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Rib Stability: Practical Considerations To Optimize Rib Design

By W. C. Smith

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	in	inch
ft	foot		

RIB STABILITY: PRACTICAL CONSIDERATIONS TO OPTIMIZE RIB DESIGN

By W. C. Smith[1]

ABSTRACT

The U.S. Bureau of Mines examined previous research on rib stability in an effort to develop a practical approach to understanding, characterizing, and controlling weak rib conditions in underground coal mines. Because success in stabilizing ribs depends on a basic knowledge of how weak ribs behave, the report reviews the mechanics of rib failure and the relationship of coal mine geology and pillar constraint to rib instability. Strategies for choosing an effective method of rib support are considered, and various rib support methods are discussed. Finally, the report documents techniques for monitoring ribs and use of models to assess rib stability; such monitoring and modeling can also help determine the most effective method for roof support.

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INTRODUCTION

Rib falls contribute to the instability of mine openings, representing more than a nuisance from the standpoint of overall mine safety. Between 1983 and 1989 there were 1,316 reported fatal and nonfatal rib-related injuries in U.S. coal mines (*1*).[2] A review of Mine Safety and Health Administration injury reports covering the 7-year period characterizes rib instability as follows:

1. A high number of rib falls appear to occur naturally for no apparent reason.
2. Almost half appear to be related to activity, e.g., drilling, bolting, continuous mining, and hanging brattice.
3. Only 5% to 10% appear to be bump related.
4. More than half of all rib falls involve large-sized slabs and/or chunks that may cause back injury, shoulder dislocations, smashed toes and fingers, etc.
5. A significant number of injuries result from avoiding rib falls rather than from direct contact with rib-fall material. This suggests that even a minor rib fall can contribute to a major injury.

This U.S. Bureau of Mines report investigates methods to improve rib stability as part of the Bureau's goal to improve the safety of miners. The sudden and detrimental nature of rib falls suggests that while rib falls are not entirely avoidable, a practical approach to understanding, characterizing, and controlling weak rib conditions is needed. This report will discuss the mechanics of rib failure, coal mine geology as related to rib behavior, rib support, rib monitoring, and physical and numerical modeling procedures for assessing rib stability.

MECHANICS OF RIB FAILURE

Successful efforts to curtail rib failure require a basic knowledge of how weak ribs behave. Two general kinds of rib failure patterns are blocky or plate-like (slabbing) failure and brittle failure, as shown in figure 1. The terms blocky or plate-like and brittle failure, as used in this paper, describe the degree of fracturing in the coal rib. Lightly or moderately fractured coal results in blocky or plate-like failure patterns, creating larger slabs or blocks of coal that may or may not be cleat related. Heavily fractured coal indicates a pronounced brittle failure pattern and much smaller and finer loose material. The failure mechanism for ribs is primarily influenced by several factors: (1) general and local stress distributions, (2) orientation and frequency of fractures and cleats, (3) shear resistance of preexisting fractures and cleats, (4) coal strength, and (5) geometry of mine opening.

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

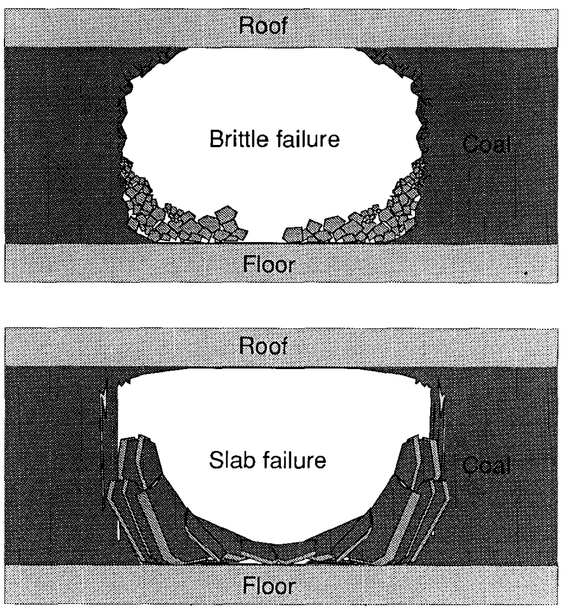

Figure 1.—Two basic types of rib failure.

BLOCKY OR PLATE-LIKE FAILURE

Blocky or plate-like failure is characterized by slabs or chunks of coal sloughing off the rib along a particular cleat or fracture surface. The presence of large pieces of material and low fracture activity indicate the coal is strong relative to current stress levels in the coal seam. As the intact strength of the coal is increased or the stress level is decreased, the propensity toward brittle failure is diminished, and failure becomes more likely along preexisting planes of weakness. When cleats and fractures open, distinct blocks are formed and, depending on their orientation, position, size, and rate of displacement relative to the mine opening, can significantly affect rib stability.

