Published in final edited form as:
Int J Min Sci Technol. 2016 January ; 26(1): 77–87. doi:10.1016/j.ijmst.2015.11.014.

Analysis of the current rib support practices and techniques in U.S. coal mines

Khaled M. Mohamed*, **Michael M. Murphy**, **Heather E. Lawson**, and **Ted Klemetti**
Office of Mine Safety and Health Research, Ground Control Branch, Pittsburgh, PA, USA

Abstract

Design of rib support systems in U.S. coal mines is based primarily on local practices and experience. A better understanding of current rib support practices in U.S. coal mines is crucial for developing a sound engineering rib support design tool. The objective of this paper is to analyze the current practices of rib control in U.S. coal mines. Twenty underground coal mines were studied representing various coal basins, coal seams, geology, loading conditions, and rib control strategies. The key findings are: (1) any rib design guideline or tool should take into account external rib support as well as internal bolting; (2) rib bolts on their own cannot contain rib spall, especially in soft ribs subjected to significant load—external rib control devices such as mesh are required in such cases to contain rib sloughing; (3) the majority of the studied mines follow the overburden depth and entry height thresholds recommended by the Program Information Bulletin 11-29 issued by the Mine Safety and Health Administration; (4) potential rib instability occurred when certain geological features prevailed—these include draw slate and/or bone coal near the rib/roof line, claystone partings, and soft coal bench overlain by rock strata; (5) 47% of the studied rib spall was classified as blocky—this could indicate a high potential of rib hazards; and (6) rib injury rates of the studied mines for the last three years emphasize the need for more rib control management for mines operating at overburden depths between 152.4 m and 304.8 m.

Keywords

Coal rib; Rib sloughing; Rib rolling; Rib support design; Rib control techniques; Rib bolts

1. Introduction

Efforts to improve the stability of underground mine ribs have continued for decades. These efforts by mining professionals around the world persisted throughout the 1990s and 2000s as well, though much of this work focused on rib support methodology and selection of proper support for a specific location. Despite these efforts, it is unfortunate that there has been a continual occurrence of rib-related fatalities in underground coal mines. While overall improvements in rib safety have been achieved, the average fatality rate is still about 1.3 per year over the last 18 years [1].

* Corresponding author. Tel.: +1 412 3864077. kmohamed@cdc.gov (K.M. Mohamed).

To manage and control the rib hazard, rib support is used in U.S. coal mines. The current rib support methods for U.S. mines fall into two main categories: rib control based on intrinsic support systems and those based on external support systems. Intrinsic or rib-bolt support requires a roof bolting machine that can install a bolt fixture into the rib. Furthermore, the appropriate level of support needed to control the ribs with an intrinsic-based support system as well as the design parameters for those support systems for various mine conditions have not been established in U.S. coal mines. Furthermore, surface control systems are often an integral part of these support systems and must be considered in the system design.

For mines that do not have the capability to install rib bolts, external rib controls are used, in the form of rib props, vertical fixtures anchored to the roof and/or floor, and pillar banding (the wrapping of pillars with support materials). Banding of pillars can be effective but in many cases is not a very practical method to control the ribs, especially when pillar recovery mining is planned. Rib control through the use of props provides a more practical solution for these mines. However, no design criteria or guidelines have been established for prop-type support systems for rib control.

The design of rib support systems in U.S. coal mines is based primarily on local practices and experience. A better understanding of current rib support practices in U.S. coal mines is crucial for developing a sound engineering rib support design tool.

The objective of this paper is to analyze the current practices of rib control in U.S. coal mines. Twenty (20) underground coal mines were studied representing various coal basins, coal seams, geology, loading conditions, and rib control strategies.

2. Description of coal mine rib database

Twenty underground coal mines were studied between 2012 and 2014. Up to five sites were studied at each mine during single-day visits. Despite limitations in access to a large number of operating coal mines, the studied mines provided detailed information for each site. The information presented in this study has not been provided by any of the studied mines; it was solely collected by the authors.

Half of the studied mines are classified as supported rib mines that include rib-bolt support (Table 1). They are referred to as SR 1 to SR 10. The other halves of the mines are classified as unsupported rib mines that do not include rib-bolt support (Table 2). They are referred to as USR 1 to USR 10. A total of 61 case studies (sites) were collected from the studied mines. The site names are composed of two parts—the mine name and the site number. The sites were chosen to represent different loading conditions (development, pillaring, and longwall head and tailgate loadings), different overburden depths, different entry heights and different geological features and stone percentages. It is important to note that the investigated sites are only snapshots of isolated locations and do not represent a comprehensive picture of the mine.

The studied mines are located in five coal basins: Northern Appalachian, Central Appalachian, Illinois, Unita, and Powder River (Fig. 1). The studied mines are operating in twelve coal seams. Five mines are in the Herrin coal seam. The Herrin coal seam has some

Author Manuscript
Author Manuscript
Author Manuscript

regional variation in nomenclature, such as the Herrin No. 6 seam in Illinois, the Herrin No. 11 seam in Western Kentucky, and the Herrin seam in Indiana. Three mines are operating in the Pittsburgh No. 8 seam, two mines in the Eagle seam, and two mines in the Springfield coal seam. The rest of the mines are operating in the Mammoth, No. 2 Gas, Imboden, Kellioka, Pocahontas No.3, Upper B, D2, and Taggart coal seams. The Herrin No. 6 and Pittsburgh No. 8 coal seams are the most heavily represented seams in this study.

Twelve of the studied mines are room-and-pillar mines and eight are longwall mines. The room-and-pillar mines operating in Illinois Coal Basin do not perform pillar extraction. The unsupported mines come almost entirely from the Illinois Coal Basin, whereas the majority of the supported mines come from the Appalachia Coal Basin.

3. Current practices of rib control in U.S. coal mines

30 Code of Federal Regulations (CRF) states that "the roof, face and ribs of areas where persons work or travel shall be supported or otherwise controlled to protect persons from the hazards related to falls of the roof, face or ribs and coal or rock bursts", cited in *Code of Federal Regulations* in 2010, America. Currently, there are no minimum design requirements for rib support. This study is part of a larger effort to develop a rib support design tool. The crucial questions toward this end are:

(1) What are the applied rib control techniques in U.S. coal mines?

(2) What are the factors affecting rib performance?

(3) How effective are the applied rib control methods to prevent rib injuries and fatalities in U.S. coal mines?

3.1. Rib control techniques applied in U.S. coal mines

The applied rib control techniques observed in underground coal mines include the following: (1) re-orienting the roadways with respect to the orientation of the cleat system in the coal seam, (2) installing intrinsic rib support systems in the form of bolts with or without meshes, (3) installing external rib support systems in the form of meshes (steel and synthetic), props, vertical fixtures anchored to the roof and/or floor, and pillar banding, etc., and (4) applying several of these methodologies simultaneously.

3.1.1. Roadway driving direction—Underground observations show that the stability of the face and the ribs in roadways depends on the relative orientation of the roadway with the strike direction of the face (principal) cleat [3]. Under unfavorable roof and/or floor conditions, such as weak roof and floor heave, the cleat system in coal seams could promote rib sloughing. Ribs in roadways tend to be in good condition when the face line is parallel to the principal cleat orientation. Rib stability problems are likely to occur when the angle between the roadway driving direction and face cleat orientation is less than 30° [3]. Face cleat orientation has the largest impact on rib performance during the development stage of mining, while during pillar extraction or longwall retreat its impact on rib performance is secondary [4].

The orientations of face cleats with respect to the driving direction of the roadways (entries and cross-cuts) were measured. Fig. 2 shows the average orientation of face cleats with respect to the direction of the mine entry. It shows that 50% of unsupported and 60% of supported entries are driven at angles greater than 30% with respect to the face cleat system. It appears that the entry orientation at the studied mines is based on factors other than the rib stability-for example, roof stability or horizontal stress, but these factors are not addressed in this research.

