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Review of current coal rib control practices

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Abstract

The instability of coal ribs in underground mines continues to result in the injuries and fatalities of mine workers. The proper estimation and evaluation of primary and secondary support for coal ribs is still a challenging problem in the field of ground control science and requires further research and study. Although mining operations have various support design criteria and support methodologies for strata control, most rib support designs are still based on experience and local practices. This review study is intended to summarize the currently applied practices for rib support and control in various countries and mining conditions. Firstly, critical parameters that control the amount and type of required rib support are considered and evaluated. The study revealed that among these parameters that control the stability of coal ribs, mining depth, rib height, cleat orientation/condition, and coal strength are the most significant parameters. Secondly, current rib support application methods were also summarized. Similar to rock mass classification systems, some studies proposed a rib control rating system for practical estimation of the current rib condition and to estimate primary support requirements. These studies are classified and summarized into two groups (categorical and empirical) based on the required inputs and methodologies. Empirically based coal rib rating systems were closely examined, and the usefulness and intuitive aspects of each rating system were compared. This comprehensive literature review demonstrates that the Australian rating system, Analysis and Design of Rib Support (ADRS), and the new U.S. rating system, Coal Pillar Rib Rating (CPRR), are highly applicable for their regions.

Keywords: Coal rib; Ground control; Rib support; Rib control techniques; ADRS; CPRR

1 Introduction

Ground control has always been of vital importance in underground coal mines for safety and productivity purposes. Roof, floor, rib, and face instabilities are the most challenging ground control problems in underground coal mines. Previous researches have mostly focused on roof support resulting in the development of a systematic support methodology for it. Consequently, a significant reduction in fatalities caused by roof falls was achieved. Most of the fatalities that have occurred in recent years are due to rib and face instabilities. According to the Mine Safety and Health Administration (MSHA), rib and face falls have caused 23 fatalities between the years 2007 and 2022 (MSHA, 2022). Coal still plays an essential role in the U. S. economy, especially in energy generation and the steel industry. In 2019, more than 706 million tons of coal were produced in the United States, with underground operations accounting for 38 % of this production (MSHA, 2020). As this demand continues, deeper mining projects and more challenging conditions will be encountered. Paramount among these challenges will be rib control. Understanding and managing rib problems will lead to the prevention of fatalities and production losses.

Due to many factors, such as the inherent heterogeneity of geologic regions and mining locales, there is no universal methodology or systematic guideline to follow for design-

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ing coal rib support, leaving mine operators to resort to a trial-and-error approach and local/legacy practices for designing rib support systems (Mohamed et al., 2016a). Therefore, researchers at the National Institute for Occupational Safety and Health (NIOSH, U.S.) are conducting extensive experimental, numerical, and empirical studies to propose a support design methodology and to optimize the support density for the coal ribs. Australian collieries generally follow more than one design methodology for roof and rib support. The common approach is to follow one of the analytical, numerical, field monitoring, and classification system methodologies and then update the design by back analysis with a different methodology (Emery et al., 2020). The Australian underground coal mining industry also uses an empirical technique, Analysis and Design of Rib Support (ADRS), developed by compiling case history data collected from 36 Australian coal mining operations (Colwell, 2005). It is noteworthy to mention that the design recommendations associated with ADRS are specific to the Australian coal industry.

This study seeks to investigate the literature on rib stability to understand the parameters affecting rib failure. Existing rib control and support techniques were also examined, and finally, a detailed evaluation was made on the available rib classification and rating systems in the literature.

2 Mechanics of rib failure and affecting factors

In underground coal mines, when entries are developed in a coal seam, sidewalls of coal with/without rock partings are formed. These vertical walls are known as ribs, also sometimes referred to as a ribline or ribside (Galvin, 2016). Coal deposits consist of various geologic beddings, cleats, non-coal partings, and pre-existing discontinuities. Therefore, coal ribs exhibit a highly variable and complex behavior and require detailed information to be analyzed and controlled. Two major failure mechanism types exist for coal ribs:

(1) **Structurally controlled instabilities:** This mechanism includes kinematic failures, i.e., planar, wedge, and toppling failures. Orientation and density of pre-existing discontinuities play an essential role in this type of failure. The blocks or wedges are formed with the intersection of joints, cleats, or bedding planes. The formed wedges may slide out or fall off their sockets under the effect of gravity or other forces (Nomikos et al., 2006). Principally, this mechanism is generally driven by the unidirectional gravitational force.

(2) **Stress-driven instabilities:** Upon removing the coal during development, normal stress acting on the rib vanishes, and tangential stress increases compared to in situ states. This situation causes an increase in deviatoric stress on the rib and triggers fracturing and dilation on the rib. Shear failure, tension failure, rib buckling, sloughing, and rib brow formation are the primary forms of stress-driven instabilities.

It should be noted that the two mechanisms described above are general forms of instabilities. More complex rib failures are frequently observed in the mines with the combination of these two primary mechanisms.

Based on extensive field studies, Bigby and Cassie (2003) reported four main rib deformation/failure mechanisms observed in U.K. coal mines. These are compression-dominant, shear-dominant, slabbing, and toppling failures, as presented in Fig. 1. Although the upper and lower stone partings are also illustrated in Fig. 1, the presented failure mechanisms are related to all types of ribs. The failure plane(s), resulting from the effect of vertical stresses, may form a wedge that is prone to failure into the opening. Sudden movements accompanied by floor heave may result in rib rotation along a shear plane. This type of failure can be hazardous as it is not realized until sudden rib movement occurs and cannot be controlled in advance (Salamon, 1995). Slabbing failure, also known as a plate-like failure, is the process of decoupling thin plates or slabs from the ribs along the near-vertical mining-induced fractures or face/butt cleats (Jones et al., 2014). In practice, when slabbing failures are observed, brittle failures are more likely to occur in the same rib (Smith, 1992). In addition, Australian researchers consider that the slabbing failure mechanism is a type of buckling failure, which is a commonly encountered failure mechanism in Australian coal seams (Colwell & Mark, 2005; Seedsman, 2006).

Toppling is the fourth main failure mechanism observed in U.K. coal mines. According to the studies performed in the U.S., the toppling failure mechanism is considered a type of slabbing mechanism and is generally known as rib brow failure (Jones et al., 2014). As presented in Fig. 1, the upper part of the rib tends to topple, as the lower rib below the partings of the rib degrades.

Smith (1992) reported two different rib failure patterns by considering the degree of fracturing; coal seams exhibiting low to moderate fracturing usually result in blocky or plate-like failure patterns, and brittle failure patterns become more prominent with an increasing degree of fracturing. Although brittle failure mainly depends on the cleat density and excavation dimensions, researchers reported that this phenomenon could be observed under low confinement levels with loads as low as one-third of the unconfined compressive strength (UCS) of weak coal (Rummel, 1971; Stacey, 1981). Brittle failures in coal ribs generally produce smaller size coal or rock pieces. The degree of fracturing and rank of the coal directly affect the size of the blocks that move into the opening (Jeremic, 1980).

It is necessary to define the factors that affect rib failure or its behavior to analyze complex failure mechanisms comprehensively. Numerous factors are listed in the litera-

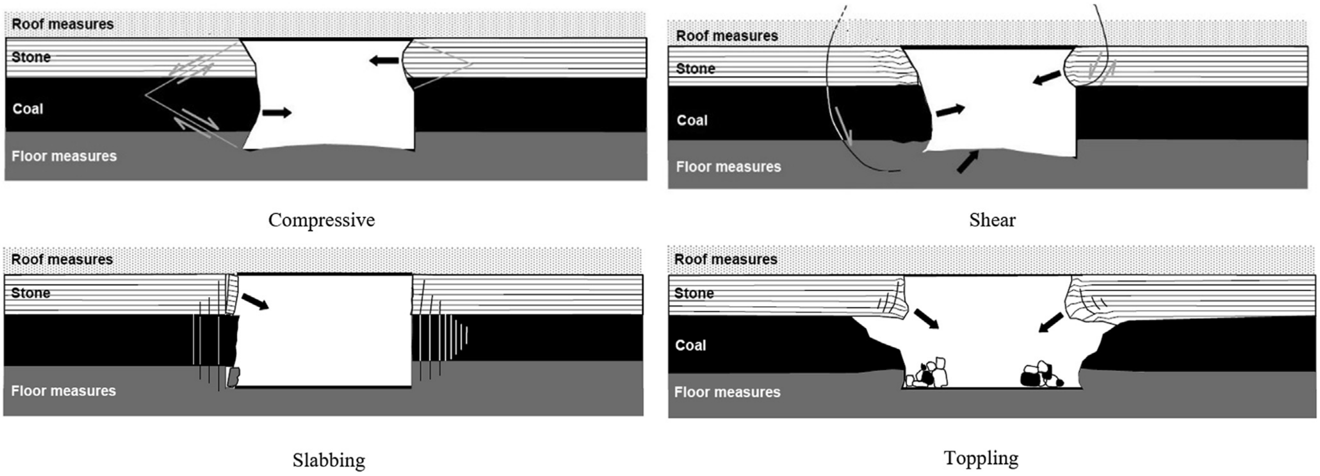


Fig. 1. Rib deformation/failure mechanisms in U.K. coal mines (Bigby & Cassie, 2003).