The orientation of the cleat system (dip and strike) relative to the rib wall usually has an immediate effect on stability, with the most dangerous orientation being vertically dipping with the strike parallel to the rib wall. The effect of cleat and entry orientations is illustrated in figures 2 and 3. British researchers have shown that a

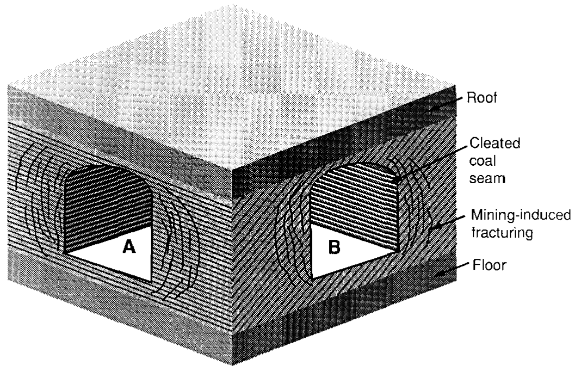

Figure 2.—Effect of cleat orientation on rib stability.

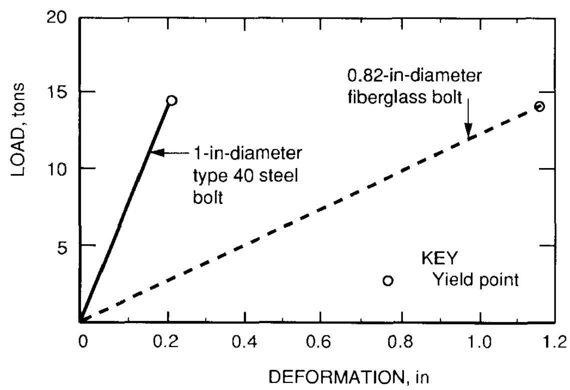

Figure 3.—Effect of changing entry orientation on rib conditions.

dramatic increase in both face and roof instabilities in longwall coal mines occurs if the angle between the strike of the cleat and the face line is less than 30° (*2*).

Chemical changes due to weathering of coal and clay stringers found in coal, particularly along cleat surfaces, may decrease coal integrity. Research in this area indicates significant weathering effects to coal at temperatures from 25° to 80° C, particularly under high humidity (*3*). Most underground coal mines fall within the lower end of that temperature range and often experience high humidity in certain areas of mine workings. Chemical changes in some clay partings found in coal may cause swelling normal to the bedding or cleat direction and contribute to splitting as a result of high tensile stress concentrations (*4*). While certainly not a leading cause of rib instability in most mines, weathering effects of coal should be considered a possible cause of rib instability in specific instances when clay stringers are present.

Once a potentially dangerous slab and block condition develops, rib instability does not occur until "loose coal" moves uncontrollably into the mine opening. The danger from such a rib fall is based on the height of the fall, the volume of material that falls, the suddenness of the fall, and the overall effect on the stability of the entire opening. Coal slab or block movement may be a reaction to stress relaxation caused by overburden or mining-induced loading, or to body forces due to gravity sufficient to influence slab and block rotations along the pillar margin. "Loose" slabs or blocks subject to little or no pillar confinement may exhibit planar sliding and toppling behaviors characteristic of rock slopes (*5*).

BRITTLE FAILURE

Brittle failure of coal induces micro- and macrofracturing, causing the coal to become almost granular as the fracturing process intensifies. The size of coal fragments depends on the degree of fracturing, cleat and/or preexisting fracture pattern, and the height of the mine opening. Brittle failure has been well documented in literature and has been shown to occur at low levels of confinement in weak coal and at loads as little as 30% of the uniaxial compressive strength (*6-7*). Brittle failure can cause greater rib dilation than larger slab and block failures as fractures open and the fracture intensity increases. As fracturing intensifies, coal strengths decrease. The decrease in strength can range from 50% to 80% of ultimate strength in soft rock (*8*).

Canadian researchers describe brittle failure in coal from the Rocky Mountain coal belt as pseudoplastic flow behavior known as extrusion deformation, and attribute microfracturing in the coal to interactions between repetitious hard and soft banding found in most bituminous coals. Interaction between individual bands of different hardnesses within the coal seam may respond to mining-induced changes in the stress field by promoting high shear stresses and subsequent failure within the coal, causing a highly fractured rib (*9*). The reduced coal strength leads to a weakened rib with flow characteristics as fractured coal moves into the entry. This behavior is characteristic of low-rank coals found throughout the Rocky Mountain coal belt and not of higher rank coals found elsewhere (*9*).