It was not possible to evaluate the effect of the face cleat orientation on the measured rib spall volume because of the inherent difficulties in separating the influence of overburden depth and other geological features on the measured rib spall volume.

3.1.2. Intrinsic or rib-bolt support system—Intrinsic rib support systems involve bolts (non-cuttable and cuttable) installed into the ribs. Non-cuttable rib bolts are made of steel, while cuttable rib bolts are made of fiberglass or plastic. Rib bolts are categorized based on their anchorage mechanism into Mechanical (M), Grouted (G), and Mechanical/Grouted (M/G) bolts. Mechanical and mechanical/grouted anchorage rib bolts are always tensioned during installation.

Rib bolts are designed to resist both tension and bending loads [4]. Hence, rib bolts support/reinforce the ribs of roadways through one or more of the following mechanisms: (1) anchoring unstable rock and/or coal into an intact portion of pillar or into the roof, (2) resisting the lateral deformation of the solid rib through frictional interlock between the grout and the rib, or by anchoring the fixture into the intact pillar, roof and/or floor, and (3) containing rib sloughing by anchoring meshes into the intact pillar, roof, and/or floor.

Table 3 summarizes the rib-bolt support systems that are applied in the supported sites. The design parameters of rib-bolt support systems are bolt type, grade, diameter, length, number of rib bolt per row, dimensions of bearing/surface plates, and coverage area of mesh if they are applied.

Steel bolts are applied in all supported sites, with the exception of two. Fiberglass bolts were installed at two sites in mine SR 2. Both fully grouted and mechanically anchored rib bolts are used equally. Two sites are using the mechanical/grouted anchored bolts. About sixty percent of the sites are using 16 mm diameter bolts, followed by 20% using 19 mm diameter, and 20% using 22 mm diameter. The length of rib bolts varies from 1.07 to 1.83 m. The majority of the rib bolts are 1.2 m long. The spacing of rib bolts varies between 1.2 and 3.6 m. Figs. 3 and 4 show the distribution of the rib spall volume per meter along the entry versus the bolt diameter and the length of the installed bolts, respectively. Figs. 3 and 4 also show that the largest rib sloughing is observed when longer, larger diameter bolts are installed. It appears that the studied mines choose rib bolts (diameter and length) through reactive action in which longer, i.e. larger diameter bolts are selected to support large rib spalls.

Almost half of the investigated sites use a single row of rib bolts, and the remaining sites use two rows of rib bolts. The exception to this observation is one site (SR 10-1) that uses three rows of rib bolts. There could be many reasons this mine made the decision to install three rows of rib bolts, such as a high overburden depth of 533m, a high mining height of 3 m, and a bone coal bench at the top section of the rib.

The design parameters of rib-bolt support systems are different from those of roof-bolt support systems. At the studied sites, rib bolts are usually a shorter, smaller diameter than the installed roof bolts. The diameter of rib bolts is smaller than the diameter of roof bolts at 72% of the studied sites. The length of rib bolts is shorter than the length of roof bolts at 84% of the sites. For about half of the sites, the rib bolts and roof bolts are installed at the same spacing (about 1.2 m). The other half of the sites install rib bolts at spacing up to three times the roof bolt spacing.

Rib bolts on their own cannot contain rib spall, especially in soft ribs subjected to significant load. Steel or synthetic meshes are required in such cases to contain rib sloughing. Mesh supports (chain link, steel, and plastic meshes) are installed at about 26% of the supported sites. Mesh supports are usually used in mains, tailgate, pillar corners, and areas subjected to multiple-seam interactions.

The performance of the rib bolt systems at the studied sites could be verified using visual observations. The following example is illustrated through photographs of the mains at mine SR 1. The ribs in the mains show significant sloughing, likely due to the influence of multiple-seam-interactions. Fig. 5a shows that the angled rib bolts were installed in soft coal band at about 0.76 m off the roof line. Fig. 5a also shows an isolated rib bolt still anchored into intact roof, but around which the rib has sloughed away. The rib bolts alone could not stop the sloughing of coal from between bolts. Fig. 5b shows the aftermath of failed rib bolts: extensive sloughing of rib material and partial brow formation. It is clear from these examples that rib bolts alone were insufficient to prevent rib sloughing at the studied sites. Use of adequate rib mesh would have likely been beneficial in mitigating the adverse effects of the multiple-seam interaction at the example mine.

3.1.3. External rib support—External rib support systems are structural elements that are not a part of the rib itself. In other words, unlike rib bolts, they are not installed into, but rather installed externally onto the rib. They are erected adjacent to or overlaid onto the roadway ribs. There are many types of external rib support, such as props, mesh held in place with props, fixtures anchored to the roof and/or floor, spray membranes, and pillar banding. External rib control methods support the ribs of roadways through the following mechanisms: (1) containing the softening/sloughing portions of the rib, and (2) restraining the lateral deformation of the detached rib. Primary external rib supports are installed during roadway advance while secondary (supplementary) rib supports are installed later on an as-needed basis.

Primary external rib supports are applied at 40% of supported mines. The studied primary external supports are: (1) welded steel mesh at mines SR 2, SR 3, SR 9, and SR 10, (2) synthetic mesh at mines SR 9 and SR 10, and (3) chain-link mesh and angle brackets attached to the roof at mine SR 10. Primary external rib supports are applied in the studied mines for the following purposes:

(1) to contain the rib sloughing at long-term mine workings, such as in the mains of mines SR 2, SR 3, and SR 10,

(2) to contain rib sloughing of roadways subjected to high over-burden depths and/or multiple-seam interactions, such as in mine SR 9, or

(3) to replace some of the primary rib bolts, as in mine SR 10.

Secondary (supplementary) external rib supports are applied at fives supported mines and two unsupported mines. The secondary external supports are: (1) welded steel mesh at mine SR 5, (2) synthetic mesh at mines SR 4, SR 5, and SR 7, (3) timber props at mines SR 5, USR 4, and USR 9, (4) steel props at mine SR 9, and (5) steel channels and angle brackets at mine SR 3. Secondary external rib supports are applied in the studied mines for the following purposes:

(1) to support formed rib brows when rib sloughing exists below the bottom row of primary rib bolts (Fig. 6a),

(2) to stabilize fractured rib brow at pillars corners (Fig. 6b),

(3) to stabilize pillar corner of mains (Fig. 7a),

(4) to contain excessive chain pillar deformation because of tail-gate loading (Fig. 7b),

(5) to restrain detached rib slabs (Fig. 8), or

(6) to limit the span of entries that exceed the designed width and/or height (Fig. 9).

One or more external primary support methods were applied at 40% of the supported mines. Secondary external rib support methods are applied at 50% of the supported mines and for 20% of the unsupported mines. Therefore, any rib design tool should consider the applicability of external rib supports.

3.2. Factors affecting rib performance

Mine geometry, geologic features, multiple-seam interactions, and support density are the main influences on rib performance. These factors were identified for the studied mines, as described below.

3.2.1. Mine geometry—In 2011, the Mine Safety and Health Administration (MSHA) issued a Program Information Bulletin (PIB) 11-29 recommending the application of rib support systems in coal mines deeper than 210 m and whose entry heights exceed 2.1 m, cited in *Program Information Bulletin* PIB11-29. 2011, MSHA.

Tables 1 and 2 summarize the geometrical data (overburden depth and entry height) of the supported and unsupported sites, respectively. Table 1 shows that the overburden depths at the supported sites are 187–765 m with an average overburden depth of 369 m. Table 2 shows that the overburden depths at the unsupported sites are 190–777 m with an average overburden depth of 375 m. The mining heights at the supported sites range from 45.7 to

335.4 m with an average height of 2.6 m. The mining heights at the unsupported sites range from 1.8 to 3.0 m with an average height of 2.3 m.