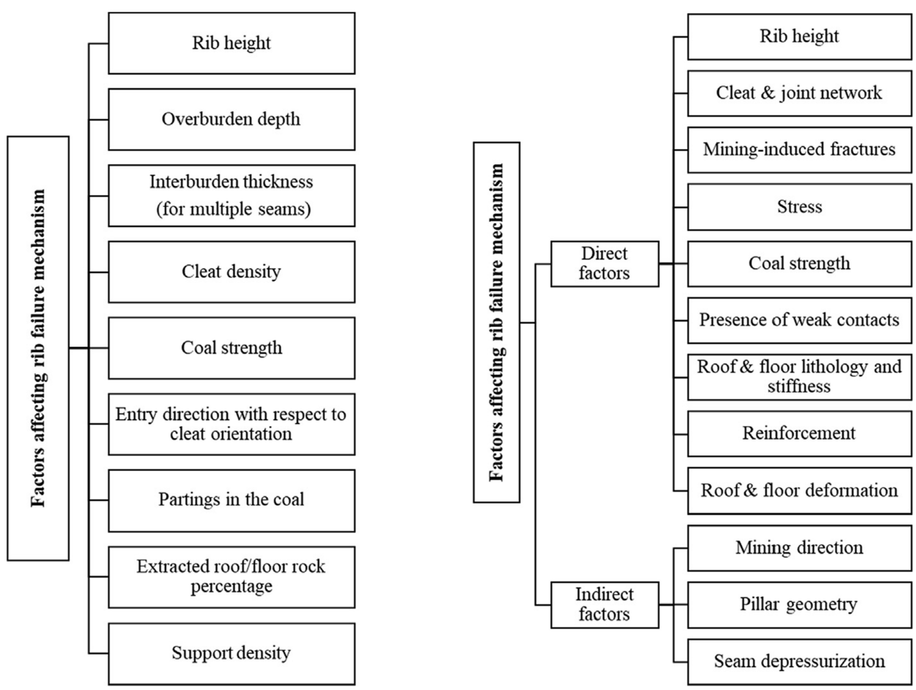


Fig. 2. Factors affecting the rib failure mechanisms and behavior in the U.S. (left) and Australian (right) coal mines.

ture for both U.S. and Australian coal mines (Jones et al., 2014; Mohamed et al., 2016a; Shepherd, 2002; Heritage, 2018; Heritage, 2019). Figure 2 shows the factors affecting the rib failure mechanisms and behavior in the U.S. and Australian coal mines.

Rib stability is a function of mutually interacted factors, such as the local geological conditions, mining layout, mining method, and depth. Due to the large number of factors contributing to coal rib stability, it is often difficult to identify which has the most dominant role in a given rib failure. To aid rib researchers in identifying these parameters, nine important factors are summarized based on previous studies and briefly explained in the following sections.

2.1 Rib height

Rib heights are generally equal to the coal seam height, except in cases where the coal seam thickness presents operational challenges, mostly ranging from 0.9 m to 4.7 m (Bieniawski, 1992; Fotta & Mallett, 1997). It has been reported that in China, some mines are currently working with rib heights over 6 meters (Zhang et al., 2016; Gray & Gibbons, 2020). Rib heights can be higher or smaller than the coal seam in some cases due to operational factors. Rib height directly affects rib stability as spalling issues become more severe in higher ribs. In addition, rib height has a direct effect on the provided confinement by roof and floor interfaces and rib stiffness. Fabjanczyk and Guy (1994) reported that the rib height parameter significantly affects rib-fall injuries more than the overburden depth in Australian coal mines.

Since many factors affect rib stability, explaining rib failures with rib height alone is not a sufficient approach. Nevertheless, researches in this area provide insight into rib height's importance. According to an analysis of accident reports, 22 of 25 rib-fall fatalities occurred in the U.S. between 2000 and 2019, for these incidences, the rib height was over 2.13 m (MSHA, 2020). Jones et al. (2014) analyzed 23 rib-related fatal accidents between 1996 and 2013 by reporting the contribution of rib height to fatalities (Fig. 3), demonstrating that fatal accidents can occur at almost any rib height but mainly occur with rib heights greater than 1.8 m.

Some countries recommend different support systems depending on the rib height. The U.S. Department of Labor, Mine Safety and Health Administration recommends two or more rows of rib bolts for ribs over 2.75 m (MSHA, 2020). In Australian coal mines, a different support system is recommended if the rib height exceeds 3 m (NSW, 2015). The roadway rib height is not suggested to be higher than 3.5 meters in New Zealand coal mines (Worksafe, 2016).

2.2 Overburden depth and stress

As it is known, rock strata are subjected to stresses in the pre-mining stage. The weight of the overburden strata causes the vertical component of this in situ stress (SV). SV is often approximated by multiplying the depth by the overburden material density. On the other hand, there are many different approaches in the literature to find the quasi-horizontal major (S_H) and minor (S_h) stress components. The correct determination of in situ stress is crucial. Various measurement techniques are available to determine the in situ stress magnitude and direction, such as hydraulic fracturing, flat jack, overcoring, and borehole breakout methods (Lin et al., 2018). Researchers have presented practical linear formulas using field studies to estimate horizontal in situ stress components just depending on the depth. It should be noted that none of these basic formulas can give exact field stress values and cannot be a substitute for field measurement. When mining operations begin, in situ stresses are redistributed according to the opening geometries and become mine-induced stresses.

Overburden depth and rib height are identified as the two major principal factors affecting rib stability: 76 % of the fatal rib failure accidents in the U.S. in the last 20 years occurred in underground mines with overburden depths of 210 m or deeper (Fig. 3, right) (Gauna & Mark, 2011; MSHA, 2020).

Mining-induced stresses are also considered a major source of rib instabilities. Stresses such as these can be induced in existing coal ribs by the removal of adjacent pillars or the mechanized excavation of a large longwall face. During longwall excavation, abutment stresses are induced upon the adjacent coal ribs; these stresses are maximized at the corners between the longwall face and gateroads due to the interaction of front and side abutment loading. Abutment loading was found to result in a higher depth of fracture in coal ribs nearby (Zhang et al., 2017).

2.3 Coal strength

Strength is a mechanical property often used as an input in most analytical and numerical studies on coal rib stability, including every classification system. It has been known to be an essential parameter for coal pillar design for over a hundred years (Daniels & Moore, 1907). While some studies argue that UCS may not be essential for coal pillar design, there is no doubt that it is crucial for coal rib design (Mark & Barton, 1996; Heritage, 2018; Mohamed et al., 2021a). According to Esterhuizen et al. (2008), rib spalling can begin when the pillar stress exceeds 11 % of UCS for non-coal ribs. If the UCS test, which is the most reliable method of finding strength, cannot be conducted, strength

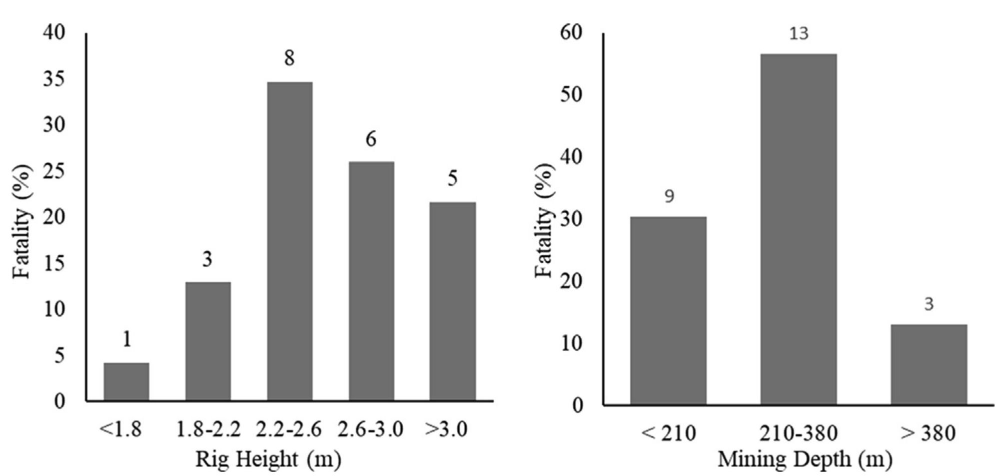


Fig. 3. Rib height/fatality and mining depth/fatality relationships (after Jones et al., 2014).

estimation can be determined by indirect methods such as point load and Schmidt hammer tests (Rashed et al., 2018).

2.4 Cleats

Cleats are vertical or near-vertical oriented natural fractures in coal. The fracture network of the coal seam generally consists of two orthogonal cleat sets: face and butt cleats. Face cleats are dominant through the coal seam, and butt cleats are generally discontinuous and commonly seen between face cleats (Fig. 4). The mechanical response of coal seams is generally controlled by these cleats and/or joints in addition to the mechanical (cohesion, internal friction angle, shear-normal stiffness, and roughness) and geometrical (orientation, spacing, persistence) properties.

Cleats also play a leading role in most structurally controlled failure mechanisms observed on the coal rib when cleats interact with mine-induced fractures, joints, or bedding planes, resulting in blocky wedges or sliding planes that can form at the intersection of these weakness planes.

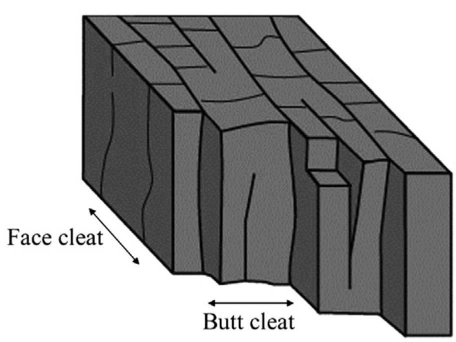


Fig. 4. Face and butt cleat system.