COMBINATION OF SLABBING AND BRITTLE RIB FAILURES

In general, both slabbing and brittle failures are increasingly likely in the same rib as mine conditions (stress field distribution, mine depth, coal strength and quality, etc.) change. The redistribution and alteration of the mine stress field ahead of an advancing longwall may cause high levels of mining-induced fracturing in the periphery of coal mine pillars where slabbing and block type failure once predominated (*10-11*). Figure 4 shows a pillar subjected to slabbing and brittle failures. Note the buckling behavior that occurs along the rib centerline. Often dramatic changes in shape due to volumetric changes in the coal indicate the onset of mining-induced failures. Some damage to coal may have previously occurred during entry development, causing yielding and crushing along the outer pillar margins. In one coal mine, substantial pillar fracturing was found to occur in 50% to 60% of the total pillar volume immediately after mining (*12*).

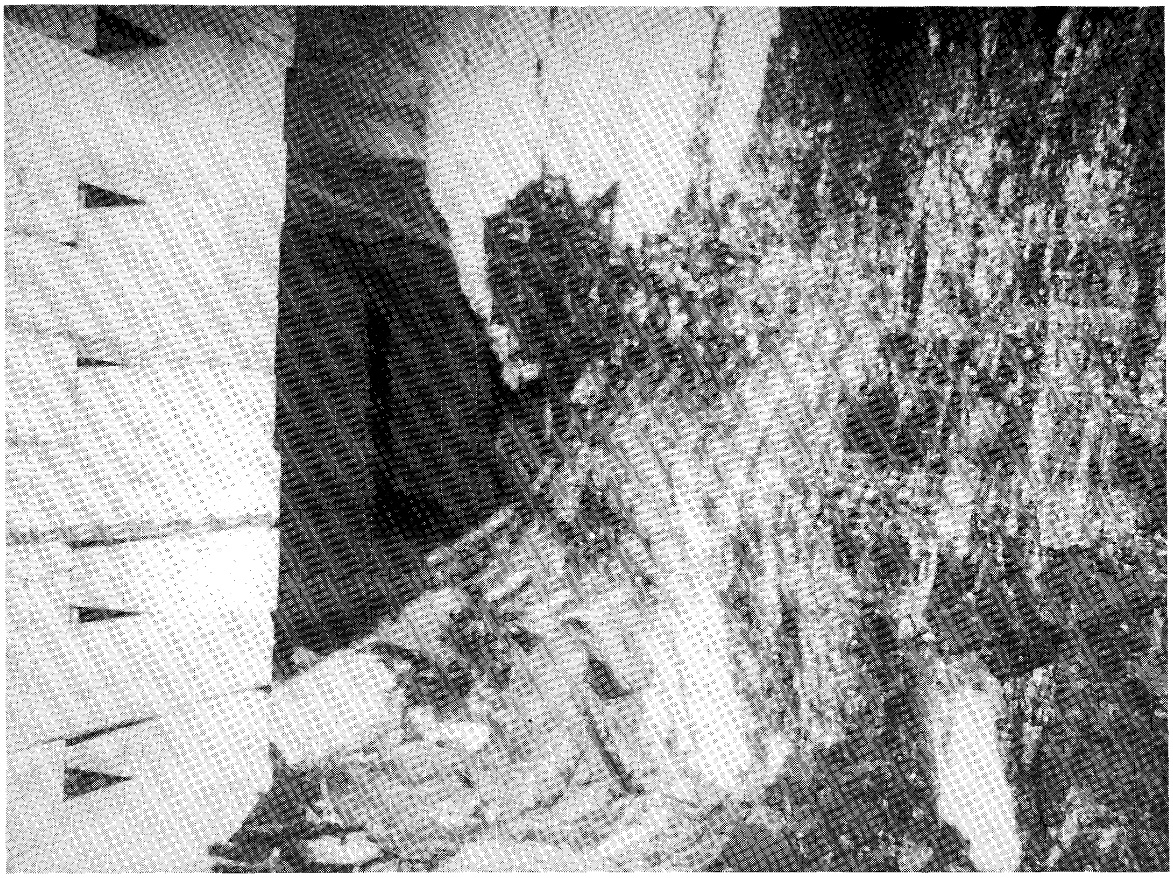

Figure 4.—Rib experiencing brittle and slabbing failure.

IMPORTANT GEOLOGIC PARAMETERS TO RIB INSTABILITY

The lithologic and structural variation of roof, rib, and floor strata in underground coal mines significantly contributes to rib and other instabilities by affecting the general stress field surrounding an entry. Geologic features that have a strong bearing on local strata conditions include (1) distribution and thicknesses of weak and strong rock strata; (2) joints and cleats; (3) anomalies, such as slickensides and pots; (4) depositional features, such as clay veins and sand pockets; (5) folds and faults; and (6) depth and dip of the mined coal seam. The implications of these parameters on overall rib stability need to be considered.

