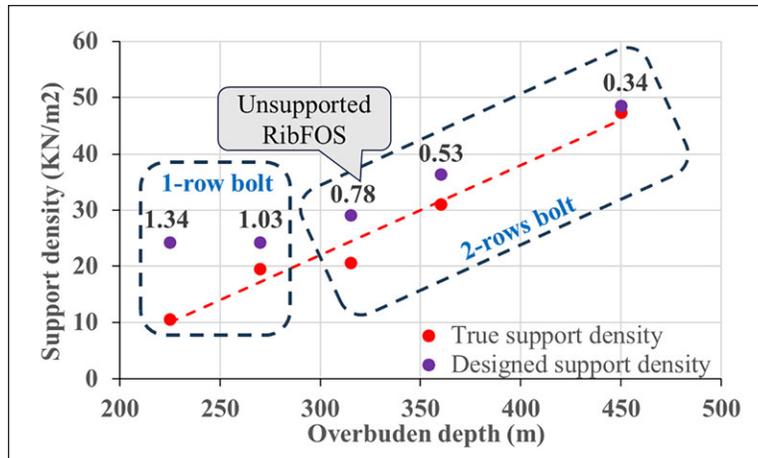
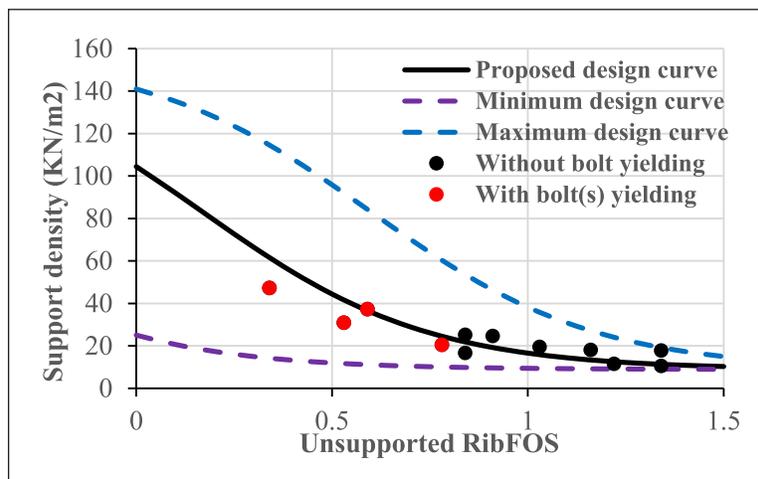**Figure 9. The variation of designed and true support density with varying overburden depth**

Figure 10. The true rib support density with unsupported RibFOS

rib support design in DORS is based on the proposed design curve. We can see that the true support density data points scatter along the proposed design curve. When the unsupported RibFOS is relatively large, the true support density is close to the designed value without yielding. However, the true support density starts to fall below the proposed design curve when the unsupported RibFOS becomes smaller and smaller. It is within the same range when the bolt starts to yield, and in general, there are more than one bolt in the design. Due to the variation in rib lateral displacement, the middle bolt yields while the upper one does not. As a result, the support capability is not fully activated, and the true support density falls below the design value even with the yielded bolt.

CONCLUSIONS

Rib bolting systems have been widely used in underground coal mines to improve rib stability. Its effectiveness is mainly dependent on the rib support design. In this study, numerical simulations were conducted to analyze bolt load and true support density based on the rib support design from DORS.

First, plane-strain 3DEC models were used to demonstrate the effect of rib bolts on rib lateral displacement and the generation of bolt load. The results show that, without pre-tension, the rib bolting is a passive support method and bolt load is generated when the rib starts to deform. It indicates that bolting location and other parameters potentially affecting the rib deformation can affect bolt load, which were further confirmed in this study.

Second, 3D simulations were conducted to investigate the bolt load with recommended rib support design. The results show that, in general, total bolt load decreases with the increase in unsupported RibFOS. Maximum lateral displacement occurs at the middle height of the rib, and the middle bolt bears the maximum bolt load. With the further reduction in unsupported RibFOS, the load in the bolt(s) increases and the middle bolt starts to yield. After yielding, the middle bolt can deform without holding extra load and more load is generated in the upper bolt. Under this condition, the mere installation of bolts cannot effectively reinforce the deforming ribs and secondary support is necessary. The results indicate a threshold

value of 0.8 in unsupported RibFOS for secondary support and the bolt(s) does not yield when the unsupported RibFOS is larger than 0.8. In addition, the simulations with varying bolt length show that the bolting system with longer bolts is stiffer than that with short bolts because a longer bolt generates more load with less bolt head displacement.

Last, true support density and designed rib support density were analyzed, and the results show that not all the bolting capability is activated to support the ribs, and true support density becomes closer to the designed value when the unsupported RibFOS decreases. When the unsupported RibFOS is larger than the threshold value in unsupported RibFOS, the true support density is close to the designed value without yielding. However, the true support density starts to fall below the proposed design curve when the unsupported RibFOS becomes smaller than the threshold value and the bolt(s) start to yield.

LIMITATIONS

In this study, numerical simulations have been conducted to investigate the bolt load and true support density under development load based on DORS's rib support design. The simulated ribs are homogeneous with solid banded-bright coal and with varying rib height (1.5 m–3.3 m) and overburden depth (225 m–450 m). Grade 60 rebar with a diameter of 19 mm and varying length (0.9 m–1.8 m) and the number of bolts per row (1–2) were simulated to reinforce the ribs. The results and conclusions from this study are based on the stated input to the simulated models and further research is needed for different scenarios. The findings and conclusions stated in this publication is specific for the evaluated scenarios and are presented to understand the relationship between rib deformation and support design under several common conditions.

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