

Entry Stabilization Utilizing Rib Bolting Procedures

By Dennis R. Dolinar and Stephen C. Tadolini

UNITED STATES DEPARTMENT OF THE INTERIOR



BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft foot

in inch

lbf pound (force)

pct percent

psi pound (force) per square inch

s second (time)

ENTRY STABILIZATION UTILIZING RIB BOLTING PROCEDURES

By Dennis R. Dolinar¹ and Stephen C. Tadolini¹

ABSTRACT

The danger to personnel, equipment, and pillar structure created by the spalling of a coal rib can be minimized by installing rib bolts. To assure that a configured support system will maintain a coal rib, the U.S. Bureau of Mines developed a rib bolt system based on a nonpreventable failure concept. A statistical equation quantitatively relates the amount of rib retained to the bolt spacing and the width of the spalled material. Laboratory test results show that the equation accurately predicts the amount of material retained and confirm the validity of the support concept. The examination of rib bolting at a coal mine experiencing rib sloughage provides evidence that the effectiveness of the support can be related to the failure pattern of the spalled material. An analysis of roof and roof support reaction to rib sloughage at the mine indicated that the rib sloughage had little effect on roof stability. Although supporting ribs might not affect roof stability, laboratory test results indicate that the material retained by the support can sustain a load up to 20 pct of the intact compressive strength of the material.

¹Mining engineer, U.S. Bureau of Mines, Denver Research Center, Denver, CO.

INTRODUCTION

Spalling or sloughage of coal ribs presents a hazard to both personnel and equipment while progressive rib spalling and failure can seriously impact the structural integrity of the pillar. To minimize the development of these conditions, coal ribs can be supported by rib bolting with varying degrees of success depending on the coal lithology and structure, coal properties, failure mechanisms, and mining parameters (1-3).² Further, there are no quantitative criteria for the design of a rib support system, only observational guidelines that identify conditions under which rib bolting will generally be successful and when additional types of support, such as straps or mesh, should be used with rib bolting (1-2). The U.S. Bureau of Mines, therefore, developed quantitative criteria for the design and performance evaluation of a rib bolt system where the design parameter of concern was the bolt spacing pattern.

In this investigation, the type of support being considered is a full-column, resin-grouted bolt. By establishing a quantitative basis for the design of a rib bolting system, objective engineering criteria can be used to determine when additional support, such as straps or mesh, should be incorporated into the support system. The bolt is still the key element in the support system, however, and in determining the success of the additional support.

By developing a suitable concept for the design of a rib support system, not only can a quantitative design of the support system be achieved, but also a general approach to support system design can be delineated. Site-specific conditions, however, must always be taken into account when selecting the bolt type or designing the support system. Such was the case in a deep underground mine in Alabama where rib support systems were stressed to the limit during the extraction of the longwall panels. The rib bolts were broken due to the increased rib dilation as a result of the increased stress magnitudes. The site-specific solution in this environment was to install yieldable bolts at 45° angles into the competent main roof (4). By providing a concept of support and a quantitative method to

design a support system, a methodology for dealing with site-specific conditions can be established. In this investigation, a rib support concept was developed that forms the foundation for the quantitative design of the rib support system.

Besides minimizing the hazard to workers and equipment due to rib sloughage, the support of the rib can have an impact on the stability of two key structural elements: the pillar and the roof. The Code of Federal Regulations (CFR) 75.201-1, Widths of Openings (5), makes the following statement:

Where excessive widths result from poor mining practices, additional roof support shall be installed before any travel or other work is done in such area. If excessive widths of openings are a result of coal sloughing, additional support shall be installed and the mining system reevaluated to determine changes that are necessary to minimize such occurrences.

As a result of rib spalling, considerable effort is required to install secondary support in the form of additional roof bolts installed along the sloughed rib or the placement of timber posts to provide support to the immediate roof. For coal pillars, by supporting the rib, progressive spalling can be limited by maintaining the structural integrity of the pillar. The supported material may also be capable of sustaining some load.

To determine the effects of rib spalling on the stability of the mine roof, test sites that monitored roof stability and support performance were established in an underground coal mine in western Colorado. At the same mine, rib bolts were installed and conditions that could impact the design of the rib support system were observed. Laboratory experiments were used to verify the support concept, the quantitative support system design criteria, and the potential loads that supported ribs could sustain.

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The authors thank Ronald Stucki, general manager, Derrel Curtis, mine foreman, James Miller, chief mining

engineer, and Robert Derick, safety director, Cyprus-Orchard Valley Mine, Cyprus Mineral Co., Paonia, CO for their continued support and use of their personnel and mining equipment required for this study.

²Italic numbers in parentheses refer to items in the list of references at the end of this report.

NONPREVENTABLE FAILURE CONCEPT FOR RIB SUPPORT DESIGN

When designing a support system based on the nonpreventable failure concept, the support does not increase the strength of the coal or alter the load at which the rib will fail, but does maintain the fractured material in place. A significant increase in coal rib strength requires a substantial confining force which would necessitate the use of massive support (6). For the nonpreventable failure concept, the supported coal rib is subjected to stresses higher than the coal strength, causing the coal rib to fracture and yield. The support system, however, is designed to retain a calculated amount of the fractured material in place. The amount of support required to hold the

material in place, therefore, is much less than would be required to increase significantly the strength of the material (7).

The failure of the coal rib can be a complex process involving various failure mechanisms. By using the nonpreventable failure concept for design, the emphasis is directed toward the final product of the failure process, which is the spalled material and the spalled material pattern along the rib. By observing the failed material and the pattern formed by the failed material, quantitative bolt spacing criteria can be developed.