A primary characteristic of sedimentary rock is the regular or irregular sequences of strata of different lithologies with different strengths and thicknesses. With few exceptions, strata thickness is often related to stability. Thick, uniform roof and floor strata usually indicate relatively stable ground conditions. The same holds true for thick, homogenous coal seams of similar rank. A destabilizing effect on coal pillars and ribs is the alternating coal bands of hard and soft coal within thick coal seams; here the interaction between strong and weak bands leads to unfavorable stress concentrations within the coal that can lead to extrusion of individual coal layers and differential shearing between coal layers of different hardnesses (*9*). When the extrusion is severe, inclined coal faces can interrupt longwall mining, particularly in thick coal seams, and cause roof falls due to increased spans.

Examining and testing cores extracted from the various rock and coal units for physical and petrological properties remain the most dependable means to distinguish between weak and strong rock and to estimate strata thicknesses. A valid approach to studying rib behavior is to compare the strengths and possible interactions between different coal members within the same coal seam. Also, data on strength and stiffness comparisons of the roof and floor rock to the coal seam should be gathered.

The behavior of jointed or cleated coal ribs is dependent on the mechanical and geometrical properties of the joints or cleats. Surface roughness, cohesion, angle of internal friction, and normal and shear stiffnesses are important mechanical properties of joints and cleats. Geometrical properties that affect rib behavior are cleat and joint orientation and spacing. Cleating often occurs in sets of two: face cleats, which are the main cleats, and butt cleats, which are oriented perpendicular to the face cleats. Cleat spacing is usually indicative of the coal's physical properties and the premining load history on the coal seam. Preexisting fractures and other joint traces may have similar origins as cleating but generally do not exhibit the same repetitious frequency of occurrence. As discussed in the previous section, mining-induced stresses may be responsible for forming new fracture systems in coal.

Conducting direct shear testing of intact coal samples is the best method to determine cleat and/or joint shear characteristics of coal. However, problems of scale need to be addressed when the orientation and distribution of cleats and joints on laboratory samples are different than those of the coal pillar. Joint surveys on the coal pillar and vicinity should be conducted.

Geologic anomalies and depositional features often tend to weaken the strata that contain them. Anomalies such as kettle bottoms, slickensides, and fossils are usually associated with convoluted, and sometimes very smooth, low-friction joint surfaces that displace easily. Depositional features represent breaks in the lithology and often consist of clay veins and sand pockets that often intersect more than one stratum. Anomalies and depositional features that represent planes of geologic weakness in or near the coal seam can cause significant reduction in the shear strength of the roof and pillar. However, detection technology for anomalies and depositional features has proved unreliable.

Folds and faults, while not limited to, are generally more pronounced along mountain belt areas such as the Rocky and Appalachian Mountains. Representing primary topologic features, folding and faulting of sedimentary strata are partly responsible for the premining stress field surrounding mine entries, including unusually high horizontal stresses not due to mining (*13*). Fault zones intersecting mine entries are frequently a leading cause of mine opening instability, resulting in massive roof falls, floor heave, and pillar yielding. Topographical investigations, such as remote sensing, have shown limited success in identifying fault traces, as have general geologic studies of the areas prior to mining.

Related to folding and faulting is the depth and dip of the mine coal seam. The thickness of overburden above a mine entry also greatly influences premining or virgin stress fields. Currently, there is a dearth of information on how seam dip affects coal rib stability other than those effects due to increasing depth and a rotation of fracture and cleavage planes from true vertical.

PILLAR CONSTRAINT

Bureau researchers demonstrated that an important factor contributing to the mode of failure is pillar constraint (*14*). Pillar constraint was shown to occur in Western underground coal mines because of sharp differences in roof, rib, and floor physical characteristics, specifically Young's modulus; Poisson's ratio; and the coefficient of sliding friction of roof, rib, and floor rock. Figure 5 shows how a stiff roof and ductile floor can affect rib displacements. Generally speaking, strong roof and floor rock enhances rib confinement pressures near the roof and floor; weak, ductile roof and floor rock reduces rib confinement pressures near the roof and floor. As was previously discussed, even the presence of hard and soft banding in the coal seam causes similar stress anomalies within the coal.

The effect of constraint was demonstrated on a simulated cleat system. A Bureau study showed that the behavior of an entire pillar was dependent on whether the cleats were open or closed (*15*). As with pillars, whether a cleat system is open or closed influences how load is transferred through the rock mass. Open cleating indicates a loss of constraint and load transfer, and is generally a sign of a progressing failure condition. In coal ribs, open cleating may indicate that slab or block formation is underway and sloughage may be imminent. Closed cleats or fractures without displacement and/or any new fracturing suggests a stable pillar and rib condition in which the pillar is not yielding.