Fig. 10 shows the distribution of mining heights and overburden depths at the investigated sites, and it also shows that most of the unsupported sites (about 78%) are operating at overburden depths of less than 210 m. Only two unsupported mines (USR 2 and USR 10, marked by hollow diamonds in Fig. 10 are operating at overburden depths greater than 210 m. The decision not to support the coal ribs at mine USR 2 despite high overburden depth (about 250 m) could be explained by low mining height (about 1.9 m) and no pillar extractions. The ribs at mine USR 10 are supported on an as-needed basis during pillar extraction which allows for mining with unsupported ribs at overburden depths greater than 210 m. Fig. 10 shows an inverse correlation between the mining height and overburden depth for the unsupported rib sites. As the overburden depth increases, the unsupported roadways have smaller mining heights.

Fig. 10 shows that all the supported sites are operating at over-burden depths greater than 210 m except for mine SR 4 and site SR 6-1 (marked as hollow squares in Fig. 10). The decision to support coal ribs at mine SR 4 despite shallow overburden depths (less than 210 m) could be attributable to the large mining height—2.1 m in this case. The collected data at site SR 6-1 was not sufficient to explain the decision about overburden depths made at this site.

The majority of the studied mines (78% of the unsupported mines and about 90% of the supported mines) follow the overburden depth and entry height thresholds recommended by the PIB-29.

The impact of overburden depth on rib performance was assessed by measuring the rib spall volume per meter along the entry. Fig. 11 shows the distribution of the rib spall volume versus the overburden depth for supported and unsupported sites. The unsupported sites have a wide range of rib spall (0–0.23 m^3/m) at an overburden depth of about 150 m. With the exception of sites: USR 9-1, USR 9-2, and USR 4-2 (marked by hollow diamonds in Fig. 11), the unsupported sites showed no rib spall for overburden depths less than 150 m. The effects of geology on those particular sites will be addressed in the next section.

Fig. 11 shows that the supported rib sites have no rib spall at overburden depths less than 270 m. The supported sites showed a wide range of rib spall (0–0.43 m^3/m) at 270 m. Decay in rib spall is observed as the overburden exceeds 300 m, except for sites: SR 9-3 and SR 9-4 (hollow squares in Fig. 11). This behavior has been observed previously and may be explained by the emphasis on the quality of rib support at high overburden depths [1].

3.2.2. Geological features—The geological features at observed sites are the percentage of stone in entry height, in the form of partings of roof or floor rock mined with the coal, and the presence of discontinuities (partings, slickenside, bone coal, etc.).

To assess whether the presence of stone in the rib profile influences the decision to use rib support, the percentage of stone in a vertical cross section of the rib was plotted against the number of sites in which rib support was or was not employed. Fig. 12 shows the histogram of stone percentage for both supported and unsupported sites regardless of the overburden depth. It shows that the numbers of supported and unsupported sites are similar for stone percentage less than 30%, while the number of supported sites are 1.7 times the number of unsupported sites for stone percentage greater than or equal to 30%. It could be concluded that the ribs whose stone percentage is greater than 30% are usually supported. This raises the question of how the overburden depth at these locations influences this observation.

To address this issue, the distribution of stone percentage versus overburden for both unsupported and supported sites was considered (Fig. 13). It shows that many ribs with a high stone percentage (greater than 35%) are not supported for shallow mines (less than 60 m deep). Those sites with a high stone percentage at mine USR 10 are not supported even when overburden depth exceeds 210 m; they maintain their practice of installing support on an as-needed basis, regardless of the percentage of stone in the rib and overburden depth. The low stone percentage (less than 30%) at mine USR 2 (marked by hollow diamonds in Fig. 13) may have played a rule into the mine's decision not to support the ribs, even when the overburden depth exceeds 210 m. Despite the low overburden depth (less than 210 m) at mine SR 4 and site SR 6-1 (hollow squares in Fig. 13), the decision was to support coal ribs for those sites.

The collected data is not conclusive regarding the influence of stone percentage on the rib control management, but the mutual interaction between the stone percentage and the overburden depth appears to correlate with the use of rib support.

About 68% of the supported sites are affected by geological features (Table 1). On the other hand, about 34% of the unsupported sites are affected by geological features (such as partings, slicken-side and bone coal) (Table 2). The rib profiles at the supported sites are usually composed of one or more thick rock strata interbedded with one or more thin coal benches.

Potential rib instability may occur when certain geological features prevail—these include draw slate and/or bone coal near the rib/roof line, claystone partings, and soft coal bench overlain by rock strata. The rib bolting objectives in such cases are:

(1) supporting the top rock by anchoring it to the intact roof strata above the rib. The top rock is usually supported using rib bolts angled up at 30–45° and located at a distance approximately 0.6 m from the roof line, or

(2) supporting detached coal/rock slabs by one or two rows of bolts. The bottom bolts are usually installed horizontally and should be long enough to anchor the detached slabs to the intact part of coal rib.

The impact of strong contact between (1) the top section of rib and immediate roof, and (2) the coal seam and rock strata on the rib performance can be demonstrated by mines SR 6 and USR 10. The rib at mine SR 6 is composed of 1.2 m of coal overlain by 0.9–1.2 m of shale (stone). A single row of fully grouted bolts is installed at about 0.5 m from the roof line and angled up at 30° (Fig. 14a). The bolts are 1.5 m long, installed at spacing of 2.4 m. The rib bolts were installed during the development cycle. The objective of the rib bolts is to anchor the top shale unit to the sandstone stone strata above the rib. During pillar extraction, a continuous miner (CM) was able to safely mine only the coal bench. The shale unit remained attached to the immediate roof for two pillar lengths inby the face.

Mine USR 10 has a very similar mine geometry (overburden depth and mining height) to mine SR 6. The rib at mine USR 10 is composed of 0.9–1.5 m of coal overlain by 0.9–1.2 m of shale. Unlike mine SR 6, a rider seam at the top section of the rib was easily separated from the immediate roof. This facilitated the detachment of the underlying shale unit which easily broke off. This condition was exacerbated by the fact that the shale unit was underlain by a bright coal bench that tended to slough easily (Fig. 14b). Mine USR 10 tried different bolt designs to support the shale unit, but none were successful. Full mesh would have solved this problem.

The impact of claystone partings on the rib performance can be demonstrated by mine SR 5. The immediate roof is sandstone. The coal seam at mine SR 5 has three benches. The rib shows very little to no deterioration during entry development, with the exception that within a few days rib brows begin to form. Rib bolting is done as part of the development cycle and consists of two rows of 1.2 m fully grouted bolts installed at 1.2 m spacing. The upper row of rib bolts is angled up at 30–45°, and the lower row of rib bolts is installed horizontally. During the mine visit, it was observed that rib brows formed wherever the rock shale is underlain by a clay-stone parting and soft coal bench (Fig. 14c).

The coal seam at sites USR 9-1 and USR 9-2 is about 0.9–1.2 m thick underlain by thick clay and stone bands of about 0.6–0.9 m (Fig. 15). Regardless of the low overburden depth (less than 60 m) at sites USR 9-1and USR 9-2, large rib slabs were formed due to squeezing of the clay band at the bottom section of the rib (Fig. 15). Significant spall volume at site USR 4-2 was attributed to slickenside planes cutting the rib (Fig. 16).