STATISTICAL APPROACH TO DESIGNING A SUPPORT SYSTEM

Because the material will spall along a failed rib, the amount of material retained by the rib bolts becomes an important measure of the support system performance. An assumption is made that to hold the failed material in place, the failed material must be intersected by the support system. The failed material parameters that should influence the rib retention include the size and size distribution of the spalled material and the location on the rib where the spalled material forms. The bolt pattern and bolt spacing are also important support parameters in rib retention. The rib retention depends on the probability that the bolt system will intersect the failed material. A statistical approach, therefore, can be used to predict the amount of material retained along a failed coal rib.

Bolts work most efficiently in the retention of a rib when slabs are formed (2). An example of how the amount of rib retained can be determined statistically will be developed for a section of rib where slabs form. An assumption is made that if one bolt intersects a slab, the slab will be retained. For large slabs, such as a rib roll or slabs of coal which weigh more than the support capacity, more than one bolt would have to be applied to the slab (8). Figure 1 shows a section of rib where slabs form along the entire rib length. If a horizontal reference line is drawn down the center of the rib and uniformly spaced support is applied along the reference line, the following equation can be used to determine the amount of rib retained for a given bolt spacing.

$$L_r = \sum_{i=j}^n W_i + \frac{\sum_{i=1}^{j-1} W_i^2}{S}$$

where L_r = length of rib retained along reference line,

W_i = width of individual slabs along reference line,

S = bolt spacing,

i = identification of individual slabs,

j = number of the first slab whose width equals or exceeds the bolt spacing,

n = total number of slabs,

and $W_n > W_{n-1} > W_{n-2} \dots W_2 > W_1$.³

The first part of the equation represents the total length of rib with slab widths greater than the bolt spacing. These slabs will definitely be retained. The second part of the equation represents those slabs with widths less than the bolt spacing, and, therefore, the slabs might be retained. The probability that the slabs will be retained is W_i/S where a slab width of W_i will be retained. As the slabs reach full opening height, the total amount of rib retained will approach the amount of rib retained along the supported reference line.

An example of the rib retention calculation can be developed. For a 30-ft section of rib, if slabs form with widths along the support line of 6, 5, 5, 4, 3, 2, 2, 1, 1,

³If the length of rib to be retained is known, the equation can be solved for the bolt spacing, S . Then the bolt spacing required to retain the desired length of rib can be calculated.

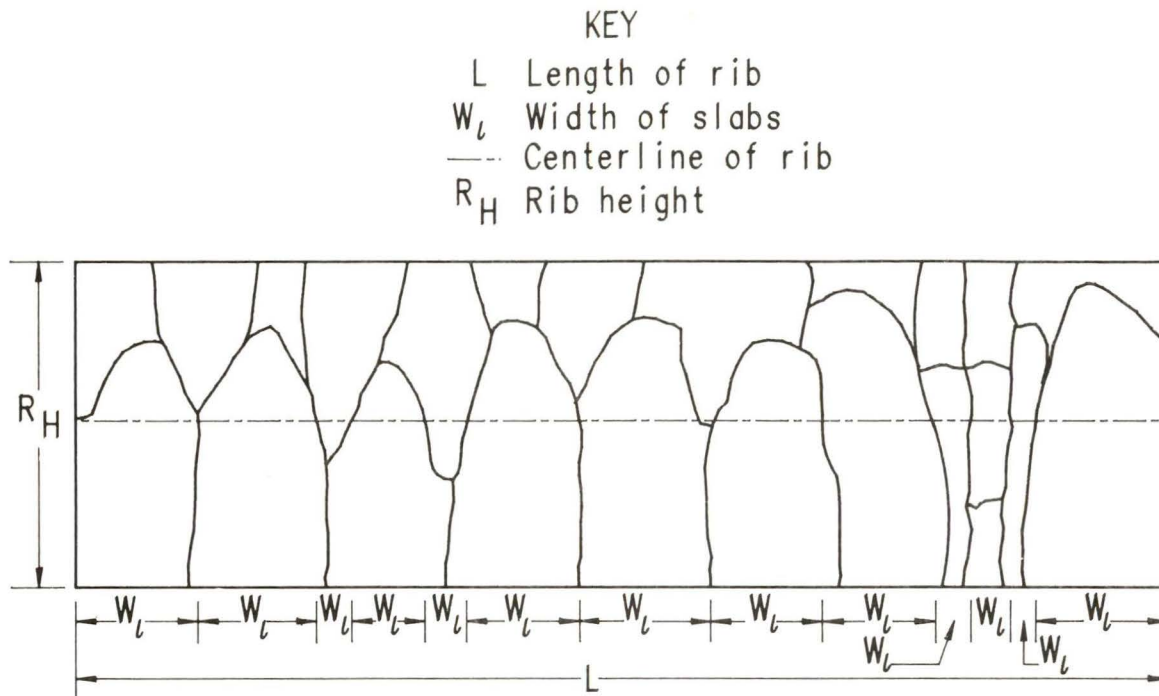


Figure 1.—Relationship between slab width and rib length along center reference line for spalled rib.

and 1 ft with a 5-ft bolt spacing, the length of rib retained is

$$L_r = 6 + (2(5)^2 + (4)^2 + (3)^2 + 2(2)^2 + 3(1)^2)/5$$

$$= 23.2 \text{ ft.}$$

Dividing the length of rib retained by the 30 ft, the percent of rib retained along the line of support is 77.3.

By measuring the slab widths for various rib lengths along a proposed line of support, the amount of material retained for a given bolt spacing for that specific area of the mine could be determined. The equation is limited, however, to predicting the amount of material along the line of support and not over the entire rib surface. As structural elements in the coal seam limit the height of the spalled material, the total amount of rib retained will also be limited.