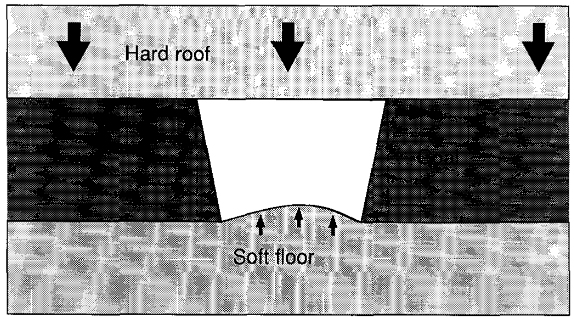

Figure 5.—Effect of stiff roof and ductile floor on rib displacements.

SUPPORT STRATEGIES

Whether to use roof support—and what type and amount of roof support is necessary—is usually a subjective decision based on site-specific factors. Some factors significantly affect support selection and strategy:

1. The magnitude, location, and direction of the high-stress regions in the pillar and vicinity.
2. The orientation of the cleat system and other geologic structures in the coal in relation to the stress field.
3. The joint and coal physical properties compared with the support characteristics.
4. The depth and extent of the fracture zone in the pillar to be stabilized and the height of coal seam.
5. The sizes, shapes, and pattern of the failed rib material to be immobilized and retained.
6. The rate and magnitude of allowable rib failure and life expectancy of the mine opening.

The mechanics of rib failure, as previously discussed, has a strong bearing on support selection and strategy, as does economics. The challenge is to sufficiently support the rib during the useful life of the mine in a practical manner. Installing rigid steel sets may adequately maintain rib stability in many mines, but such installations are impractical in temporary coal mine workings such as gateroads near a longwall panel. Figure 6 shows practical rib support ideas for coal mines. In the following sections, rib support alternatives for different rib conditions in underground coal mines will be presented.

RIB BOLTING

In coal ribs where slabbing or plate-like rib failures dominate, bolting will improve rib integrity. Securely anchored bolts must effectively increase the frictional forces between slabs to restrict horizontal and vertical movements, e.g., toppling, buckling, and sliding (*16*). This assumes that the shear properties of the bolts are high enough to prevent bolt failure, regardless of the orientation of rib cleat or fractures.

Bureau research has developed an approach to designing a bolting pattern based on average slab widths and distribution along the rib centerline (*17*). The method allows for variability of bolt spacing to account for changes in slab size and overlap. In most cases, depending on slab configuration, one or two rows of bolts are sufficient to secure slabs in place. Unless highly yielding coal is encountered, resin-grouted or expansion-anchor bolts can be used in combination with mesh and pans to provide additional constraint on smaller sized pieces of coal.

The question arises, How long should the bolts be? Progressive pillar failure theory estimates the yielding zone around average-sized pillars to range from 10 to 30 ft. The obvious answer is the bolts need only be long enough to ensure stability in the opening. Creating an integral shell of "broken" rib coal that adequately confines coal fragments behind the rib would be one valid approach. Unfortunately, no easy method is available to determine how thick this shell should be. The usual approach is strictly an exercise in trial and error until an effective bolt length is found and rib stability occurs. Angle bolting from rib to roof may be a good idea in fractured coal under competent roof, which can serve as an anchoring base for the "broken" rib.

Another question concerning bolts is, What kind of bolt should be used? The answer is to use a bolt that interacts with the rock mass in such a way to develop forces conducive to stabilizing the rock mass whether tensioned or nontensioned bolts are used. In other words, the deformability characteristics of the rock mass and bolts should be matched. Stiff, stronger coal seams can tolerate stiffer support, while a yielding coal mass requires yieldable support. Otherwise, failure will arise in the support or rock mass before stability is achieved.

Progressive fracturing of the coal rib represents an unstable condition that is controllable in one of two ways: (1) reduce local stresses, or (2) increase confinement stresses. Because of high levels of frictional energy often associated with this type of failure, the desired approach to improve rib and pillar stability is to use yieldable support, which reduces local stresses by allowing small, controllable displacements while still maintaining adequate confinement pressure to the rib.

Some underground coal mines that have a history of rib rolls frequently experience rib support failures, such as bolt heads "popping off" conventional resin and expansion-anchor-type bolts. Yieldable bolt designs that have been utilized in such mines appear to stabilize the coal seam and ribs more effectively by controlling displacements to reduce stress buildup. Important considerations before designing yieldable bolts are to estimate the magnitude of the rib and pillar stresses and instability to be encountered, and then the maximum allowable deformation that can