3.2.3. Rib support density—Colwell et al. developed an empirical model to rate the rib support density for Australian coal mines [4]. The model was developed for ribs that are supported by bolts both with and without mesh. The rib support rating (RIBSUP) is estimated as

$$RIBSUP = \frac{L_{rb} \times N_{rb} \times \sqrt{Sh_{rb}}}{S_{rb} \times h} + \sqrt{\frac{A_{fp}}{A_{sp}}} + \left[1+3 \times \frac{A_s}{100}\right]$$

where L_{rb} is the length of the rib bolt/dowel in meters; N_{rb} the average number of bolts/ dowels per vertical row; Sh_{rb} the typical shear strength of the rib bolt/dowel in kilo-Newton; S_{rb} the spacing between vertical rows of bolt/dowels in meters; h the development height in meters; A_{fb} the area of face plate, m^2; A_{sp} the area of standard plate, m^2, and A_s the percentage of surface area covered.

Steel plates with dimensions 0.165 m^2 are the most commonly used in the studied mines. Therefore, the area of standard plate (A_{sp}) as assumed to be 400 mm × 400 mm.

The rib support (RIBSUP) rating was calculated to estimate the density of rib support at the supported sites (Table 3). Fig. 17 shows the histogram distribution of rib support density for supported sites. It shows that the supported sites can be divided into two groups: (1) low-density support sites in which RIBSUP is less than 4, and (2) high-density support sites in which RIBSUB is greater than 6. The latter includes sites where bigger bolts with narrow spacing are installed both with and without liners.

To assess the impact of overburden depth of rib support density, the distribution of these values was plotted (Fig. 18). The sites of low-density rib support are marked by squares and diamonds marks the high-density support sites. With the exception of site SR 3-4, (marked by hollow square in Fig. 18), the overburden depths at the low-support sites are less than 380 m. Sites with low support densities are usually free of excessive loading conditions such as multiple-seam interactions and tailgate side loading. The RIBSUP rating of the sites of low-density support do not correlate with overburden depth.

It should be noted in Fig. 18 that squares means low-density support sites, while diamonds indicate high-density support sites.

The high-density support sites could be subdivided into two subgroups: (1) low overburden depth sites of less than 315 m (marked by black diamonds in Fig. 18) in which the high-support rating was achieved through bolt design (such as SR 1 mine) or using mesh in addition to rib bolts (such as sites SR 4-2 and SR 7-1), and (2) high overburden depth sites of more than 493 m (marked by red diamonds in Fig. 18) in which mesh is consistently used in addition to rib bolts.

Fig. 19 shows the distribution of rib support rating versus the spall volume, and it shows that there is no correlation between the applied rib support density and the measured spall volume. The spall volume ranges from 0 to 0.43 m^3/m for both low- and high-rib support densities.

3.2.4. Multiple-seam interaction—Multiple-seam mining was recorded for two unsupported mines (USR 5 and USR 7) and three supported mines (SR 1, SR 3, and SR 5). The interburden thicknesses at unsupported mines USR 5 and USR 7 are 19.5 and 31.2 m, respectively. The interburden thicknesses at supported sites SR 1, SR 3, and SR 5 are 55, 114, and 144 m, respectively.

There were no additional measures (such as standing rib support) implemented at mines USR 5 and USR 7 to address the effect of multiple-seam-interactions. This is because of shallow overburden depths and no pillar extraction practices. The measured rib spall at mines USR 5 and USR 7 were 0 and 0.09 m^3/m-long, respectively.

High-support densities were applied at mines SR 1 and SR 3, while support density at mine SR 5 was low. This contrast could be explained by relatively lower overburden depth and relatively large interburden thickness at mine SR 5 compared with mines SR 1 and SR 3.

3.3. Effectiveness of rib control to prevent rib injuries in the studied mines

Based on the shape and size of the spalled ribs, four types of rib failures were identified: slabby, slabby/blocky, blocky, and friable. The type of rib failure can be one of the most significant components of the overall hazard of rib failure. In a previous study for the rib fatalities in underground coal mines, it was found that 74% of rib fatalities resulted from blocky types of different mechanisms (brow, mine-induced fracture, and slippage along plane of weakness such as slickenside or joint) [1].

Tables 1 and 2 list the type of rib failure at each site, they show that 47% of the rib spall was classified as blocky—this could indicate a high potential of rib hazards.

The rib injury data for the studied mines was obtained from the U.S. Mine Safety and Health Administration databases, cited in Accident, Illness and Injury and Employment Self-Extracting Files in 2011–2013, MSHA. The acquired data for each mine was composed of the number of non-fatal day loss operator injuries and total operating hours for the period of 2011–2013. Rib-outburst-related injuries were excluded from this study because outbursts are likely to be influenced by a variety of factors independent of rib support and are beyond the scope of this research. Injury rates were computed by calculating the number of rib incidents in the period of 2011–2013 for every 200,000 h/year.

The overburden depth at the studied mines by far is the most influential factor on rib control. Therefore, the impact of rib control management at the studied mines was assessed by correlating the overburden depth to the computed rib injury rate. The MSHA database does not include the overburden depth at the injury site. Therefore, the overburden depth was computed from an overburden map for each mine as an average overburden depth for the period of the study (2012–2013). Fig. 20 shows the distribution of rib injury rate versus the calculated overburdens at the investigated sites, and it shows that there is no reported rib injury for mines operating at an overburden depth less than 150 m, with the exception of one case at mine USR 4. The highest rib injury rates are reported for the unsupported and supported mines that are operating at overburden depths between 150 and 300 m. Deep mines (greater than 300 m) showed no reported rib injuries, except for mine SR 9.

Fig. 20 emphasizes the need for more rib control management for mines operating at overburden depths between 150 and 300 m. Similar observations were drawn from the analysis of rib fatalities between 2010 and 2013. The rib fatality rate at mid-depth mines (213–380 m) was found to increase by 225% compared with low-depth mines (less than 213 m). Meanwhile, the rib fatality rate at deep (greater than 380 m) mines was reduced by 61% compared with mid-depth mines [1].

4. Summary

Twenty underground coal mines were studied to identify current rib control practices in U.S. coal mines. The studied mines were selected to represent various coal basins, coal seams, geology, loading conditions, and rib control strategies. The collected information will be used to develop a rib support design tool for U.S. coal mines.

The major findings of this paper are:

(1) At the studied mines, rib bolts are designed based on reactive actions; in which longer and larger diameter bolts are selected to support large rib spalls.

(2) Rib bolts on their own cannot contain rib spall, especially in soft ribs subjected to significant load. External rib control devices such as mesh (such as; chain link, steel and plastic) are required in such cases to contain rib sloughing.

(3) One or more external primary support methods were applied at 40% of the supported mines. Secondary (supplementary) external rib support methods were applied at 50% of the supported mines and at 20% of the unsupported mines. Therefore, any rib design tool should consider the application of external rib supports.

(4) The majority of the studied mines follow the overburden depth and entry height thresholds recommended by the Program Information Bulletin (PIB) 11-29.

(5) The collected data is not conclusive regarding the influence of stone percentage on rib control management, but the mutual-interaction between the stone percentage and the overburden depth appears to correlate with the use of rib support.

(6) The number of geological features at supported sites is twice those of the unsupported sites. Potential rib instability occurred when certain geological features prevailed—these include draw slate and/or bone coal near the rib/roof line, claystone partings, and soft coal bench overlain by rock strata.

(7) There is no correlation between the applied rib support density and the measured spall volume.

(8) At unsupported mines of shallow overburden depths with no pillar extraction practices, there were no applied measures (such as standing rib support) to address the effect of multiple-seam interactions.

(9) Forty-seven percent of the observed rib spall was classified as blocky; this could indicate a high potential of rib hazards.

(10) Rib injury rates of the studied mines stress the need for more rib control management for mines operating at overburden depths between 150 m and 300 m.

Acknowledgments

The authors wish to acknowledge Dr. Tristan Jones for his efforts in collecting much of the field data supporting the results of this paper while employed at NIOSH.