LABORATORY TEST OF SUPPORT CONCEPT AND STATISTICAL DESIGN EQUATIONS

A laboratory experiment was designed and conducted to test the bolt spacing equation and the nonpreventable failure concept. In this experiment, rectangular specimens prepared from a high-strength gypsum cement were supported with full-column, grouted bolts.⁴ The specimens were 5.3 in long, 2.0 in wide, and between 2.0 and 2.1 in high. Steel bolts with bearing plates were installed in two

of the long sides of the specimens which represented the rib of a pillar that could be subjected to spalling. Two bolts were also placed in each end of the specimens to minimize the effects of end failure where the entire length of the specimen could be used to evaluate the rib bolting. Figure 2 shows the bolt configurations where the bolt spacing was 0, 0.83, 0.63, 0.42 and 0.21 bolt per inch. The specimens were loaded in compression to the ultimate strength of the material and then deformed further until a specimen strain of about 4.5 pct was achieved.

At this strain level, 100 pct of the surface of the unsupported specimens spalled. Figure 3 shows specimens after testing for each bolt configuration. The maximum

⁴The cement-to-water ratio was 3.25:1 where the specimens were allowed to cure 14 days before being tested. The steel bolts used were 1 in long and 0.08 in. in diameter. The bolts were grouted in 0.096-in-diam holes with a water-soluble adhesive. The bearing plates were 0.3 in. in diameter.

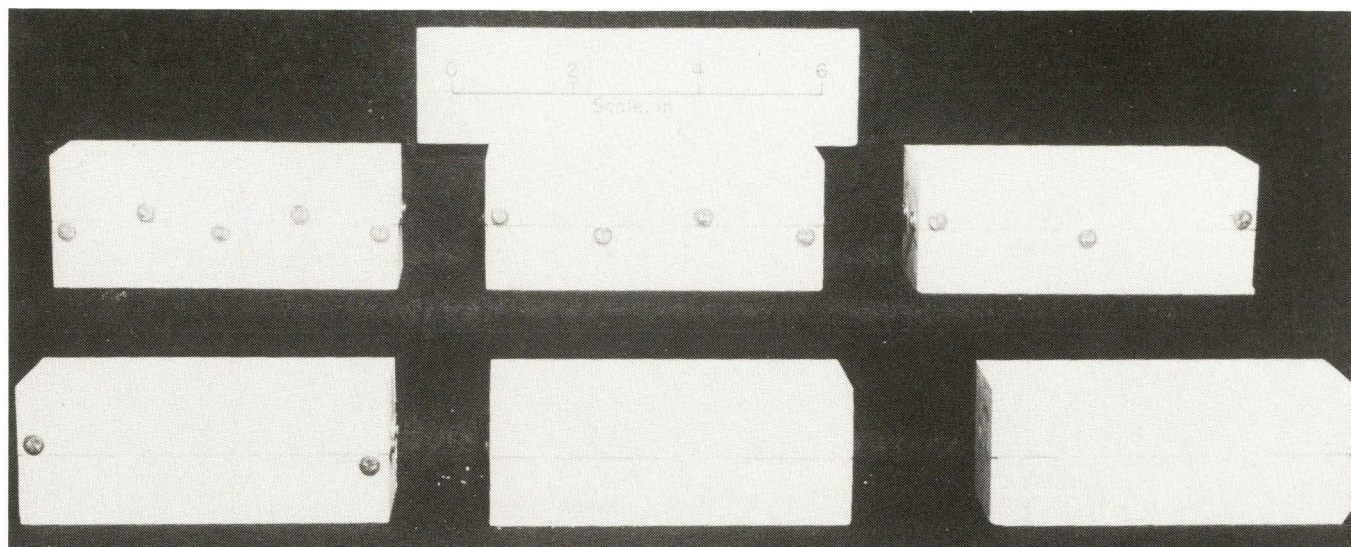


Figure 2.—Test specimens showing different bolt configurations used in experiment.

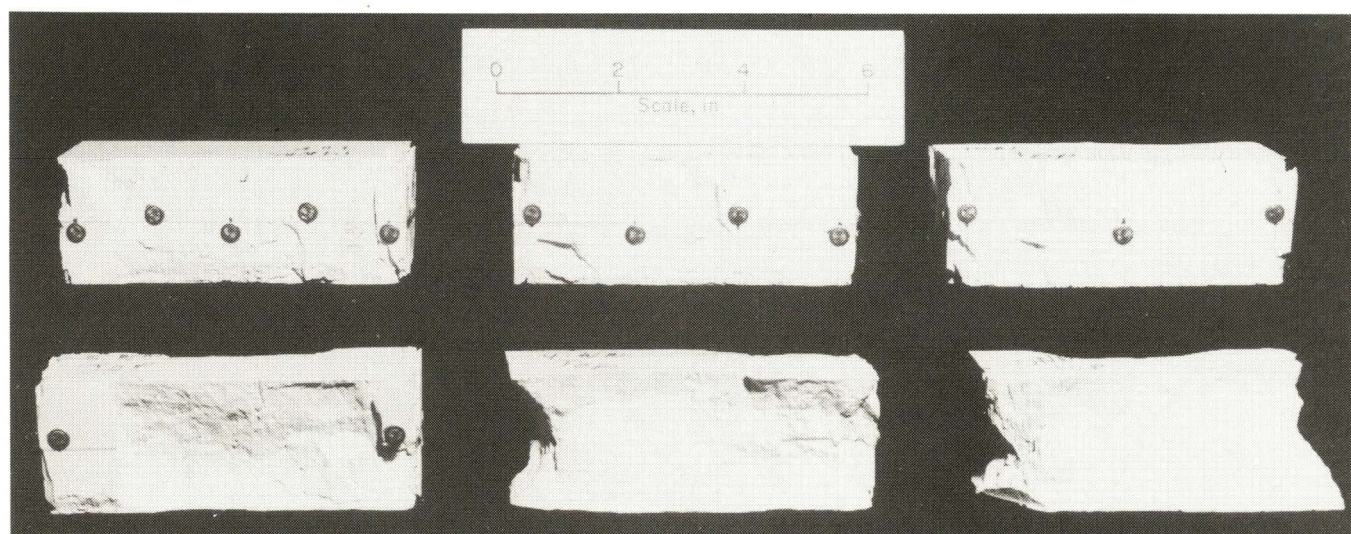


Figure 3.—Unsupported and supported test specimens.