As presented in Fig. 5, the slabby rib fall mechanism is strongly dependent on face cleat orientation and mining direction (O'Beirne & Shepherd, 1984). Assuming that the cleats are vertically aligned, slabby failures are most likely to occur when the mining advance and the strike of the face cleat directions are parallel. In cases where slabbing is critical, it is recommended to re-orient mining/roadway advance directions by considering at least 30° differences between advance direction and face cleat strike (Holmes, 1981; Farmer, 1985). For these reasons, cleat mapping is of significant importance. The cleat mapping studies must be done carefully to distinguish between the cleat and mining-induced fractures. In U.S. mines, mining direction is controlled by roof control and horizontal stress direction.

2.5 Mining-induced fractures (MIF)

Mining-induced fractures or mining-induced cleavage, proposed by Hanes and Shepherd (1981), are curve-shaped fractures that form in a near-vertical orientation, taking place ahead of the coal face. The change in stresses (in situ to induced) around the coal face and the reduction in confining stress in the mining advance direction are the main reasons for the development of MIFs. MIFs develop at a microscopic scale and coalesce to form induced cleavage planes in the coal seam (Barczak et al., 1993).

MIFs that develop independently of the cleat system can be observed along the entire rib as mining advances. Typical MIF geometry is presented in Fig. 5. Since face and butt cleats, bedding planes, and joints are already present in the current rib conditions, the addition of MIFs may cause the forming of wedges or blocks along the rib. Unlike Australian collieries, low friction partings and clay bed-

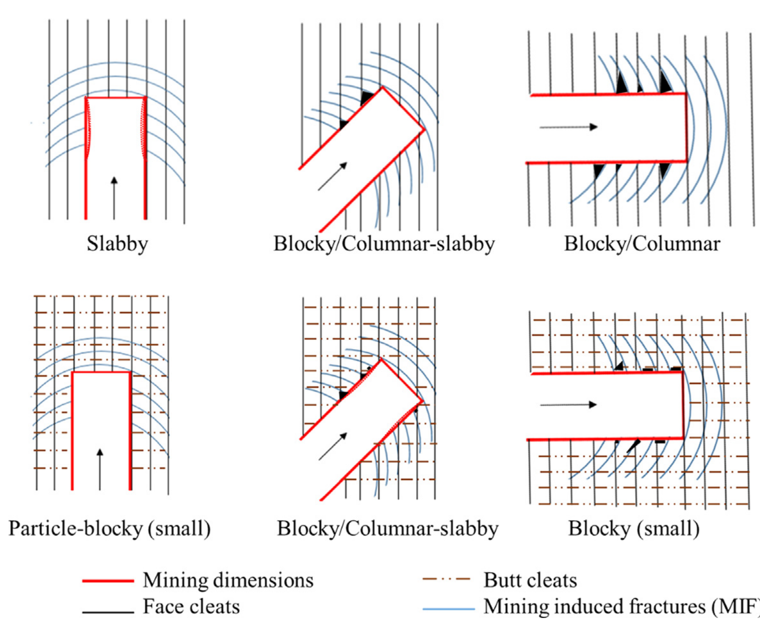


Fig. 5. Effects of cleat orientation, MIF, and entry direction on a coal rib with possible failure types (modified after Shepherd et al., 1984; O'Beirne et al., 1986).

dings are frequently present in U.S. coal seams. Through the weak layers and the MIF intersections, blocky rib failures are often experienced in U.S. coal mines (Jones et al., 2014).

2.6 Entry direction

Although entry/roadway operations in coal mines are primarily designed based on production planning, the direction of the advance can determine the stability of the rib in terms of cleat and MIF interactions. The importance of roadway direction for rib stability and the possible failure types expected for each orientation are presented in Fig. 5.

2.7 In-seam partings

Partings are the layers of non-coal units in the rib material. Depending on the formation geology of the coal basin, the partings' mineralogy and thickness vary, but almost all coal seams have one or more parting layers (Peng, 2008). Partings control the coal seam quality and mining rate to some extent. From a stability point of view, partings exhibit significantly different behavior compared to the coal in the rib, as they have different mechanical material properties. In-seam partings may act as stabilizing member within the coal seam, especially when the parting unit is stronger than the coal units (Xue & Mohamed, 2021). A high degree of heterogeneity in terms of the strength of constituent units within a coal rib, however, may result in instabilities as well.

It is known that strong and weak partings in the coal seam cause similar stress anomalies within the coal. The interaction between strong and weak partings leads to unfavorable stress concentrations within the coal rib. This phenomenon may lead to the extrusion of individual coal units and differential shearing between coal layers (Jeremic, 1980). The presence of the partings in the coal rib may serve as another weakness plane and thus is considered one of the reasons for kinematic failures. The shale rock partings may weather or deteriorate with moisture and time, potentially affecting the rib stability. Rock partings in the rib may trigger buckling action and lead to fracturing and toppling of the upper coal rib with spalling in the lower rib. Mohamed et al. (2019) categorized coal ribs according to the parting thickness and roof brow conditions by considering a critical parting thickness of 5 cm (thin partings) and 15 cm (thick partings).

2.8 Roof and floor conditions

The properties and conditions of the host rock material affect rib stability. Competent or high-strength roof and floor units may transmit vertical stresses onto weaker coal units in the rib, resulting in instabilities. Local rib instabilities are common when weak roof and floor units are noted. Moreover, continuous or excessive floor heave can cause changes in the stress state of the rib and may trigger various forms of rib failures. In the event of a sharp difference between roof and floor material properties, the rib profile loses its vertical alignment, and excessive deformation is expected in parts close to the weaker formation (Smith, 1992).

Researchers generally assumed that roof and floor units behave as elastic materials in previously conducted numerical modeling studies to understand rib behavior (Mohamed et al., 2019; Sinha & Walton, 2020). A detailed examination of the effect of inelastic roof/floor conditions on rib failure behavior will aid in understanding more complex failure mechanisms.

2.9 Support density

Support density generally refers to the amount of unit support applied to the rib. Properly applied primary and secondary support systems increase the stability of the rib by promoting integrity. As a rule of practice, rib supports are systematically installed in Australian collieries when the overburden depth exceeds 150–200 m (Heritage, 2018).

Although steel arches are still preferred for roof and rib support in different parts of the world, rib bolts provide the best protection against rib falls (Hou, 2013; Kang, 2014). Generally, most of the reported rib failures occur within the newly excavated working section; therefore, rib bolts are most effective when installed in a timely and consistent pattern concurrently with roof bolting (MSHA, 2020). In addition to rib bolts, mesh, straps, liner, and other support elements can be used under site-specific conditions. Since support density is a practical and quantitative parameter, researchers usually recommend the preliminary support density rather than specific support elements. All the parameters listed above affect the required support density. Detailed information about the support systems used for rib control is presented in the next section.

3 Current rib control and support strategies

Countries and regions have various approaches in the field of rib control and support. In this section, the applied rib support plans in Australia, the U.S., and China are presented in a general framework. There is no systematic approach to rib support design methodologies anywhere in the world at present. Considering the variation on the coal seam/host rock lithology, depth, mechanical material properties, rib height, partings/stone amount, and operational conditions, it is inevitable for each mine to have different application methods.

3.1 Rib support techniques in Australian coal mines

Rock bolting is the primary means of rib support in most coal mines in Australia. For a typical roadway of

3.5-m height, usually-two bolts are installed for each row at about 1.0–1.5-m spacing. Rib bolt designs typically locate a row of bolts in the top 0.5 m of the rib. Steel bolts, split sets, and dowels are preferred, with a length of 1.2–1.8 m (slightly shorter than roof bolts), depending on the situation. In order to provide confinement as secondary support, wire mesh, faceplates (butterfly), tendon, and liners (in some cases) are also utilized. According to Ostle et al. (1998), the flexibility of the secondary support is critical, a feature that is not available in shotcrete, which is far too rigid and brittle on failure. They emphasize the possibility of thin and flexible liners as secondary support. According to Heritage (2020), relatively consistent rib support geometries are used across the Australian collieries. Another characteristic of Australian coal mining is that mining companies give weight to field monitoring. The first study using field-monitoring data as a rock bolt design parameter was conducted in Australian coal mines (Hebblewhite et al., 1998). Monitoring is currently used in almost all major coal mining operations for rib control and support design. With these data, the current stability condition of the rib is detected, and if required, action response or remedial measures are taken.

Coal mining operations in Australia are mainly located in New South Wales (NSW) and Queensland. The NSW government has prepared a Code of Practice legislation for implementation in underground coal mines (2015). Sample primary rib support plans are presented in this detailed document (Fig. 6). The New Zealand government also recommends this Code of Practice (Worksafe, 2016). Rib conditions are color-coded (red, yellow, and green) depending on a pre-determined set of criteria (rib height, coal properties, mining depth) in the document's sections for rib support with trigger action response plans. In this document, regular monitoring and mapping are frequently emphasized.

The Analysis of Longwall Tailgate Serviceability (ALTS) design methodology, a software developed based on empirical data, is widely used as a preliminary design tool in Australia. With the addition of Analysis and Design of Rib Support (ADRS) to the ALTS 2009 methodology, this empirical approach has started to be used for rib support as well (Colwell & Frith, 2009).