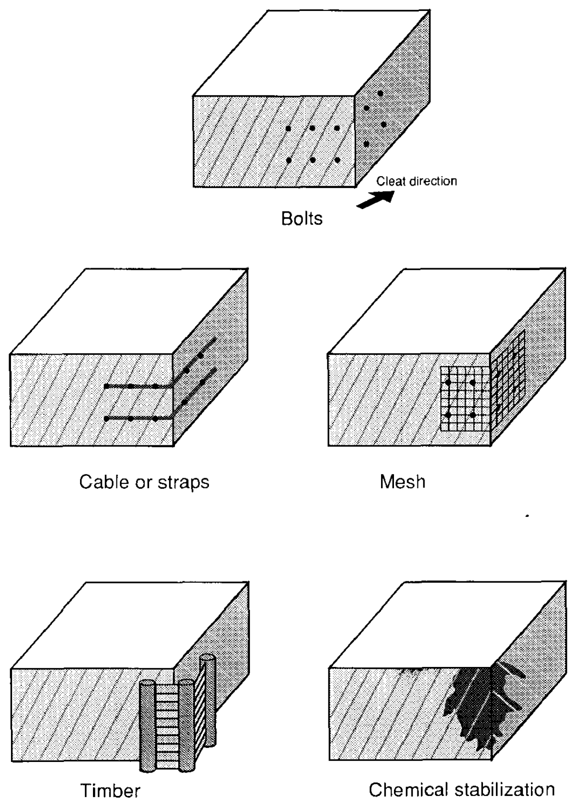

Figure 6.—Several support types that improve rib stability.

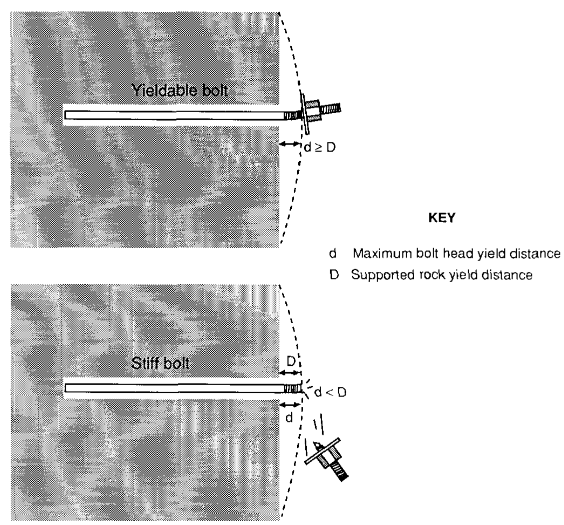

Figure 7.—Compatibility of support with expected rib deformation. Top, Yieldable bolt matches deformability characteristics of rib; bottom, shift bolt is not compatible with deformation and bolt head "pops off."

be expected and tolerated in the support. It should be remembered that the plastic deformation of conventional steel expansion-anchor bolts is limited to only a couple of inches and that any rib dilation greater than that around the bolt head would most likely result in premature bolt failure. The importance of matching the deformability characteristics of the support to that of the rib is illustrated in figure 7. Figure 8 shows other promising techniques for supporting yielding coal ribs.

Two yieldable bolt designs that require special fabrication are helical and smooth-bore-die yieldable bolts. The flexible helical rock bolt (*18*) appears to support load well in a yieldable coal rib but is difficult to install, often requiring an oversized hole. Another yieldable bolt tested by the Bureau consists of a standard expansion-anchor bolt with a yieldable collar or smooth-bore die that deforms along the threaded portion of the bolt head (*19*). This bolt design is used extensively in deep coal mines in the Republic of South Africa to prevent coal bumps and shows promise for many U.S. coal mines with similar problems.

A less expensive and perhaps equally effective approach to designing a yieldable bolt is to convert a standard resin-grouted or expansion-anchor bolt into a more yieldable bolt design by inserting yieldable structures between the bolt head and plate, e.g., wooden blocks, sections of steel tubing, or polyvinyl chloride (PVC). One coal mine successfully controlled violent rib failures by installing angle bolts with split-steel tubes between the bolt heads and plates (*20*).

Other materials to replace steel bolts are available, such as wooden dowels, fiberglass, and PVC bolts. An advantage of wood, fiberglass, and PVC bolts is that they can be mined through with a cutter or shearer during pillar extraction without serious damage to mine machinery and personnel. Wooden dowels have been successfully tried in many coal mines, especially in forepoling procedures for pre-reinforcement of roof and rib in room-and-pillar mining. Fiberglass bolts, used in an underground borate mine, but not in U.S. coal mines, have yield characteristics that may benefit failing coal ribs. Figure 9 shows contrasting deformation differences between fully grouted steel and fiberglass bolts with similar yield strengths. Australian coal mines have successfully applied fiberglass and PVC bolting to rib support (*21*).

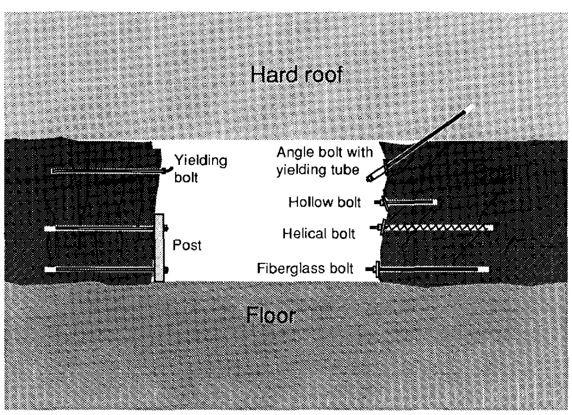

Figure 8.—Rib support types designed for yielding rib.