References

1. Jones, T.; Mohamed, K.; Klemetti, T. Investigating the contributing factors to rib fatalities through historical analysis.. Proceedings of the 33rd international conference on ground control in mining; Morgantown. 2014; p. 113-22.
2. East JA. Coal fields of the conterminous United States: national coal resource assessment updated version. U.S. geological survey open-file report 2012-1205. 2013
3. Paul, Holmes. Relations between geology and the stability of faces and roadways in the Barnsley seam. Dev Geotech Eng. 1981; 32:118–22.

4. Colwell, MG.; Mark, C. Analysis and design of rib support (ADRS): a rib support design methodology for Australian Collieries.. Proceedings of 24th international conference in ground control in mining; Morgantown, WV. 2005; p. 12-22.

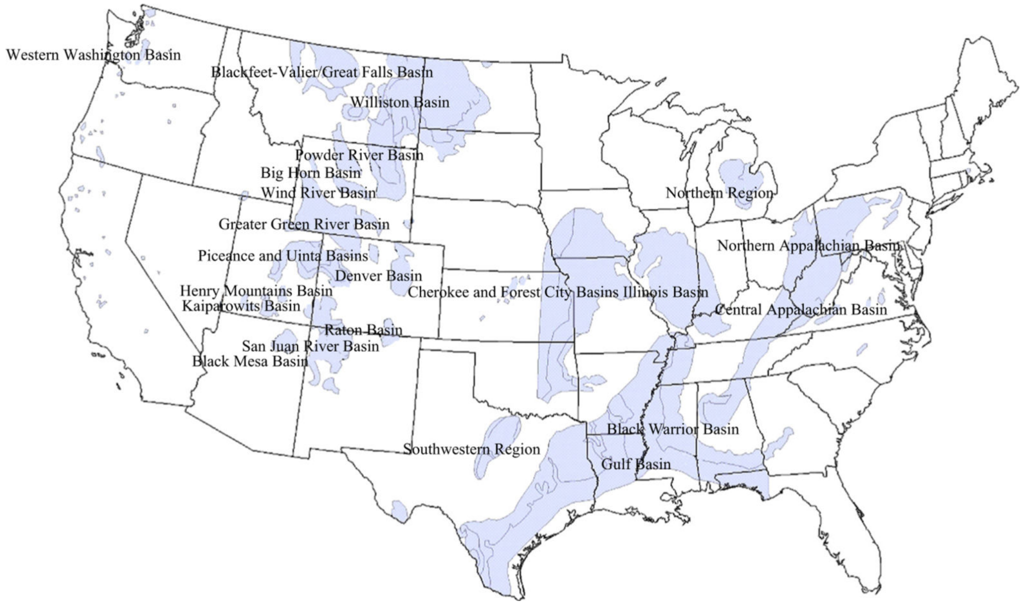


Fig. 1.
US coal basins [2].

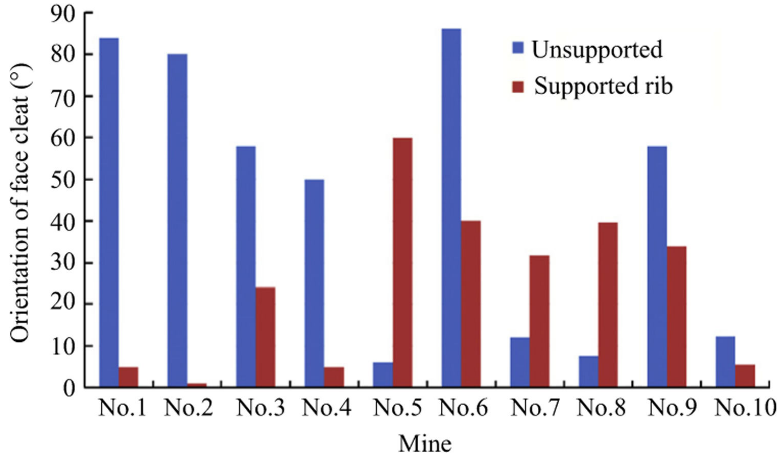


Fig. 2.
Average face cleat orientation with respect to the driving direction of the mine entry.

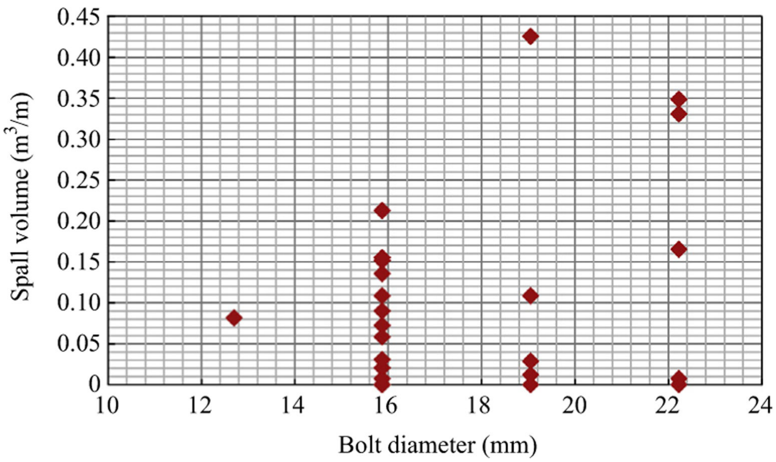


Fig. 3.
Bolt size vs. rib spall volume at the surveyed sites.

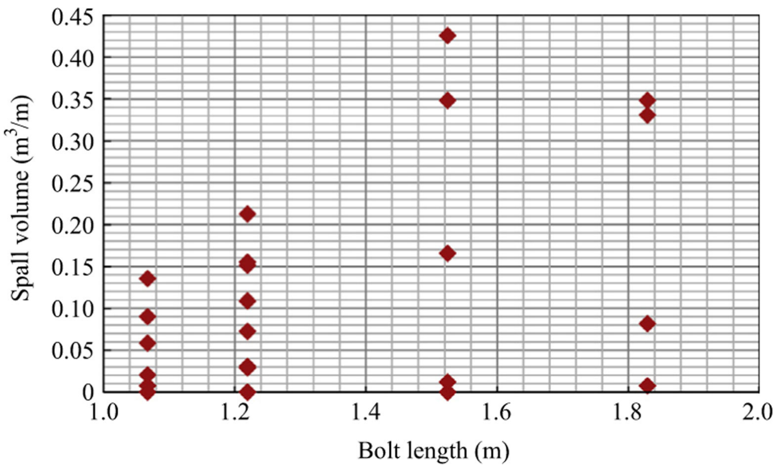


Fig. 4.
Bolt length vs. rib spall volume at the surveyed sites.

(a) Isolated rib bolts (b) Failed rib bolts

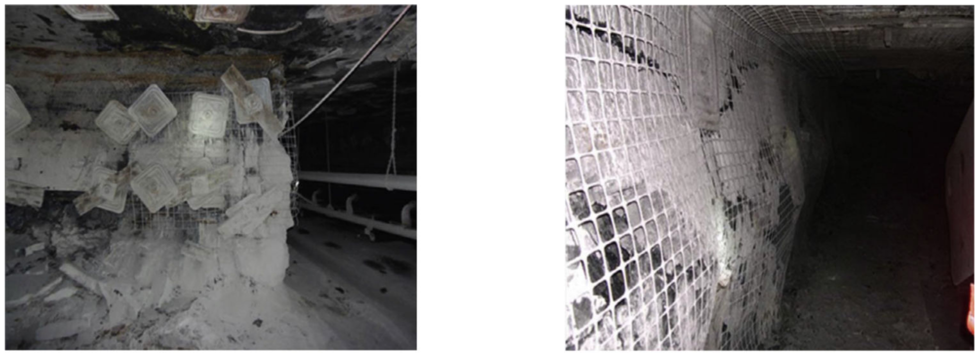
Fig. 5.