compressive strength and the amount of material retained on the specimens were noted. The unsupported specimens were used to establish a data base on the size and width of the spalled material, on the width and weight of the spalled material, and on the amount of material that would spall without support. Thirty-six specimens were tested, with six specimens representing each bolt configuration.

Figure 4 (top) shows the percent of material retained by line length along the specimen, and figure 4 (bottom) shows the percent of material retained by weight measured

in the experiment and calculated from the equation.⁵ The calculated material retained closely follows the trend of the measured values. At each bolt spacing there was no statistical difference between the measured and calculated

⁵To determine the material retained by weight (W_t) the width of the slab (W_i) is replaced by the weight of the slab (W_t) where the amount of material retained is calculated. The probability that a slab will be retained, however, is still W_i/S ; therefore, the second term in the equation is $W_t W_i/S$.

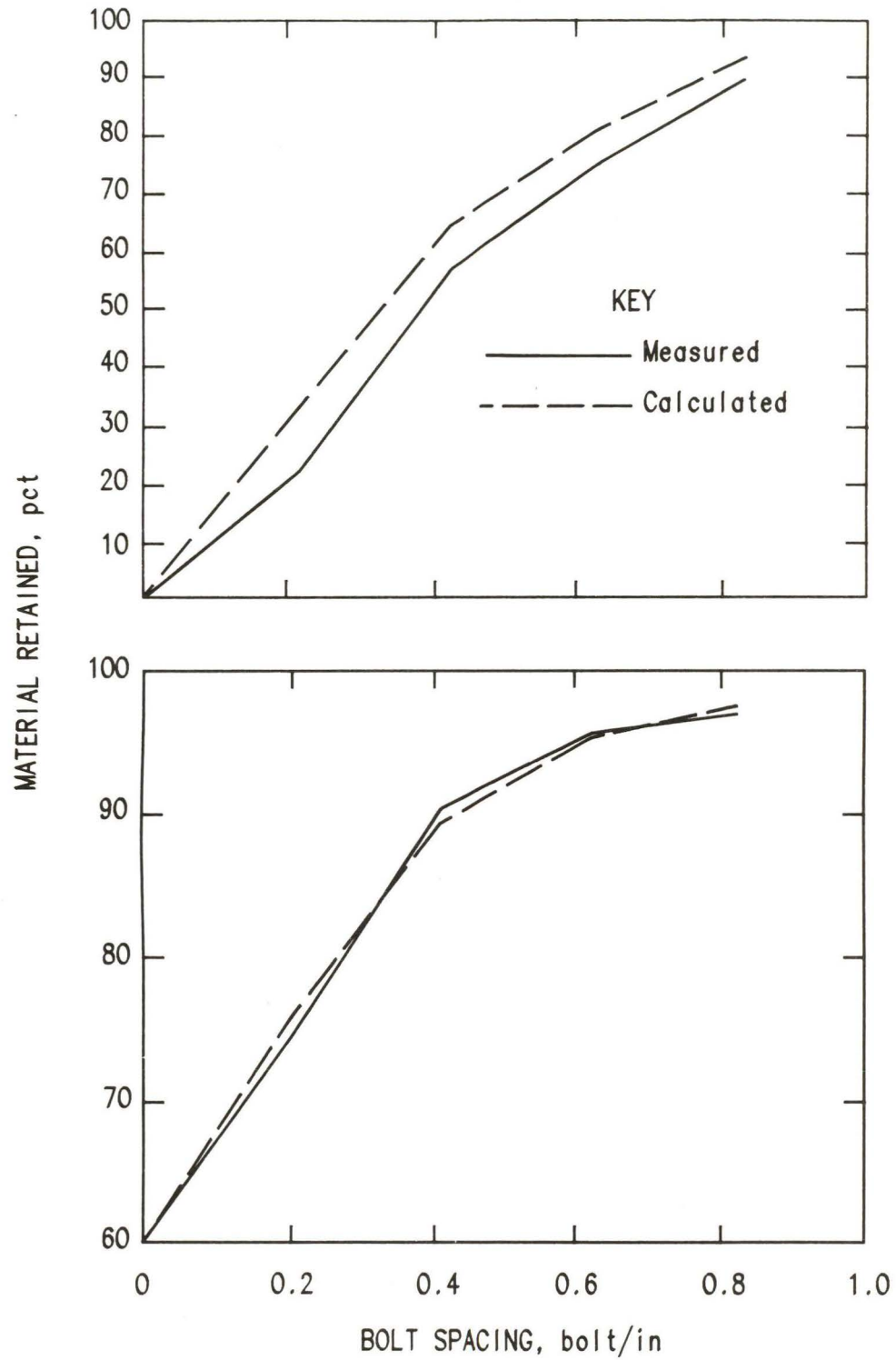


Figure 4.—Percentage of material retained by line length (top) and weight (bottom).

amount of material retained. Statistical equations of this type, therefore, accurately predict the material retention for a given bolt spacing. Also, the results based on the equation strongly indicate that the slab or failed material size (width) is an important parameter in designing the support system.