3.2 Rib support techniques in China's coal mines

China is currently the world's largest coal producer, with more than 40 coal mines working at depths exceeding 1000 m (Kang, 2014). Practical empirical equations, numerical approaches, and site-specific experiences are used for rib support design in China. To the best of the authors' knowledge, there are no details on rib classification, rating, or ranking approaches for deciding the rib support system. As mining depth increases, thicker coal seams and complex conditions also require specific support designs. Current practices show that the applied support densities are higher than those in Australian and U.S. mines. China's rib control systems heavily rely on rock bolts, diamond mesh, and steel ladder beam application. Cable bolts and liners are also used in site-specific applications. In addition, a recently developed support system called active steel support (consisting of a steel pipe support filled with concrete) is also used on roadway support (Chen et al., 2013).

Kang (2014) proposed a rock bolt design methodology based on characteristics of roadways (excavation geometry and coal mechanical properties) in China's coal mines, called the dynamic and informational rock bolting design method. The design methodology consists of five stages that include an initial field investigation, a detailed design process, and field measurements of the supported rib (Fig. 7).

Researchers utilize two basic equations for solid coal rib to determine bolt length (Meng, 2020) as follows:

$$\text{Cable boltvLength} \geq L_{s1} + L_{s2} + L_{s3}, \tag{1}$$

$$\text{Rockbolt length} \geq L_{g1} + h_1 \times \sin\left(45 - \frac{\phi}{2}\right) + L_{g3}, \tag{2}$$

where L_{s1} and L_{g1} are the lengths of the exposed cable and rock bolt end, L_{s2} is the width of the internal stress field, which is equal to the distance between the main roof's fracture line and solid coal rib, L_{s3} and L_{g3} are the anchorage lengths of anchor cables outside internal stress field ($\geq$1.5 m for cable), h_1 is the height for protecting rib, and ϕ is the internal friction angle of the coal. It should be noted that internal and external stress fields may be calcu-

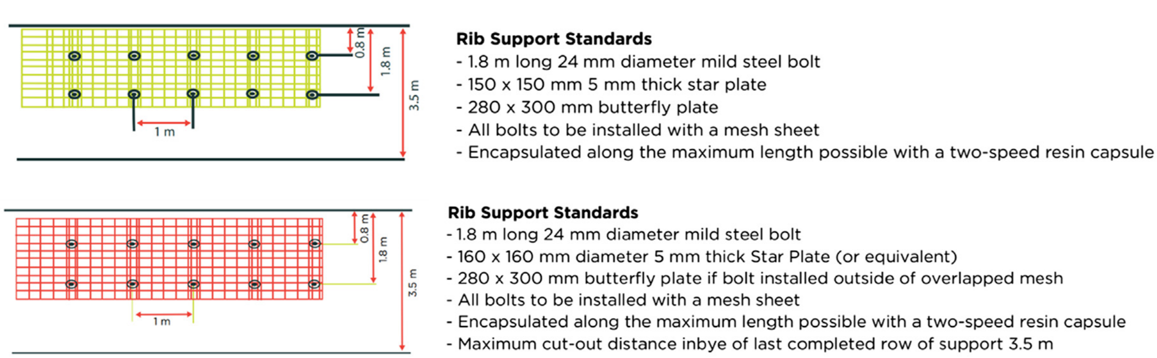


Fig. 6. Code green and code red support plan (NSW, 2015).

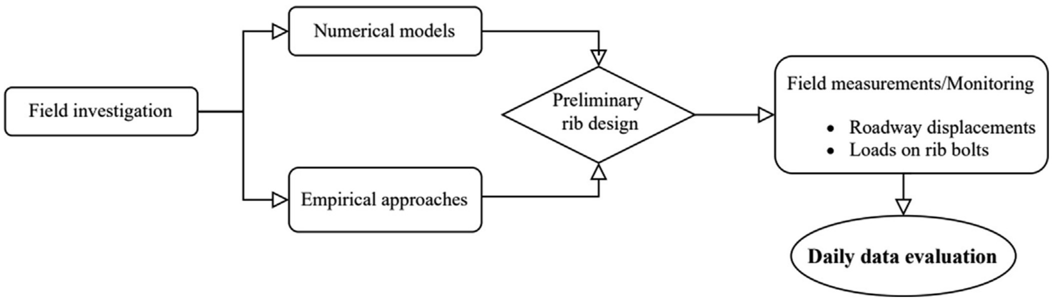


Fig. 7. Rib bolting design methodology as proposed by Kang (2014).

lated from numerical models as an alternative to costly or time-intensive field studies. The required parameters for bolt length selection are shown in Fig. 8.

Since the mining depths and vein thicknesses vary widely, there is no consistent rib support geometry. For this reason, instead of giving a typical support plan, three different rib support applications described in the literature are adopted in Chinese mines.

In the first case, developed for mines in Northeast China, the current support system was analyzed with numerical modeling due to the excessive convergence problems on the roadway. The coal seam is 5.5 m in thickness and 574 m in depth. High-strength steel bolts with a diameter of 20 mm and a length of 2.2 m were used at a spacing of 0.9 m × 0.8 m. In addition to steel bolts, steel anchor cables with a diameter of 17.8 mm and a length of 4.2 m were installed in the rib. Steel ladder beams with a 12-mm diameter were used to connect bolts and cables. All bolts and cables were pre-tensioned with 50 and 250 kN, respectively. The detailed rib support plan of the first case is presented in Fig. 9. The applied rib support measure successfully reduced the displacement values by 80 %.

The second case was developed for a mine at a depth of 710 m and located in eastern China. The coal seam was mined by fully mechanized excavation technology. The average solid coal thickness is about 9 m. The successfully implemented support strategy for solid coal rib tail entry was explained by Meng (2020). Bolt lengths were calculated using Eqs. (1) and (2), and internal and external stress fields were determined by field monitoring. Two 22-mm-diameter and 8.5-m-long anchor cables are installed in the solid coal rib for each row with a 1.6-m spacing. In order to ensure the anchoring effect, the cable bolts were pre-tensioned with 80 kN. The installed rock bolts are 2.0 m in length, with a diameter of 20 mm and a 0.8-m spacing. Double wire meshes with a grid size of 50 mm × 50 mm were used. A 2-m-long T-type steel channel was adopted in the solid coal side to connect long cables in the vertical direction. The final support design of the solid coal rib is shown in Fig. 10.

Satisfactory results were obtained for case 2 by using the above-mentioned support system. The final displacement of the solid rib was measured as 0.83 m, which met the design requirements.

A rib support application in a Chinese mine, with conditions similar to those in the U.S. and Australia, was chosen as the third case with the following conditions: 210-m-deep flat coal seam with an average thickness of 1.3 m and operated with a fully mechanized longwall mining technology. The host rock is relatively soft. The presented study mainly focused on implementing the gob-side entry retainer (GER) technology and roadside backfill body (RBB) applications

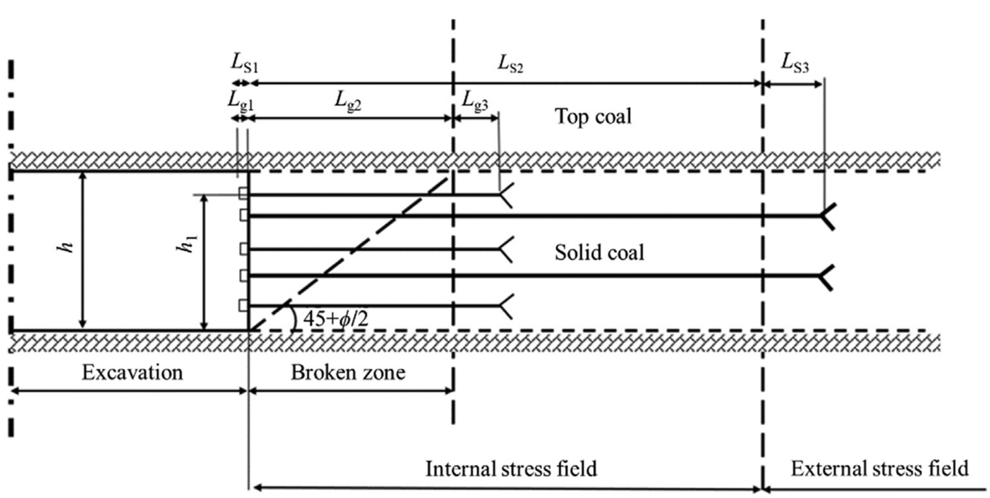


Fig. 8. Parameters for bolt length calculations in solid coal rib (Meng, 2020).

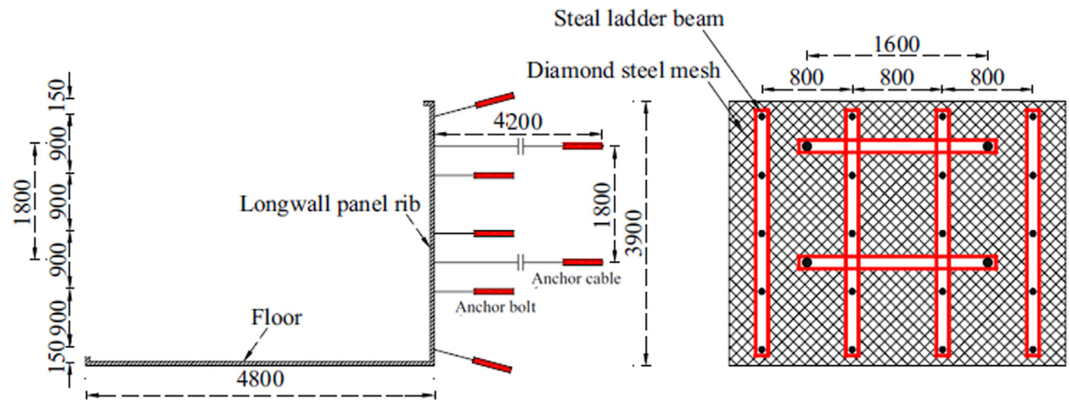


Fig. 9. Case 1 – Longwall Panel Rib Support Plan (Bai et al., 2019) (Unit: mm).