Inadequate rib bolting in the mains of mine SR 1.

(a) Rib brow with spalling extended above the bottom row of rib bolts

(b) Fractured brow at intersection

Fig. 6.
Timber props (152 mm × 152 mm) used as secondary supports at the SR 5 mine.



(a) 1.21 m straps of welded steel mesh at the pillar corner of mains, mine SR 5

(b) Synthetic grid mesh at the tailgate entry, mine SR 4

Fig. 7.

External liner support.

(a) Mine USR 4 (b) Mine USR 9

Fig. 8.

Timber props (152 mm × 152 mm) restraining detached rib slabs.

Fig. 9.
Steel channels and timber props at SR 5 mine installed at an entry that exceeded the design width and height.

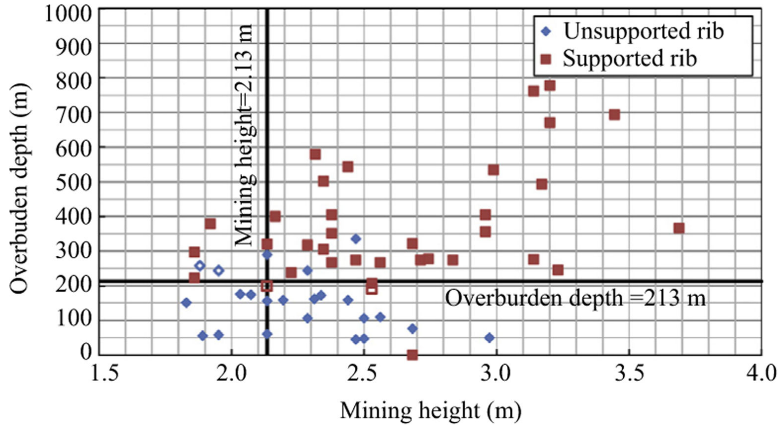


Fig. 10.

Mining height vs. overburden depth at the surveyed sites.

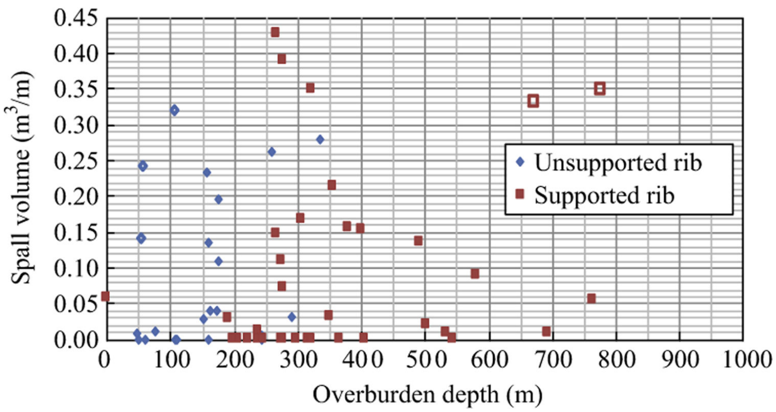


Fig. 11.

Overburden depth vs. rib spall volume at the surveyed sites.

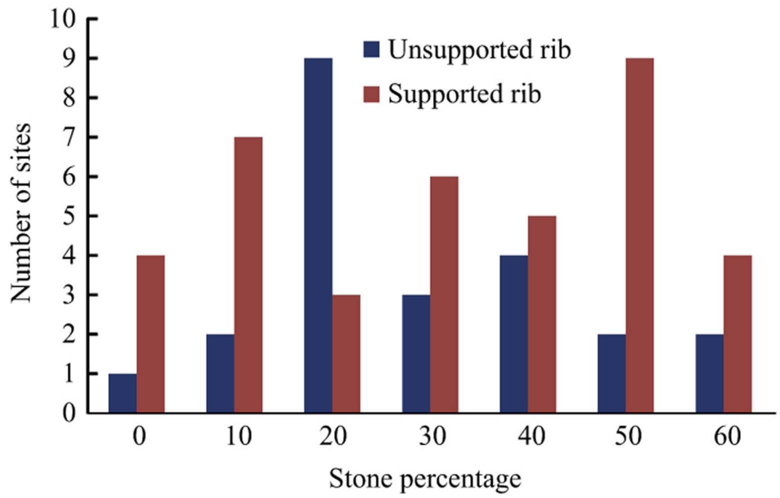


Fig. 12.
Distribution of stone percentage in the surveyed sites.

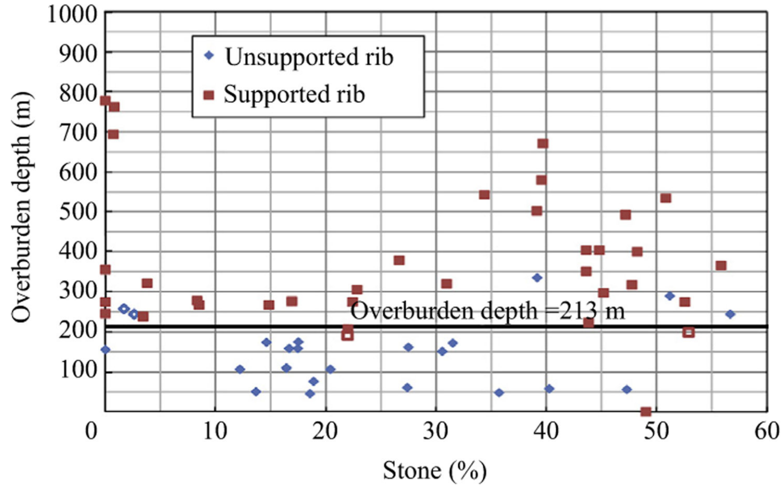


Fig. 13.

Stone percentage vs. overburden depth at the surveyed sites.

(a) Strong contact between the top section and immediate roof in mine SR 6

(b) Weak contact between the top section and immediate roof in mine USR 10

(c) Clay band in the rib at mine SR 5

Fig. 14.

Effect of geological features on rib performance.

Fig. 15.
Large slab formed as result of a thick clay band squeeze at mine USR 9.

Fig. 16.
Large slab formed as result of slickenside plan chuting the rib at mine USR 4.

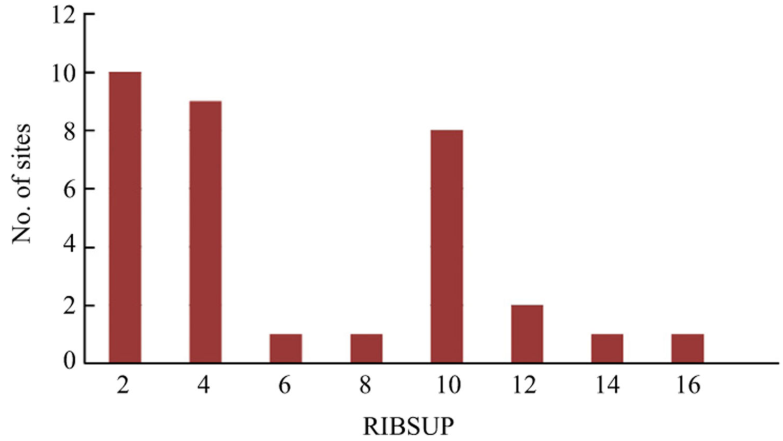


Fig. 17.
Distribution of rib support (RIBSUP) rating at the surveyed sites.