For the nonpreventable failure concept, the average maximum compressive strength for 12 unsupported specimens was $8,065 \pm 431$ psi and the average maximum

compressive strength for 6 specimens with 0.83 bolt per inch was $8,165 \pm 593$ psi. At a confidence level of 0.95 for a t-test, there is no statistical difference in the compressive strengths (9). Since the bolts did not increase the compressive strength, the point where failure occurred was not altered; hence, the support did not prevent failure. However, 96.9 pct by weight of the supported specimens was retained while only 60 pct by weight of the unsupported specimens was retained.

IN SITU EVALUATION OF RIB BOLT PERFORMANCE

At the Cyprus Orchard Valley Mine near Paonia, CO, which is owned by Cyprus Mineral Co., a partial rib-bolting program was started in a section of the mine to minimize rib sloughage and the necessity to place secondary support due to the increase in roof span. Although no quantitative survey of the failed material and of the amount of material retained by the rib support was conducted, a descriptive evaluation of the pattern of material failure and the support system interaction is discussed.

The support system consisted of 4-ft, full-column, grouted bolts. The bolts were placed down a line along the center of the rib at 4- to 5-ft centers. A strong unidirectional cleat exists in the mine; in the panel where rib bolting was conducted, the cleat direction is about 55° off the direction of main entries. Pillars in the section are 100 by 60 ft, and the mining height is between 8 and 10 ft. Figure 5 shows the relationship between the pillar and the cleat direction. Four zones (A, B, C, and D) around the pillar are indicated where different material failure patterns and various sizes of failed material develop. The variation in the failed material is the result of the cleat and the mining or stress-induced fractures (2). The zones include two different types of failure patterns for the ribs and for the corners.

Zone A - Slabs are formed along the rib that approach the height of the opening. This rib side is 55° off the cleat direction. Slabs range from about 24 to 36 in wide. In forming the slabs, one failure surface cuts across the cleat and the other surface follows the cleat. The cleat appears to minimize the slab width development. Figure 6 shows a supported rib where slabs have formed in this zone.

Zone B - The failure of these pillar corners is along the cleat where large, thin slabs form, then fail into the intersection. Failure of the slabs may progress several feet into the pillar perpendicular to the cleat. The failure of these corners will impact the ribs on both sides for a distance of at least 10 ft. Buckling may be the primary method of failure of the slabs. Figure 7 shows this type of corner failure.

Zone C - The failure of this rib occurs along the cleat where buckling is the primary mode of failure. The failure progresses perpendicular to the cleat, but the depth is

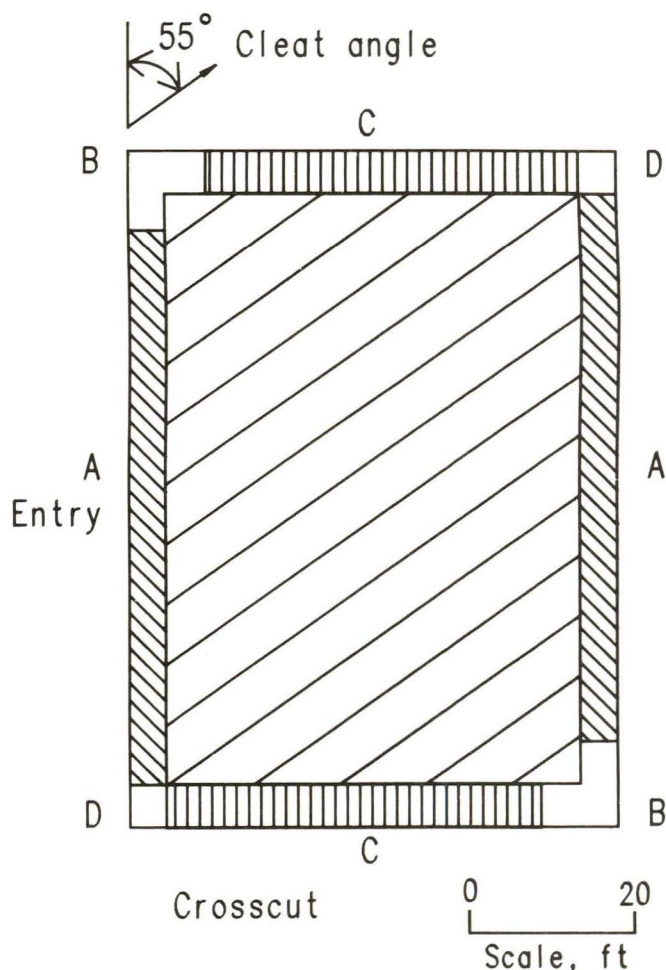


Figure 5.—Cleat orientation with respect to pillar and four different failure zones A, B, C, and D.



Figure 6.—Slab formation and rib bolting along zone A of pillar.

limited by the amount of exposed cleat. Thin slabs, 1 to 2 ft wide, will form along the exposed cleat. Several progressive failures may be observed along the rib; however, more spalling occurs near the zone B corners. A parting along the rib also enhances the buckling of the slabs. Figure 8 shows the zone C rib failure.

Zone D - Blocky material, 2 to 4 in wide, forms between the cleats on this type of corner. Only a limited amount of spalling occurs. Figure 9 shows this type of corner.

The success of the rib bolting in maintaining the rib varies for each zone. For zone A, where slabs formed along the rib, bolts held most of the slabs in place (fig. 6). As higher loads were encountered on the pillar, the amount of material lost between the bolts increased. The

loss of material occurs primarily between the cleats, which limits the size of the slabs that form. A tighter bolt spacing could maintain more of the rib; however, straps or pans would more efficiently support the smaller material forming between the bolts, primarily because the straps will intersect a larger number of the smaller pieces than the bolts.