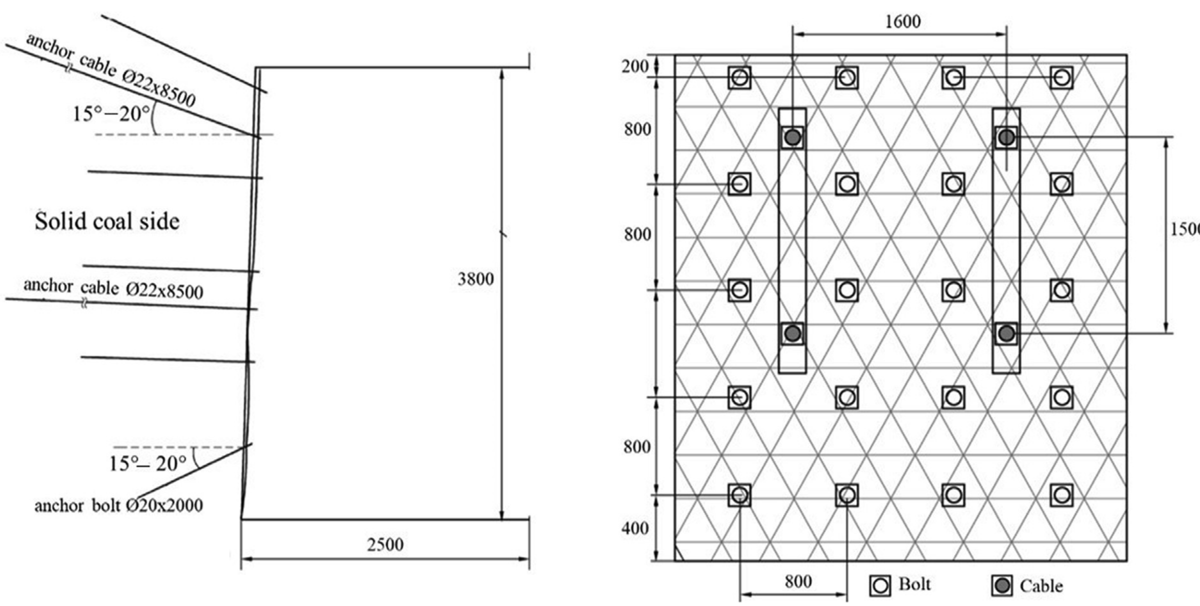


Fig. 10. Case 2 – Solid Coal Rib Support Plan (Meng, 2020)(Unit: mm).

and the modification of the rib support system after these applications (Tian et al., 2020). Since this literature review examines the existing support methods, the support technique before the GER and RBB applications is emphasized. The coal rib was supported by 18-mm × 2000-mm bolts (three rows with a spacing of 0.9 m × 1.0 m). The bolts were arranged by the steel ladder beam with a 14-mm diameter and a 2.1-m length. The coal rib was wrapped with a 2.3-m-wide and 1.1-m-long net. The final support design of coal rib in Case 3 is given in Fig. 11.

The innovative strategies developed by the study of Chinese coal mines could be utilized by mine operators and researchers around the globe, as these practices rely on an empirical approach rooted in both numerical and field studies. Currently, however, rib support rating systems such as the ADRS, utilized in Australia, and Coal Pillar Rib Rating (CPRR), which is utilized and still being tested in the U.S., are not compatible for use in many Chinese coal mines, as the mining depth and rib height of these mines are not reflected in the datasets that were used to develop the rating systems.

3.3 Rib support techniques in U.S. coal mines

The U.S. is one of the first countries to use rock bolts for coal support (Peng & Tang, 1984). Although rock bolting was primarily used for roof support for coal mines, it is a critical support element for coal ribs. Currently, rock bolts are used as the primary support for any coal ribs deemed to require support from an operational standing. In addition, secondary support elements are also used in sections with rib spalling. As in the other countries mentioned in this report, there is not yet an accepted methodology for rib support in the United States. Support methodologies are generally implemented according to local practices and experience. The Mine Safety and Health Administration

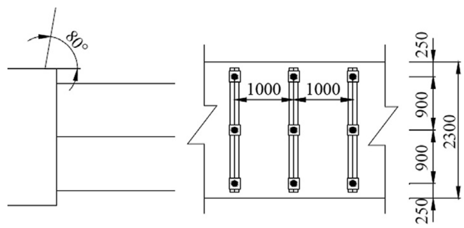


Fig. 11. Case 3 – Coal Rib Support Plan (Tian et al., 2020) (Unit: mm).

(MSHA, 2020) has determined a depth of 200 m and a rib height above 2 m as critical for rib failures. In previous reports (MSHA, 2011), rib supports were recommended for ribs at 200-m overburden depth and mining heights of 2 m and above. Mohamed et al. (2016a) analyzed and reported current rib support techniques used in the U.S by surveying 38 ribs in 10 underground coal mines (5 room & pillar and 5 longwall). The summary of the reported data for supported ribs is presented in Fig. 12.

According to the study conducted by Mohamed et al. (2016a), steel bolts are preferred over fiberglass bolts. The use of fully grouted and mechanically grouted bolts was found to be equally effective when a bolt diameter of 16 mm is considered. Bolts with lengths of 1.07–1.83 m are used and installed with a spacing of 1.20–3.66 m in U.S. coal ribs. Generally, 1 or 2 bolts are installed per row except for one case with 3 bolts/row, a 500-m depth, and a 3-m rib height. It must be noted that the diameter and the length of the bolts used for rib support were generally smaller compared with those for roof bolt applications. In addition, secondary or external rib supports, including chain link, steel, and plastic meshes, are applied in approximately 40 % of the supported mines. Mesh, steel and timber props, spray membranes, pillar bands, steel channels,

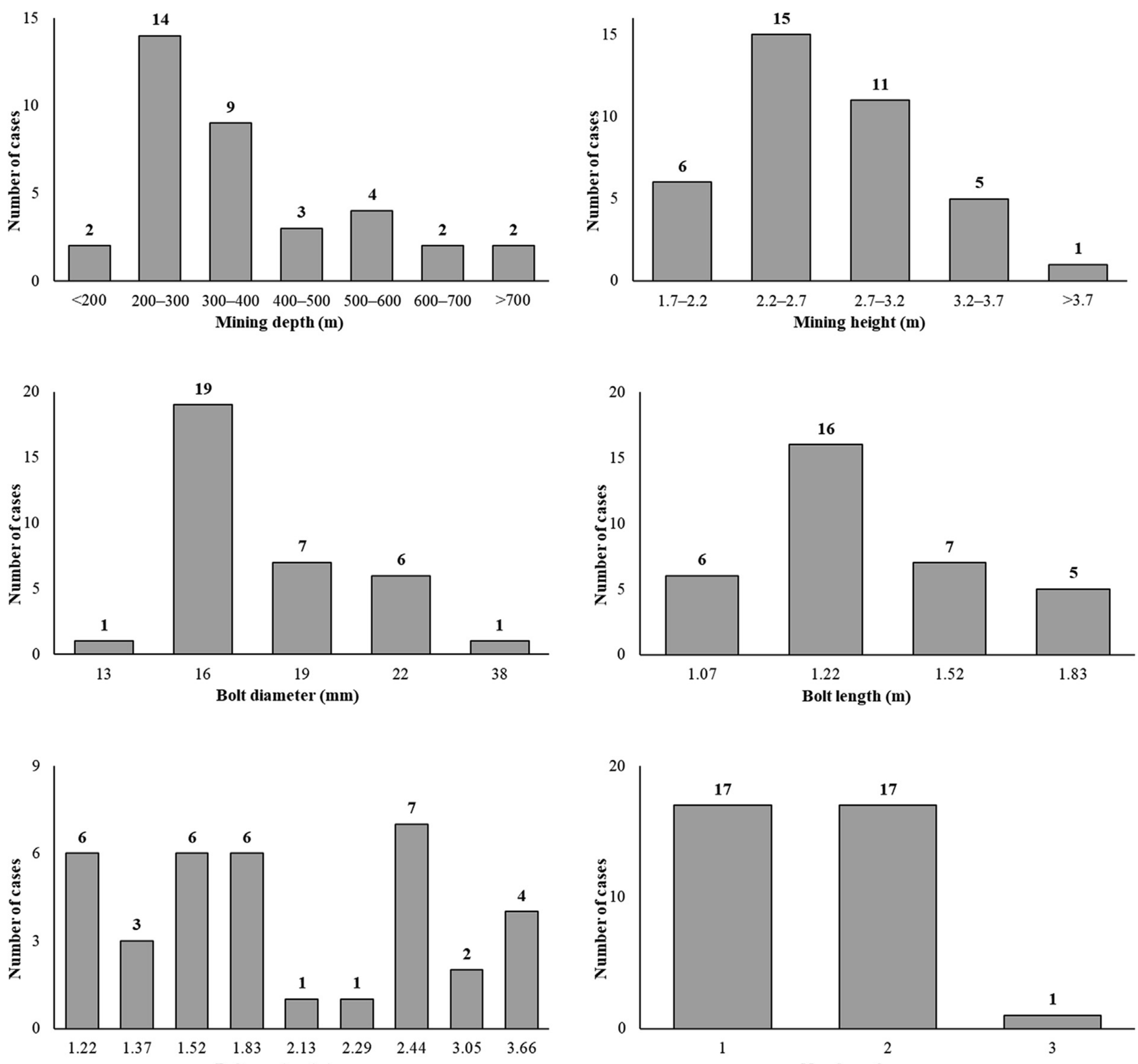


Fig. 12. Intrinsic rib support practices in U.S. coal mines (Mohamed et al., 2016a).

and angle brackets applications have also been reported in a few operations as secondary external rib support applications.