Author Manuscript
Author Manuscript
Author Manuscript

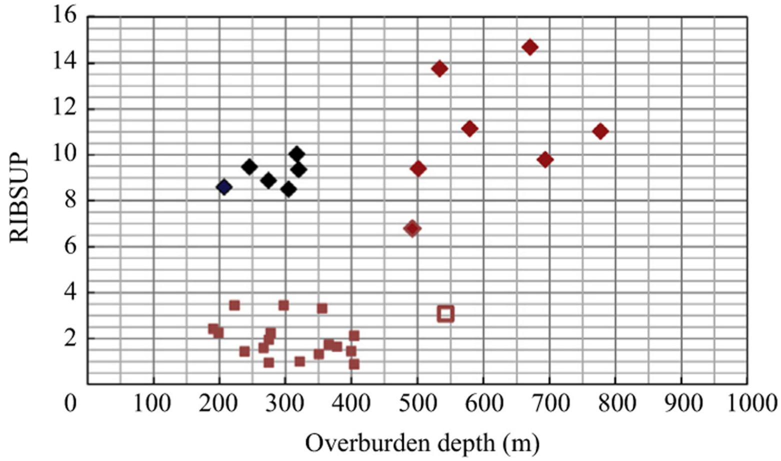


Fig. 18.
Overburden depth vs. RIBSUP at the surveyed sites.

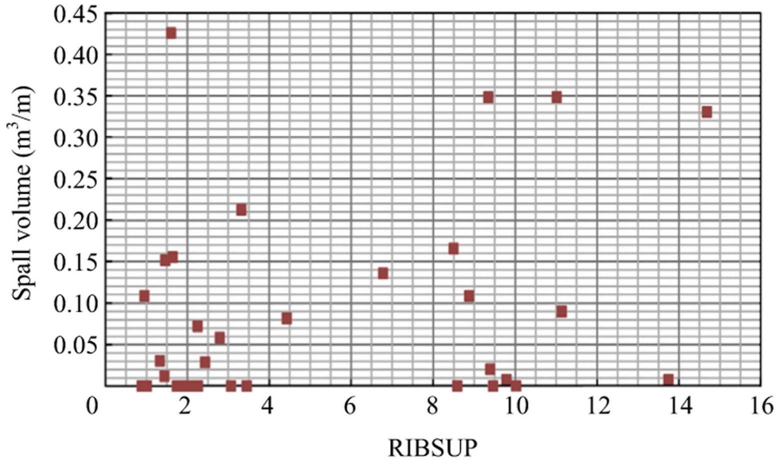


Fig. 19.
RIBSUP vs. spall volume at the surveyed sites.

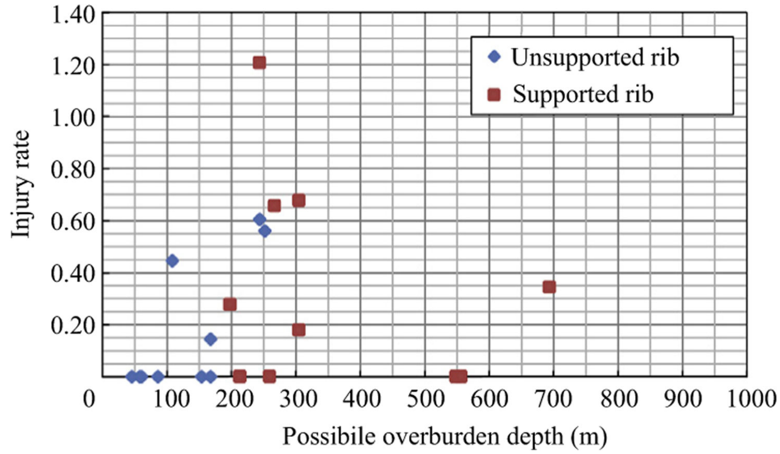


Fig. 20.

Non-fatal days lost (NFDL) operator rib incidence rate vs. overburden depth at the surveyed sites for 2011–2013.

Table 1

Geometrical data and geological features at the supported sites.

Mine name	Mine type	#Site	Mining cycle	Over-burden depth (m)	Entry height (m)	Stone (%)	Geologic feature	Spall volume (m^3/m)	Type of rib failure
SR 1	R&P	SR 1-1	DEV	317.1	2.3	48	No	0	None
		SR 1-3	DEV	320.1	2.1	23	Yes	0.165	2
		SR 1-2	DEV	304.9	2.3	31	Yes	0.349	2
SR 2	LW	SR 2-1	DEV	274.4	2.7	22	Yes	0.109	3
		SR 2-2	HGS	237.8	2.2	3	Yes	0.012	3
		SR 2-3	HGS	237.8	2.2	3	Yes	0	3
		SR 2-4	TGF	266.8	2.4	9	Yes	0.426	3
		SR 2-5	TGF	266.8	2.6	15	Yes	0.147	3
SR 3	R&P	SR 3-1	DEV	492.4	3.2	47	Yes	0.136	3
		SR 3-2	DEV	N/A	2.7	49	Yes	0.059	3
		SR 3-4	DEV	501.5	2.3	34	Yes	0	3
		SR 3-3	DEV	542.7	2.4	39	Yes	0.020	3
SR 4	LW	SR 4-1	HGF	190.5	2.5	22	Yes	0.029	2
		SR 4-2	TGF	207.3	2.5	22	Yes	0	1
SR 5	R&P	SR 5-1	DEV	297.3	1.9	45	Yes	0	None
		SR 5-3	DEV	222.6	1.9	56	Yes	0	None
		SR 5-2	DEV	365.9	3.7	44	No	0	None
SR 6	R&P	SR 6-1	PIL	198.2	2.1	53	No	0	None
		SR 6-2	DEV	274.4	2.5	53	No	0	None
SR 7	LW	SR 7-1	TGS	245.4	3.2	0	No	0	None
		SR 7-2	TGS	355.2	3.0	0	Yes	0.213	1
		SR 7-3	HGS	321.6	2.7	4	Yes	0	None
		SR 7-4	TGF	274.4	2.8	0	Yes	0.109	1
		SR 7-5	TGS	277.4	2.7	8	No	0.073	3
		SR 7-6	TGS	275.9	3.1	17	No	0	1
		SR 7-7	HGF	275.9	3.1	17	Yes	0.388	4
SR 8	LW	SR 8-1	DEV	350.6	2.4	44	Yes	0.031	3
		SR 8-2	HGS	378.0	1.9	27	Yes	0.155	3

Mine name	Mine type	#Site	Mining cycle	Over-burden depth (m)	Entry height (m)	Stone (%)	Geologic feature	Spall volume (m^3/m)	Type of rib failure
		SR 8-3	HGF	399.4	2.2	48	Yes	0.152	3
		SR 8-4	DEV	404.0	2.4	44	No	0	None
		SR 8-5	DEV	404.0	3.0	45	No	0	None
SR 9	LW	SR 9-1	DEV	693.6	3.4	1	Yes	0	3
		SR 9-2	HGF	762.2	3.1	1	Yes	0.054	2
		SR 9-3	HGS	777.4	3.2	0	No	0.349	2
		SR 9-4	TGS	670.7	3.2	40	Yes	0.331	3
SR 10	R&P	SR 10-1	DEV	533.5	3.0	51	Yes	0.007	3
		SR 10-2	DEV	N/A	1.7	25	No	0.082	3
		SR 10-3	DEV	579.3	2.3	40	No	0.090	3

Note: LW = Longwall; R & P = Room & pillar; DEV = Development; HGS = Headgate side abutment; TGF = Tailgate corner front abutment; HGF = Headgate corner front abutment; TGS = Tailgate side abutment; PIL = Pillaring; 1 = Slabby; 2 = Slabby/blocky; 3 = Blocky; and 4 = Friable.

Table 2

Geometrical data and geological features at the unsupported sites.