For zone B, the bolts applied perpendicular to the ribs were not effective in maintaining the corner. Because the support was at either a 35° or a 55° angle to the cleat and not directly across the cleat, the resistance to movement perpendicular to the cleat was minimized, while the bolts lost anchorage and effectiveness because of the extension of the cleat openings. Buckling of slabs would also occur below the height where the support was placed, with brows often forming (fig. 7). To be effective, the bolts would have to be installed perpendicular to the cleat.

In zone C, there was general failure of the rib below the line of support because of buckling of slabs. To minimize the height of the slabs, at least one more row of supports could be added. Along the line of support, the rib is held in place around the bolts, but spalling between the bolts occurs as a sufficient width of slab along the cleat is exposed and as failure of the lower portion of the rib extends upward. Because of the failure mechanism and the cleat direction, the width of material formed along the rib or line of support is small. Either a tighter bolt spacing or the use of pans or straps is required, therefore, to maintain more of the material. For the corner (zone B) and rib (zone C) where buckling occurs, the failure mechanism will probably be altered with the proper application of support. The maximum loads these zones are able to withstand will probably increase. Since these are high stress zones, however, yielding or failure may still occur, especially as extension takes place across the cleat. When buckling occurs, the support pattern has to reflect the minimum height and width of a slab that could buckle. These minimum dimensions could be considered as the size and geometry of a spalled piece of rib or rib that could spall.

Because of the limited spalling in zone D, these corners require the least amount of special consideration when designing the support system. If the ribs are properly supported, enough confinement across the cleat should occur to minimize any spalling and any progressive corner failure.



Figure 7.—Failure of zone B corner.



Figure 8.—Rib spalling and bolting along zone C of pillar.



Figure 9.—Failure of zone D corner.

STRUCTURAL BENEFITS OF SUPPORTING COAL RIBS

ROOF STABILITY AND RIB SLOUGHAGE

A field investigation was performed at the Cyprus Orchard Valley Mine to determine the effects of rib sloughage on the stability of the roof. The mining method in the test area is a room-and-pillar configuration. The test site was located in an entry and an adjacent room, under approximately 720 ft of cover. To measure the loads generated on the primary support system and monitor the subsequent roof movements, 16 Goodyear⁶ pressure pads were placed between the bearing plates and 8-ft threaded Dywi Dag roof bolts, and 6 differential sag stations were installed to monitor the roof movement. To observe the pillar sloughages and movements, two techniques were applied. The first method involved hanging a plumb-bob line from a predetermined location and measuring the distance between the line and the coal pillar at the same position for repetitious readings. The second method was a photographic technique. A straight

white polyvinyl chloride (PVC) pole was attached to a predetermined location and permitted to hang vertically to the ground. A camera was set up under a plumb-bob, to assure the same location, approximately 50 ft away from the pole. Without any additional light sources, a cap lamp was used to paint the pole while the shutter on the camera was opened for 15 s. This provided an excellent profile of the pillar and at the same time permitted distances to be determined between the vertical pole and the ribline. Additionally, observation boreholes were placed in the immediate roof and in the pillar to observe any separations or partings. The purpose of the field instrumentation and the rib monitoring program was to establish the effect, if any, of rib sloughage on the primary roof support system and determine the subsequent behavior in the immediate roof. The test site instrumentation (fig. 10) was read and evaluated five times in an 8-month period.

After the test site was instrumented on-cycle, the baseline data were taken immediately after primary support installation. The ribs showed no immediate signs of yielding or sloughing. A predominant cleat pattern was already visible, however, with a major set of joints forming with a

⁶Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

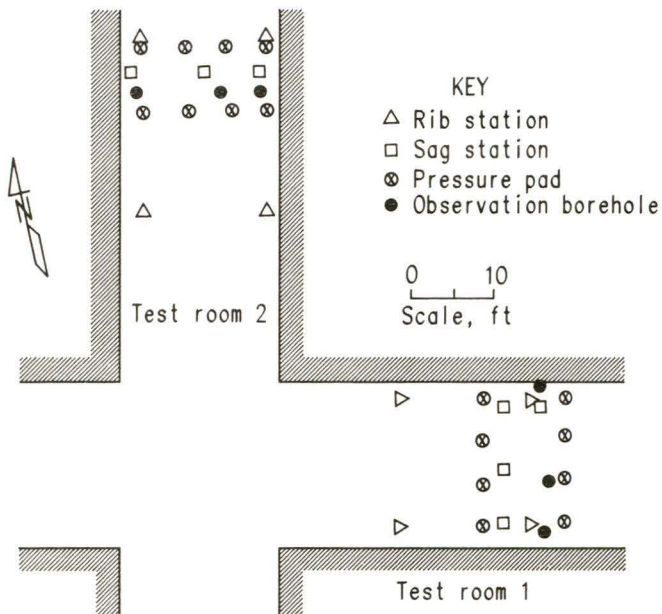


Figure 10.—Experimental instrumentation configuration of test rooms 1 and 2.

spacing of about 10 to 12 in. The initial bolt load values in test room 1 ranged from 2,690 to 10,447 lbf. The average load was 5,900 lbf. The initial bolt load values in test room 2, the main entry, ranged from 4,295 to 8,842 lbf. The average load measured on the roof bolts was 6,284 lbf.

The test area was monitored 2 days after the initial installation. The loads generated on the support system were fluctuating in both directions due to the close proximity of mining. The average load in test room 1 increased approximately 400 lbf, while the average load in test room 2 decreased approximately 400 lbf. The rib located on the south side of test room 1 had begun to form distinct rib pattern failures to a depth of approximately 12 in. The separated material, however, remained intact and was confined between the roof and the floor.