As a result of extensive research and applications for roof control, a specific support framework has been developed. In addition to the Coal Mine Roof Rating (CMRR) application, which is widely used throughout the country for preliminary roof support design (Mark & Molinda, 2005), it is anticipated that the recently proposed CPRR, a rating for coal rib similar to the CMRR for the roof, will be used for preliminary rib support design in the near future.

3.4 Rib support techniques in other countries

German coal mines often utilize steel-yielding arches as the standard primary support by means of roof and rib control. As the mining depth increases, combinations with yieldable steel arches and rock bolting are used as ground control. Polish coal mines also follow similar ground control technology, in which they use roof bolting only for supplementary support purposes. Neither German nor Polish mines have any specific rib control plan to the authors' knowledge. Recently, the largest coal producer in the European Union has initiated a project to change the standard roof and rib support practices with rock bolting in Polish coal mines as the first modern attempt. Promising preliminary results using inclined rib bolts have been published (Dyczko et al., 2021).

South African collieries generally have much better mining conditions with 2–4 m seam heights and less than 300 m overburden depths. The coal ribs are uncleated and generally strong (Mark, 1999). The collieries are responsible for following a Code of Practice "Combat Rockfall Accidents (Rockfall Accidents in Collieries)" (Department of Minerals and Energy, 1996). This code of practice does not contain any specific rib support recommendations, and the rib support decision is left to the opinion of the responsible official. Lear and Hill (1989) underline the necessity of rib bolting at overburden depths greater than 200 m as considerable rib spalling is commonly encountered in collieries.

3.5 Common rib monitoring strategies

As demonstrated by the review of rib control strategies detailed in Sections 3.1–3.3, rib monitoring has become an integral part of assessing the stability of coal ribs as well as determining the appropriate support needed. In order to aid in selecting and developing a practical coal rib monitoring design, a brief overview of some of the most common rib monitoring techniques is presented in this section.

Some of the commonly accepted roof monitoring technologies can easily be adapted for monitoring coal ribs. Geotechnical monitoring in coal mines can be limited or costly, as the equipment must either be intrinsically safe or totally mechanical, due to the potentially combustible atmosphere found in coal mines because of the presence of methane. Convergence monitors can be utilized to detect the closing or opening of an excavation in the roof-to-floor or rib-to-rib directions. A micrometer or other measuring device is used to determine the amount of convergence from rib to rib. As the monitor must be in contact with both ribs of an excavation, these solutions are often not practical, as they block roadways and are easily tampered with (Brady & Brown, 1985). Convergence monitors are used to assess the stability of a gob-side entry retaining wall in a longwall coal mine (Zhang et al., 2015) and are commonly used as supplemental instruments to other monitors, as their low cost and ease of installation facilitate their use in coal mines.

Borehole extensometers can be utilized in coal mines to measure displacements between sedimentary layers in the roof rocks, a practice that is gaining popularity but is not widely routine in the mining industry as of yet (Emery et al., 2020). An extensive study of the ribs and roof of an Australian coal mine utilized extensometers, shear strips (extensometers configured to measure shear rather than axial displacements), and instrumented rock bolts driven into the coal ribs at various depths (Heritage, 2019). The results were used to identify excessive strains along a thin, in-seam parting. Numerical models of the entry were calibrated with monitoring data, and a new support strategy was determined to control strains along the in-seam parting. Borehole extensometers can be configured to measure displacement along the entire length of the borehole or at multiple points from the toe of the hole to the collar. Multi-Point Borehole Extensometers (MPBX) are generally preferable for long instrumentation holes, as the depth of failure within the coal rib can be localized depending on the spatial resolution of the MPBX. An instrumentation suite of MPBXs, rib bolt load cells, and borehole pressure cells was used to monitor a coal pillar while adjacent pillars were mined (Rashed et al., 2021). The monitoring campaign results were used to compare the deformations across various locations and depths within the mine. An additional finding of this research determined that the rib support density in specific locations was excessive and could be reduced safely without compromising the stability of the rib.

Two methods that are gaining attraction in underground metal mines, 3D laser scanning and 3D photogrammetry, are also being adopted by the coal mining industry. The premise is simple: create a point cloud of the excavation using any 3D laser scanning device, repeat after a period of time, and compare the scans. Any convergence or divergence in the ribs, roof, or floor will be identified as a departure from the original shape of the excavation. As this technology is electronically intensive, intrinsically safe options are rare but in existence. Many metal mines have begun to use aerial or ground-based drones (unmanned ground vehicles) to perform successive laser scans in potentially hazardous excavations. Researchers utilized eight 3D laser scans of coal pillar ribs in a non-gassy mine for over

14 months to measure the convergence in an excavation (Kukutsch et al., 2016; Kajzar et al., 2017). The researchers utilized the findings to draw conclusions on both the installed rib supports' short- and long-term effectiveness. Advancements in data processing techniques such as simultaneous localization and mapping allow mine personnel to utilize hand-held or drone-mounted laser scanners to identify rib displacements, as was demonstrated in an underground coal mine using a hand-held system (Raval et al., 2019). The use of photogrammetry has been demonstrated in underground coal mines (Slaker & Mohamed, 2017). While the intent of the research was for coal rib characterization, successive photogrammetric meshes could be used to identify convergence or divergence in coal ribs.

4 Rib classification/rating systems

Classification systems are used extensively in rock engineering. These systems are generally based on case histories and empirical approaches. In general, ease of application, practicality, and the ability to make relatively realistic estimates are the main factors that determine the widespread use of these systems. The first well-known rock classification system was proposed by Terzaghi (1968) to aid the design of steel supports in tunnels, named the "rock load classification system." After Terzaghi's work, many different rock classification systems have been reported so far. Among all these rock classification systems, the four most widely used classification systems are (1) Rock Quality Designation (Deere, 1963), (2) Rock Mass Rating (RMR) (Bieniawski, 1973), (3) Q-Index, (Barton et al., 1974), and (4) Geological Strength Index (Hoek, 1994). These classification systems are used effectively in many different open pit/underground mining and tunneling projects worldwide. However, the aforementioned classification systems are "rock" classification systems, and significant coal mass parameters such as cleat density/orientation and coal heterogeneity are not incorporated in any of them. In addition, these systems are mainly based on case histories that are rarely relevant to coal mass. As the coal, roof, and floor units vary considerably in their constitution and behavior, different classification systems have been developed to address each constituent. Molinda and Mark (1994) developed the Coal Mine Roof Rating (CMRR) System to use in coal mine roof support selection and design for U.S. coal seams. In addition to roof rating systems, floor and entry rating systems have been proposed by different researchers recently (Mo et al., 2020; Van Dyke, et al., 2021). Researchers on coal rib stability have focused on proposing classification/rating systems for rib support design. Examples include research works and rib rating classification studies in the literature, presented in Table 1. While the majority of the presented studies focused solely on visually determining the amount of rib sloughing, some researchers suggest using site-specific parameters, similar to other well-known classification systems. For this reason, rib classification system studies are divided into two groups— categorical (C) and empirical (E)—to distinguish a rib rating system by placing ribs in one or more categories based on visual estimates (categorical) or the concatenation of field measurements (empirical).

4.1 Categorical classification systems

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

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

In the literature, risk-assessment-based rib classification systems have also been proposed. In these types of studies, the general risk assessment of the mine is estimated by

Table 1
Rib classification systems.

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

* C: Categorical and E: Empirical.
** Europe.

assigning values between 1–6 to parameters such as geological structure, rib condition, roadway dimension, groundwater condition, and stress change (Bigby & Cassie, 2003). In the study conducted by Bigby and Cassie, visual descriptions were used for three different U.K. coal mines, and based on these descriptions, six different rib conditions were defined. The rib rating methods used for general purposes have similar ranking approaches. The general comparison of these ratings is presented in Table 2.

4.2 Empirical rib classification systems

In this section, four different rating systems are discussed in detail. The systems are described chronologically.

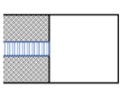
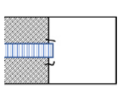
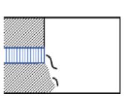
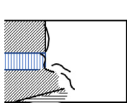
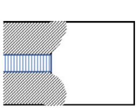
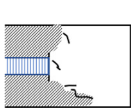
4.2.1 Coal mine classification rating (CMCR)

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

Fundamentally, the CMCR rating consists of 6 main and 1 adjustment parameters. These parameters and calculation algorithms are presented in Fig. 13. Each parameter can be easily determined from the associated table or graph. The parameters include the coal UCS, moisture content, groundwater condition, as well as information on the geologic characteristics of the coal, such as the presence of bedding planes and the fissility (the ability of a rock to split along flat weakness planes) of coal. This rating system contains several sub-parameters that can reflect the current field conditions. For example, multiple different graphs/tables are proposed by Whittles (2000) to determine each parameter given in Fig. 13.