Mine name	Mine type	#Site	Mining cycle	Over-burden depth (m)	Entry height (m)	Stone (%)	Geologic feature	Spall volume (m^3/m)	Type of rib failure
USR 1	LW	USR 1-1	DEV	161.6	2.3	27	Yes	0.039	2
		USR 1-2	HGS	175.3	2.0	18	Yes	0.196	3
		USR 1-3	TGF	172.3	2.3	32	No	0.039	3
USR 2	R&P	USR 2-1	DEV	243.9	2.0	3	No	0.005	2
		USR 2-2	DEV	257.6	1.9	2	Yes	0.261	1
USR 3	R&P	USR 3-1	DEV	155.5	2.1	0	No	0.234	1
		USR 3-2	DEV	151.2	1.8	31	No	0.027	2
USR 4	R&P	USR 4-1	DEV	106.7	2.3	12	Yes	0	None
		USR 4-2	DEV	106.7	2.5	20	Yes	0.319	3
		USR 4-3	DEV	109.8	2.6	16	Yes	0.000	None
USR 5	R&P	USR 5-1	DEV	45.7	2.5	19	No	0.007	4
		USR 5-2	DEV	76.2	2.7	19	No	0.012	4
USR 6	LW	USR 6-1	DEV	50.3	3.0	14	No	0	None
USR 7	R&P	USR 7-1	DEV	48.2	2.5	36	No	0	3
USR 8	LW	USR 8-1	DEV	173.8	2.1	15	No	0.109	3
		USR 8-2	DEV	158.5	2.4	17	No	N/A	3
		USR 8-3	HGS	158.5	2.2	17	No	0.136	2
USR 9	R&P	USR 9-1	DEV	58.2	2.0	40	Yes	0.242	3
		USR 9-2	DEV	55.8	1.9	47	No	0.139	3
		USR 9-3	DEV	61.0	2.1	27	No	N/A	3
USR 10	R&P	USR 10-1	PIL	335.4	2.5	39	Yes	0.279	3
		USR 10-2	DEV	243.9	2.3	57	No	0	None
		USR 10-3	DEV	289.6	2.1	51	No	0.031	2

Note: LW = Longwall; R & P = Room & pillar; DEV = Development; HGS = Headgate side abutment; TGF = Tailgate corner front abutment; HGF = Headgate corner front abutment; TGS = Tailgate side abutment; PIL = Pillaring; 1 = Slabby; 2 = Slabby/blocky; 3 = Blocky; and 4 = Friable.

Table 3

Intrinsic rib support and the rib support rating (RIBSUP) of the surveyed mines.

#Site	Bolt								Plate		Mesh				Rib	Note
	Type	Grade	Diameter (mm)	Shear strength (kN)	No. of row	Length (m)	Spacing (m)	Rib bolt	Plate area (m^2)	Face plate	Liner type	Control area per 3 m rib line (m^2)	Coverage (%)	CF		
SR 1-1	FG	60	22	72.20	2	1.52	1.37	8.720	0.16	1.00	None	3.72			8.720	5
SR 1-2	FG	60	22	72.20	2	1.52	1.37	9.340	0.16	1.00	None				9.340	
SR 1-3	FG	60	22	72.20	2	1.52	1.37	8.490	0.16	1.00	None				8.490	
SR 2-1	FG	60	19	53.00	2	1.22	1.83	3.780	0.16	1.00	Steel mesh		45	2.30	8.880	1
SR 2-2	M/G	60	19	53.00	1	1.52	3.66	1.440	0.16	1.00	None				1.440	
SR 2-3	Cut	N/A	N/A		1		3.66					6.04				
SR 2-4	M/G	60	19	53.00	1	1.52	3.66	1.350	0.23	1.19	None				1.600	
SR 2-5	Cut	N/A	N/A	0.000	1		3.66					4.65				
SR 3-1	M	60	16	36.80	2	1.07	1.83	2.360	0.16	1.00	Steel mesh		63	2.80	6.780	1
SR 3-2	M	60	16	36.80	2	1.07	1.83	2.790	0.16	1.00	None				2.790	5
SR 3-3	M	60	16	36.80	2	1.07	1.83	3.190	0.16	1.00	Plastic Mesh	6.50	65	2.90	9.390	2,5
SR 3-4	M	60	16	36.80	2	1.07	1.83	3.070	0.16	1.00	None				3.070	5
SR 4-1	M	60	19	53.00	2	1.22	3.05	2.430	0.16	1.00	None				2.430	
SR 4-2	M	60	19	53.00	2	1.22	3.05	2.430	0.16	1.00	Plastic Mesh		84	3.50	8.580	3
SR 5-1	FG	60	16	36.80	1	1.22	1.22	3.450	0.16	1.00	None				3.450	5
SR 5-2	FG	60	16	36.80	1	1.22	1.22	3.450	0.16	1.00	None				3.450	5
SR 5-3	FG	60	16	36.80	1	1.22	1.22	1.740	0.16	1.00	None	6.50			1.740	5
SR 6-1	FG	60	19	53.00	1	1.52	2.44	2.250	0.17	1.00	None	6.19			2.260	
SR 6-2	FG	60	19	53.00	1	1.52	2.44	1.950	0.17	1.00	None				1.950	
SR 7-1	M	75	16	36.80		1.22	1.52	3.170	0.12	0.84	Plastic		66	2.98	9.460	4
SR 7-2	M	75	16	36.80	1	1.22	2.44	1.080	0.12	0.84	Plastic		69	3.06	3.320	4
SR 7-3	M	75	16	36.80	1	1.22	2.44	1.190	0.12	0.84	None				1.010	
SR 7-4	M	75	16	36.80	1	1.22	2.44	1.130	0.12	0.84	None				0.950	
SR 7-5	M	75	16	36.80	2	1.22	2.13	2.670	0.12	0.84	None				2.250	
SR 7-6	US															
SR 7-7	US															

Author Manuscript
Author Manuscript
Author Manuscript

#Site	Bolt								Plate		Mesh				Rib	Note
	Type	Grade	Diameter (mm)	Shear strength (kN)	No. of row	Length (m)	Spacing (m)	Rib bolt	Plate area (m^2)	Face plate	Liner type	Control area per 3 m rib line (m^2)	Coverage (%)	CF		
SR 8-1	FG	60	16	36.80	1	1.22	1.52	2.160	0.06	0.61	None				1.330	
SR 8-2	FG	60	16	36.80	1	1.22	1.52	2.670	0.06	0.61	None				1.640	
SR 8-3	FG	60	16	36.80	1	1.22	1.52	2.370	0.06	0.61	None	5.26			1.460	
SR 8-4	FG	60	16	36.80	1	1.22	2.29	1.440	0.06	0.61	None	5.54			0.880	
SR 8-5	FG	60	16	36.80	2	1.22	1.52	3.470	0.06	0.61	None	5.26			2.130	
SR 9-1	FG	60	22	72.20	2	1.83	2.44	3.910	0.06	0.61	Steel mesh	5.26	50	2.50	9.790	
SR 9-2	FG	75	38	212.1	2	1.83	1.52	11.76	0.02	0.38	Steel mesh	4.65	58	2.74		
SR 9-3	FG	60	22	72.20	2	1.83	2.44	4.200	0.06	0.61	Steel mesh		54	2.62	11.01	
SR 9-4	FG	60	22	72.20	2	1.83	1.83	5.610	0.06	0.61	Steel mesh	2.79	54	2.62	14.68	4
SR 10-1	M	60	16	36.80	3	1.07	1.22	5.630	0.16	1.00	Steel mesh	3.72	48	2.44	13.74	
SR 10-2	M	60	13	23.60	1	1.83	1.22	4.430	0.16	1.00	None				4.430	
SR 10-3	M	60	16	36.80	2	1.07	1.22	4.840	0.16	1.00	Chain Link		43	2.30	11.14	

Note: FG = Fully grouted bolt; M = Mechanical bolt; Cut = Cuttable; US = Unsupported sites;1 = Mains; 2 = Pillar retreat section; 3= Tailgate front abutment loading; 4 = Tailgate side abutment loading; and 5 = Multiple seam interaction mining.