The test area was monitored and evaluated 42 days after the initial installation. The loads in test room 1 ranged from 3,760 to 12,052 lbf, with the average load being 6,646 lbf, or an increase of 536 lbf. The measured loads in test room 2 ranged from a minimum of 2,990 lbf to a maximum of 9,778 lbf. The loads generated on the roof bolts in this room had increased an average of 222 lbf. During this same period, the ribs in test room 1 underwent extensive sloughage on the south side of the test room. The initial span in the room was 18 ft 11 in and the span, 42 days after installation, had increased to 20 ft 11 in. This is an increase in the visible span of 11 pct. Drill holes placed in the pillar indicated that the

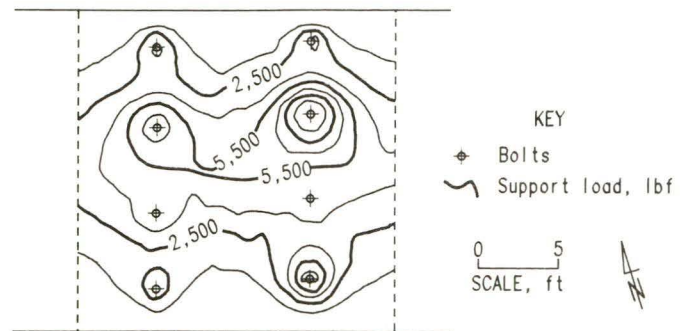


Figure 11.—Isopleth of support loads 42 days after support installation in test room 1.

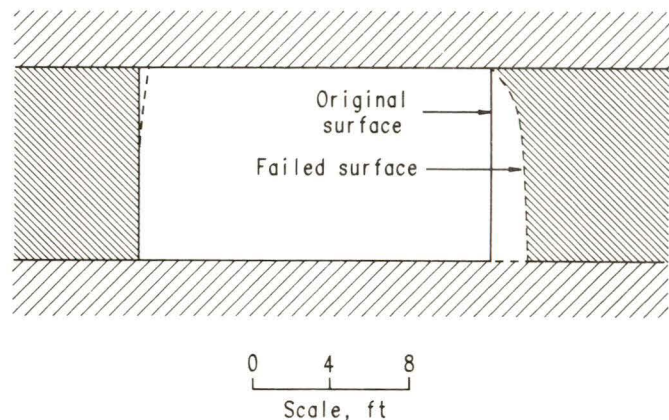


Figure 12.—Initial and 42-day rib profile for test room 1.

yield zone of the pillar extended an additional 14 in on both sides. This increase would surmise an effective span increase to 23 ft 3 in or 23 pct. To assist in the visualization of the existing support behavior, figure 11 shows a support load isopleth. Figure 12 shows the initial rib profile and the subsequent profile 42 days after the initial installation. The ribs in test room 2 remained stable with very little or no signs of rib movement. In fact, the ribs actually dilated on the east rib approximately 3 in. Representation of the data from test room 2 is shown in a load isopleth in figure 13. The observation boreholes drilled in the pillars showed no separations or parting to a hole depth of 10 ft.

The test areas were monitored and evaluated 86 days after installation. Now the mining section had advanced 900 ft inby, and the roof reaction indicated the abutment loads had transferred back to the test area. The average loads generated on the support systems in both test areas had increased 1,822 lbf in room 1 and 1,187 lbf in room 2. The ribs had stabilized, however, with no significant changes in profile or yield zone.

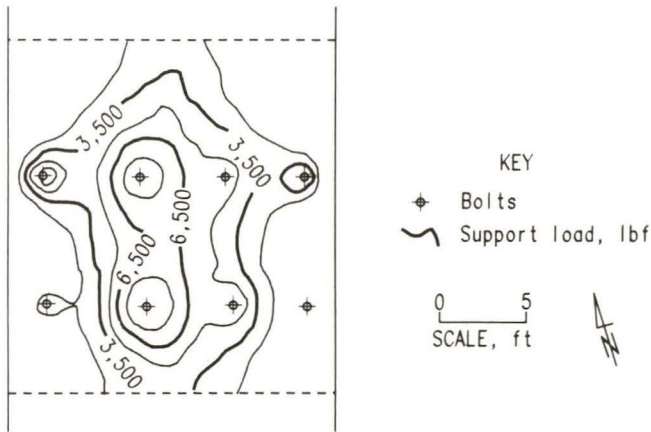


Figure 13.—Isopleth of support loads 42 days after support installation in test room 2.

The readings obtained 125 days after installation indicated that the test areas had stabilized. The loads measured in test room 1, which had undergone extensive rib sloughage, ranged from 4,830 to 12,196 lbf. The average load on the test site support system was 7,556 lbf. The loads in test room 2, which had experienced no signs of rib sloughage and remained stable, ranged from 3,269 to 10,714 lbf. The average load on the supports was 7,493 lbf. This is an average difference of 63 lbf, or 0.8 pct, which is beyond the accuracy of the instruments used in this investigation.

The test site had stabilized and was not monitored for 117 days. The working face was approximately 1,500 ft inby. The loads generated on the primary roof support in both test areas had dropped approximately 35 pct in both areas. The average loads for test room 1 and test room 2 were 5,565 and 5,691 lbf, respectively. The differential sag stations installed in the roof to monitor the strata behavior indicated that the immediate roof had undergone a complex behavior. The immediate roof had a 1-in band of a wet, soft shale that actually permitted the roof to dilate upward with respect to time. The soft layer also permitted differential movements which makes the explanation complex and far beyond the scope of this report. However, it should be pointed out that the support behavior and subsequent roof movements in test room 1 and test room 2 appeared nearly identical. Figure 14 illustrates the average support loading patterns (top) and the change (bottom) in loads for each of the test rooms.