The cleat orientation adjustment factor presented in this research was also considered in the studies conducted by different researchers (Fig. 14). The cleat adjustment rating provides an adjustment of ±10 points depending on two parameters: cleat orientation with respect to entry direction and joint roughness coefficient (Barton et al., 1974). As pointed out in the *Cleats* section of this study, smooth-planar cleat surfaces oriented parallel to the roadway is the most unfavorable condition for the cleat sets.

Table 2
Rib classification criteria.

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

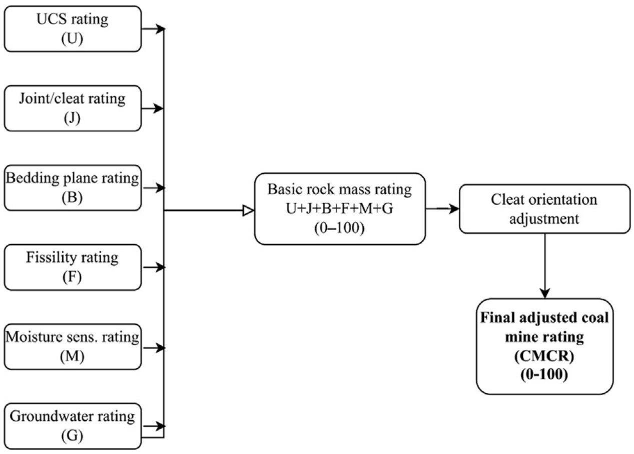


Fig. 13. CMCR Calculation Algorithm (Whittles, 2000).

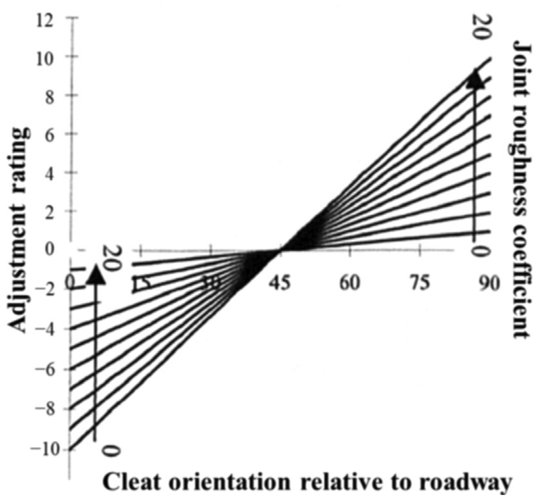


Fig. 14. Adjustment rating for cleat orientation with respect to entry direction (Whittles, 2000).

Whittles (2000) also presented the percentage significance values of all parameters used in the classification system, considering the five different rib deformation mechanisms defined in his study. According to Whittles, if rib spalling is the primary deformation mechanism, the most significant parameter for spalling is the UCS value. On the other hand, the cleat rating parameter is crucial for the deformation mechanisms of cleat dilation and yield zone development. The importance of UCS and cleat rating is also emphasized in this study. It is noteworthy that the cleat orientation adjustment factor is not included in this importance rating study. Table 3 presents the critical ratings (in percent) of required parameters for the calculation of CMCR.

4.2.2 Overall assessment for CMCR

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

Another critical point is that the proposed rating systems must be supported with case histories to gain the trust of mining professionals. This work, which has been done with great effort, could be considered as preliminary work in this study. Unfortunately, the rib rating part of the presented classification system has not been updated since its development. Updates were made by adding case histories

Table 3
Importance ratings of CMCR parameters (Whittles, 2000).

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

and numerical model results (Whittles et al., 2007). This research, which is thought to be highly effective in its use, is included in this review, as it has potential in rib classification and is considered functional for further studies.

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

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

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

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

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

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

$$\mathrm{RIBSUP} = 41h + 2.58\sigma_\mathrm{p} + 0.47\,\mathrm{HGI} - 169. \tag{4}$$

Various support systems have been suggested to keep the pillar rib at moderate to moderate-low risk levels at the end of this extensive study. Mining professionals can estimate the suggested support system using the average pillar stresses on the rib and the RIBSUP values as summarized in Table 4.

4.2.4 Overall assessment for RIBSUP and ADRS

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

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

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

Table 4
Recommended support levels for various RIBSUP and σ_P values (Colwell & Mark, 2005).

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

4.2.5 Rib deformation rating (RDR) and rib rating index (RRI)

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

RDR is a highly general value, and when it intersects with three different design lines presented in Fig. 15, a wide range of PRDI values can be estimated. Therefore, using the upper design line value is considered suitable for practical use in estimating the maximum preliminary reinforcement density. This study also presents a general trend between a calculated RDR value and bolt length. This general trend is shown in Fig. 16 just to provide an idea of it on a global scale.

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

$$\mathrm{RRI} = \frac{H \times R_h}{S}, \tag{5}$$

where H is the depth of cover in meters, R_h is the roadway height in meters, and S is the average in situ coal strength in MPa (determined using a Sonic derived UCS from site-specific geophysical data). The database has been updated only for Australian collieries cases, taking the form in Fig. 17. As it can be seen, although the regression coefficient value remains steady, the upper and lower design lines get closer to each other.

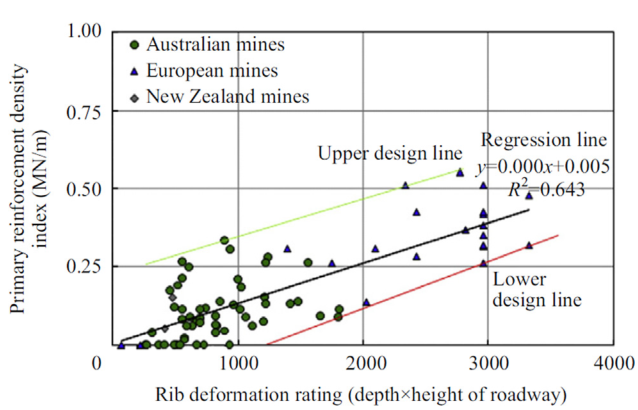


Fig. 15. Golder's primary rib support database (Stone, 2016).

4.2.6 Overall assessment for RDR and RRI

The empirical classification system presented is based on 40 different case histories. If more detailed information about case histories were used while creating the database, it is thought that more precise estimates could be made. For example, since effective parameters for rib behavior

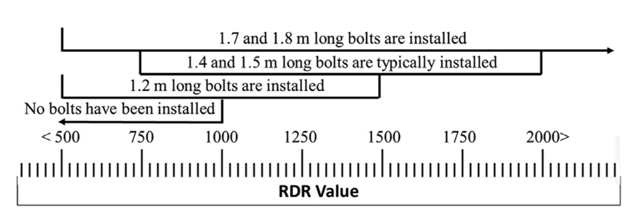


Fig. 16. General trend between RDR and bolt length (Stone, 2016).

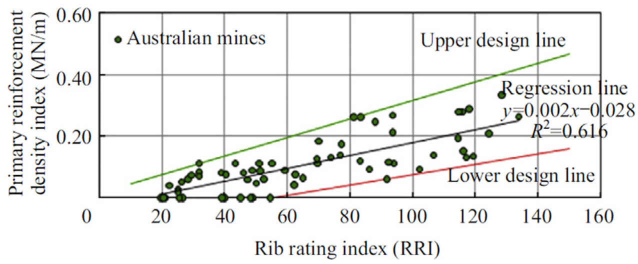


Fig. 17. Updated database (RRI versus PRDI) (Stone, 2016).

such as cleat density, cleat mechanical properties, condition-type of bedding in the coal seam, and cleat direction with respect to roadway were not taken into account for the estimation, this rating system can generally be able to make a rough estimation.

4.2.7 Coal pillar rib rating (CPRR)

Researchers at NIOSH conducted a comprehensive mining project to propose a design methodology for rib control in coal mines. A new engineering-based rib classification method, the Coal Pillar Rib Rating (CPRR), is currently being developed. Similar to the widely used rock mass rating systems, CPRR uses a linear scale between 1 and 100. CPRR 1 designates the weakest pillar rib, and 100 designates the strongest pillar rib. A hybrid numerical-empirical approach is being used for the proposed rating system. The empirical data gathered from 22 underground coal mines in the U.S. and over 1500 numerically generated data are the basis of the CPRR system. The CPRR was developed using underground site observations, calibrated and validated rib models, and the findings presented in published papers pertaining to geology and underground coal rib performance. Through the examination of current rib support practices and techniques in U.S. coal mines, three distinct rib categories were identified: (1) solid coal ribs with no partings or parting thickness less than 5 cm, (2) coal ribs with greater than 15 cm in-seam partings, and (3) coal ribs with a roof brow (Fig. 18). Among these rib categories, the current form of CPRR is applicable to solid coal ribs without partings, thin partings (<5 cm), and coal ribs with greater than 15 cm in-seam partings (Fig. 18-i and ii) (Mohamed et al., 2019).

In the rib data collection procedure, various parameters potentially affecting rib performance were recorded. These parameters are entry dimensions and orientation, overburden depth, spalling block size, spalling-sloughing type, coal brightness, groundwater condition, roof and floor type-strength, coal unit thicknesses, face and butt cleat properties (spacing, persistence, orientation, condition), current support practice, and rib deterioration index. It is worth noting that such a detailed parameter collection has not been done in any previous rib study. Moreover, it is observed that the prepared table for the determination of the rib deterioration index is consistent with the previous studies as stated in the general rib classification systems (Section 4.1) of the study.

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

According to the developed methodology, CPRR has five parameters (measurable in the field): rib homogeneity strength, bedding condition, rock parting condition, face cleat orientation with respect to entry direction, and coal unit thickness. Mohamed et al. (2021b) updated the developed CPRR to be used for the first and second rib categories (Fig. 17) and are working to extend the potential for usage of the CPRR for most coal ribs.