OTHER LOOSE ROCK CONFINEMENT METHODS

In addition to bolting, other methods available for the confinement of loose rib rock include mesh, cable slings,

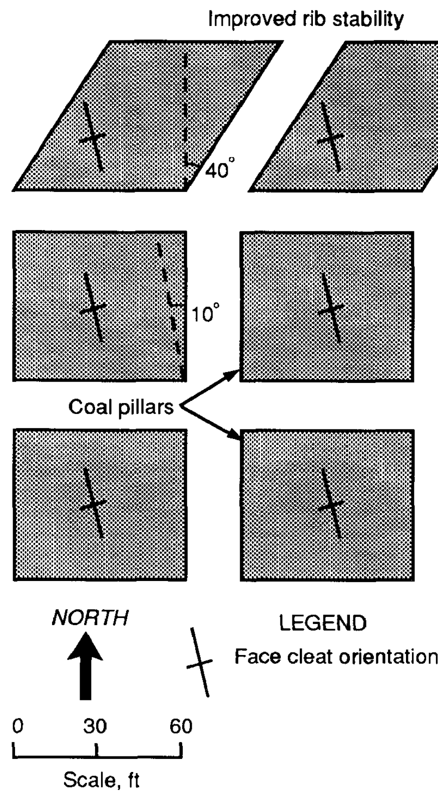

Figure 9.—Pull-test results of fully grouted steel and fiberglass bolts.

steel bands, post and timbers, and chemical stabilization. As shown in figure 6, with the exception of timbers and chemical stabilization techniques, these methods are generally used in conjunction with bolting.

Research indicates that small radial forces applied to the rib wall can have significant results in reducing the progression of rib failure (*22*). Ideally, it is preferable to apply confinement before rib failure has progressed to the point where fractures have opened than to apply confinement after significant fracture separations have occurred. As a general rule of thumb, support should be installed at the earliest possible time while most of the failed material is in place and frictional contact along fractures is maintained.

Friable coal ribs usually require liners or strapping to hold "broken coal" in place. Steel mesh is the most widely available liner material for use in coal mines and comes in various mesh sizes. Figure 10 shows one strategy for using wire mesh for rib control. Alternative materials for meshing and strapping, such as polyethylene netting and geotextiles, are more widely used in Europe and Australia (*21*).

Cable bolting can be usefully applied to the outside of unstable ribs. Wrapping cable around the pillar is another method to provide active confinement to coal ribs when larger slab formation is expected. Wrapping pillars with cable has been effective in reducing high shear stress along roof and rib fractures (*23*). Generally, cable bolting works most effectively in combination with bolting, meshing, and/or shotcreting to handle different sizes of "broken coal." Wire rope can be used to reinforce large sections of wire mesh, allowing the mesh to withstand greater pressures from large slab and block displacements in large areas of rib. This technique has been shown to prevent face sloughing in thick coal seams (*24*).

Installing timbers and posts close to the rib to halt sloughing coal is another method to contain loose coal and provide some stability. Since active support is not applied, confinement pressures do not develop with this method until significant block and slab displacement occur in the rib. Depending on timber-to-rib distances, considerable block and slab movement may be necessary before stability is achieved. In situations of oversized pillar dimensions, these larger displacements may be more tolerable when intact pillar core is adequate. Using wooden posts and headers with bolts represents another variation that combines the yieldable characteristics of wood with the anchorage capabilities of bolts. This approach has been successful in restraining large slab movements.

Grout, polyurethane, and foam injection techniques are effective methods for the stabilization of fragmented strata, particularly on longwall faces in thick coal seams. Brought over from Europe, these methods have been successfully tested in U.S. coal mines with highly fractured, and often highly faulted, coal seams (*24*). Properties that make chemical rock stabilization effective are (1) high expansion to fill voids and cracks, (2) variable viscosity (low initial viscosity to fill all cracks, followed by high viscosity once cracks are filled), (3) good adherence to rock material and support, and (4) plasticity to deform with rock movement. In theory, rib stability can be increased with this method by decreasing the number of active fracture surfaces. This method works well in highly fractured, highly stressed coal faces, particularly in thick-seam deep longwall mines. Cheaper and more effective chemical and grout delivery systems are needed to encourage more widespread use of the procedure in gateroad coal pillar and rib stability designs.

Figure 10.—Using wire mesh for rib control.

TEST SITE MONITORING TECHNIQUES

Rib monitoring techniques should be compatible with the types of rib failures expected. Movement of coal into the mine opening is a primary concern and should be monitored if instability is expected. Two regions of rib that may require routine monitoring are the rib profile and the immediate thickness of coal that comprises the rib.