The results of the field experiments proved that rib sloughages and pillar spalling, which increased the visible and effective spans in test room 1, had little or no effect on the primary support system. The loads and roof behavior were nearly identical, even with an increase in effective roof span of 4 ft, or 22 pct.

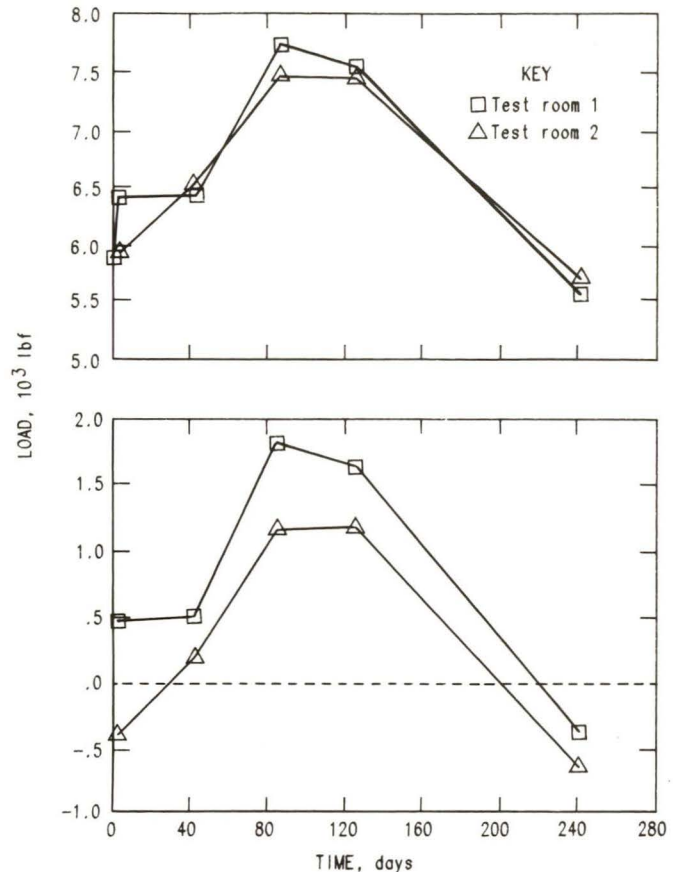


Figure 14.—Average support loads (top) and load changes (bottom) in test rooms 1 and 2 developed with respect to time.

POTENTIAL LOAD-BEARING CAPACITY OF SUPPORTED RIBS

Based on the laboratory tests for material retention for a given bolt spacing, the loads carried by the supported material can be calculated by examining the postfailure strengths of both unsupported and supported specimens. For the unbolted specimens subject to a 4.5-pct strain, where 60 pct of the material is retained, the postfailure strength was 2,363 psi. For the specimens with 0.83 bolt per inch, where 96.9 pct of the material retained, the postfailure strength was 3,285 psi (7).

Because of the way the specimens were tested, a portion of the load is being carried by fractured material held in place by the steel platens. To eliminate this effect, both unsupported and supported specimens were taken from between the steel platens. This allowed for the removal of any spalled material that was sustaining some load. The specimens were reloaded up to the maximum postfailure strength the specimens could carry. The unbolted specimens were able to carry a load of 4,660 lbf. The specimens with 0.83 bolt per inch carry a load of

21,700 lbf. The material being retained, therefore, is supporting a load of 17,040 lbf, or 20 pct of the maximum compressive failure load of 86,925 lbf for the specimens.

An increase in the number of bolts beyond a bolt spacing of 0.83 bolt per inch would probably increase the load-carrying capabilities of the fractured material. This is indicated by the difference between the original and

retested postfailure specimen loads. The postfailure strength decreased from 34,100 to 21,700 lbf for a 0.83 bolt per inch spacing. The platens provided a resistance to the movement of the fractured material. Not only is material retention important, therefore, in maintaining the load-carrying capability of the fractured material, but also how well the material is held in place.

CONCLUSIONS

Results of the laboratory experiment indicate that the nonpreventable failure concept is a viable approach for designing a support system to maintain coal ribs. The support does not prevent the failure of laboratory specimens which were designed to represent unsupported and supported ribs, but instead retains the failed or fractured material in place. Laboratory tests confirmed that the ultimate strength of test specimens did not increase while being supported by the grouted bolts, yet the support system retained up to 96.3 pct of the failed specimens.

A statistical method can be used to quantify the amount of material retained by the support system. In this quantitative analysis, the size of the spalled material (width) becomes an important parameter in determining the bolt spacing or the amount of material retained for a given bolt spacing.

Even though the failure of a coal rib can be a complex process, the support requirements for a given situation can be obtained by observing the failure pattern of material formed along a coal rib and by measuring the size of the

spalled material. Once a rib is supported, an analysis can be conducted on the success or failure of support in maintaining the rib. Modifications of the bolt pattern and system or the use of additional support can then be implemented. Different failure patterns can occur around a pillar. In the underground case evaluated in this investigation, a unidirectional cleat caused the formation of four zones around a pillar where different material failure patterns developed. Each zone had different support requirements. Based on in situ measurements of roof movement and roof bolt loads, though the visible and effective roof span was increased, rib sloughage did not affect the stability of the mine roof. Rib bolting or rib stabilization in some mines, therefore, may not increase roof stability. From laboratory tests, if the spalled material is held in place, however, the load-carrying capacity of the retained material can be as much as 20 pct of the original material strength. The load that can be sustained is not only dependent on the amount of material retained, but also on how well the material is held in place.

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