The calculation methodology of the CPRR is summarized in Table 5. Each parameter presented in Table 5 is calculated with the help of different equation(s). Further information can be found in Mohamed et al. (2021b).

After the CPRR is determined, the factor of safety of the pillar rib (RibFOS) and the performance categories of solid ribs can be estimated by Eq. (6). Also, four different performance categories are presented depending on RibFOS values. The RibFOS values of 0.9, 1.5, and 4.5 are the boundaries of these categories.

$$\text{RibFOS} = 6.02 \times \frac{\text{CPRR}}{\text{overburden depth (m)}} \quad (6)$$

In the final part of this paper, an empirical relationship between the RibFOS and the applied rib support density is presented based on surveyed cases. The support density is proposed in the primary rib support density index (PRSD) from Eq. (7):

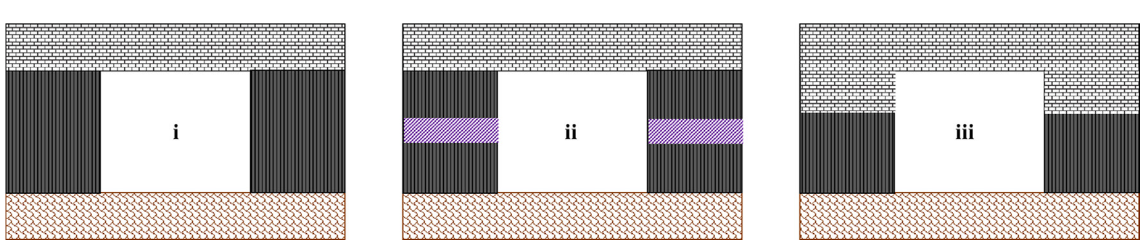


Fig. 18. Main rib categories, after Mohamed et al., 2019.

Table 5
CPRR calculation steps (Mohamed et al., 2021b).

i) Measure the rib height and thickness of each coal and parting unit

ii) Find UCS of each coal and parting unit

iii) Calculate the weighted average UCS *(use i and ii)*

iv) Measure the angle between face cleat orientation and roadway direction

v) Mark the bedding condition

vi) Calculate rib homogeneity index (r) ($min\left[\frac{\sigma_k}{\sigma_{k-1}}, \frac{\sigma_k}{\sigma_{k+1}}\right]$ σ_k:minimum UCS of rib unit)

Parameter 1: *The rib homogeneity rating* ***$\beta(i)_h$***
Use iii and vi

Parameter 2: *Bedding condition rating* ***$\beta(i)_{in\text{-}seam\text{-}bedding}$***
Use iii and v

$$\beta(i)_h + \beta(i)_{in\text{-}seam\text{-}bedding} = CUR_{BASIC}$$

Parameter 3: *Adjustment for the adjacent rock parting and the condition of the coal/rock interface* ***$\alpha(i)_{parting}$***
Use iii, CURbasıc

Parameter 4: *Adjustment for the thickness of coal units* ***$\alpha(i)_t$***
Use CURbasıc

Parameter 5: *Face cleat orientation adjustment* ***$\alpha(i)_{cleat}$***
Applicable when iv ≥ 20°
Use iii

$$CUR_{BASIC} + \alpha(i)_{parting} + \alpha(i)_t + \alpha_{cleat} = CUR(i)$$

$$\mathbf{CPRR = min_{i=1:n}[CUR(i)]}$$

$$\mathrm{PRSD} = \frac{\tau_{rb} \times N}{S \times h}, \tag{7}$$

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

Users can also reach the suggested PRSD value by estimating the RibFOS using the CPRR value. Since the rib support methodologies are different for room, pillar and longwall mines in the U.S., Mohamed et al. (2021b) proposed separate equations for each mining method. Estimated PRSD values can be calculated by Eq. (8). If CPRR users already know the current PRSD values, they will be able to estimate the RibFOS values from the proposed graphs.

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

$$\text{Longwall PRSD}\left(\frac{\mathrm{t}}{\mathrm{m}^2}\right) = \frac{64.56}{1 + e^{(5\times(\mathrm{RibFos}+0.03))}} + 0.1 \tag{8}$$

In order to provide users with practical calculations for CPRR, RibFOS, and PRSD, a MATLAB-based application called Design of Rib Support, or simply DORS, is proposed.

4.2.8 Overall assessment for CPRR

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

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

The stress-driven failure mechanism is realistically simulated in the parametric studies performed while developing the CPRR. However, kinematic failure, which is another common failure mechanism, and the situations where these two mechanisms cause failure together could not be solved by numerical modeling due to the continuum-mechanics-based nature of the code. For further studies, it is recommended to use a discontinuum mechanics-based solver so that CPRR can be updated considering all these failure mechanisms. With this solver, the effects of butt cleats, mining-induced fractures, faults, and other discontinuity sets on rib stability can also be analyzed.

4.3 Comparison of the available rib classification/rating systems

This section analyzes the main similarities and differences between studies that can be considered categorical and empirical rib classification/rating systems. Studies classified as categorical classification systems only include visually analyzed current rib conditions. While 0 or 1 point is given for the intact rib condition, 5 or 6 points are given for the gross rib or pillar failure cases. Another common characteristic of categorical rib classification study cases is that the obtained rib classification rating value is only used to specify the current rib state quantitatively. Although the determined rib rating value has been evaluated as a risk factor in some studies, generally, these values cannot be used for purposes such as primary support estimation or rib factor-of-safety evaluation. It is observed that the studies made for this categorical classification form a basis for subsequent empirical studies. It is noteworthy that the concept of the "rib deterioration index" utilized in recent studies was developed by considering these initial studies.

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

First of all, the considered parameters for developing the rating systems and the parameters required for the calculation are presented in Table 6. According to Table 6, many parameters are considered for the development of CMCR and CPRR and compared with other systems. Overburden depth, rib height, and strength-stress parameters, known to be significant, are considered in almost all classification systems. On the other hand, fissility-moisture and Hardgrove Grindability Index parameters are considered and then used in only one system.

Suppose the classification systems are evaluated only by considering them in terms of used/required parameters. In these cases, CMCR and CPRR systems come to the forefront. It must be noted that the cleat and bedding plane parameters are critical and should be used in rating calculations. When the practicality concept is considered, the RDR-RRI system is thought to be the most effective system. CPRR calculation is also practical as well compared with the other systems. The principal methodology for the data collection for each system is presented in Section 4.2. Although the number of case histories used in the RDR-RRI system is much more than those in the other systems, the variety of data is limited. For example, parameters such as rib condition, cleat, or bedding information were not included. Therefore, in the estimations to be made with this system, the actual field conditions may not be represented precisely, and a broad range of rating values may be obtained. On the other hand, CMCR, the system requiring the largest number of parameters in the calculation, is based on only three case histories. While generating the database, it is recommended to use the field data based on as many reliable, representative parameters and larger sample sizes as possible. If feasible, increase the data of the rating system by performing parametric studies with numerical approaches.

As a result of the evaluation made among empirical classification systems, strong (green) and less strong (yellow) features of each system were determined, as shown in Table 7. It should be noted that this assessment is only the authors' opinion and highlights the strengths and weaknesses, not to praise or disparage a researcher's work but to critique the research.

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

Table 6
Considered and required parameters for rib rating/classifications.

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

* C: Considered; R: Required for calculation.

Table 7
Strong and less strong features of rib rating/classification systems.

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

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

5 Concluding remarks

This study presents the current rib control and support techniques. In the first part of the research, rib failure mechanisms and the factors affecting these failures were evaluated. Accordingly, researchers agreed that the following four parameters most significantly affect rib deformation: rib height, depth of cover, cleat orientation, and coal strength. Since the local conditions, the mine layout, and mining method can play a significant role, it is hard to estimate which of the above-mentioned factors has a more dominant role in rib failure.

During the examination of the rib support and control practices worldwide, it has been concluded that rib monitoring is of great importance. Despite the fact that countries have similar support strategies, differences in practical applications stand out due to the different mining conditions of each country/coal seam. Since rock bolts significantly enhance the rib integrity, they have been installed in almost all cases that require support and where it is possible to apply. Mesh and liner are used as external support to prevent spalling problems in ribs, especially with low stiffness. In addition, the use of cable bolts under extreme conditions has also been reported.

Since well-known rock mass classification systems are not applicable for rib classification, researchers have proposed various classification systems worldwide. The ADRS system is widely used in Australia. In addition, a recent rib rating system, the CPRR system has also been developed for coal mines in the U.S. It is anticipated that this system will reach widespread use within the U.S. by updating the database.

According to this research conducted for rib control, the following rib support/control methodology is summarized by considering their successful applications around the world:

(1) Collecting field data, including parameters affecting rib deformation in accordance with standards and keeping discontinuity-cleat mapping up to date.
(2) Analyzing initial support design with numerical simulations or existing rib classification systems and empirical approaches used in similar field conditions.
(3) Determining threshold limits for the rib and preparing action response or remedial measures for at least three different rib support layouts.
(4) Monitoring the applied primary support design and ground deformation. Apply the secondary support system if necessary. Determine the mine-induced fracture limit and update the bolt lengths. Decide the use of liner or mesh depending on the rib condition.
(5) Updating the design parameters with the aid of monitoring and visual inspection data, and rearranging different rib support action plans if necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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The findings and conclusions in this study are those of the author(s) 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 an endorsement by NIOSH.

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