Monitoring the rib profile provides input on the nature of the failure from roof to floor. One simple method to detect changes in the rib profile is by applying rock dust. A drawback of this method is that it is strictly visual and does not provide information on the rate of movement or degree of sloughage. Photographic methods, however, work well as visual aids for qualitative determination of rib deterioration.

A radical change in the rib profile often is a precursor to a burst. To detect potentially dangerous rib conditions in Australian mines, monitoring rods are erected alongside the rib and horizontal rib movements are routinely monitored at different elevations on the rod (*21*). This method of rib monitoring using a vertical line of reference, as shown in figure 11, can be helpful in evaluating rib response during face advancement.

Another practical reason for monitoring rib behavior is to determine the extent and depth of the yield rib zone so that the proper length dowels or bolts can be installed. As shown in figure 12, installing horizontal multipoint

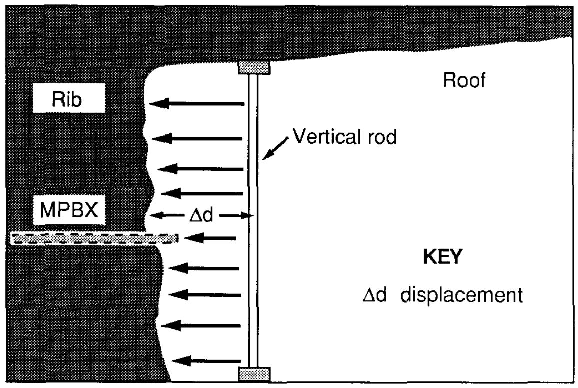

Figure 11.—Technique for quantitatively monitoring rib profile. (MPBX = multipoint borehole extensometer).

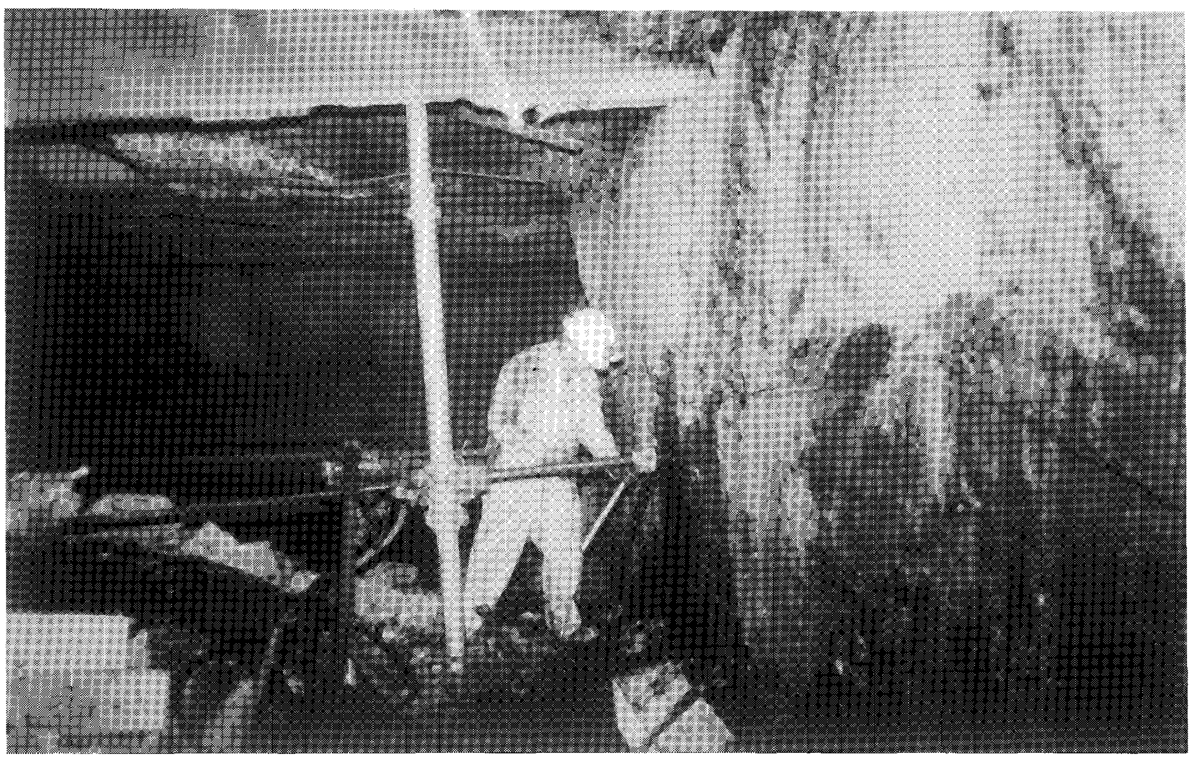

Figure 12.—Drilling horizontally in coal to install instrumentation.

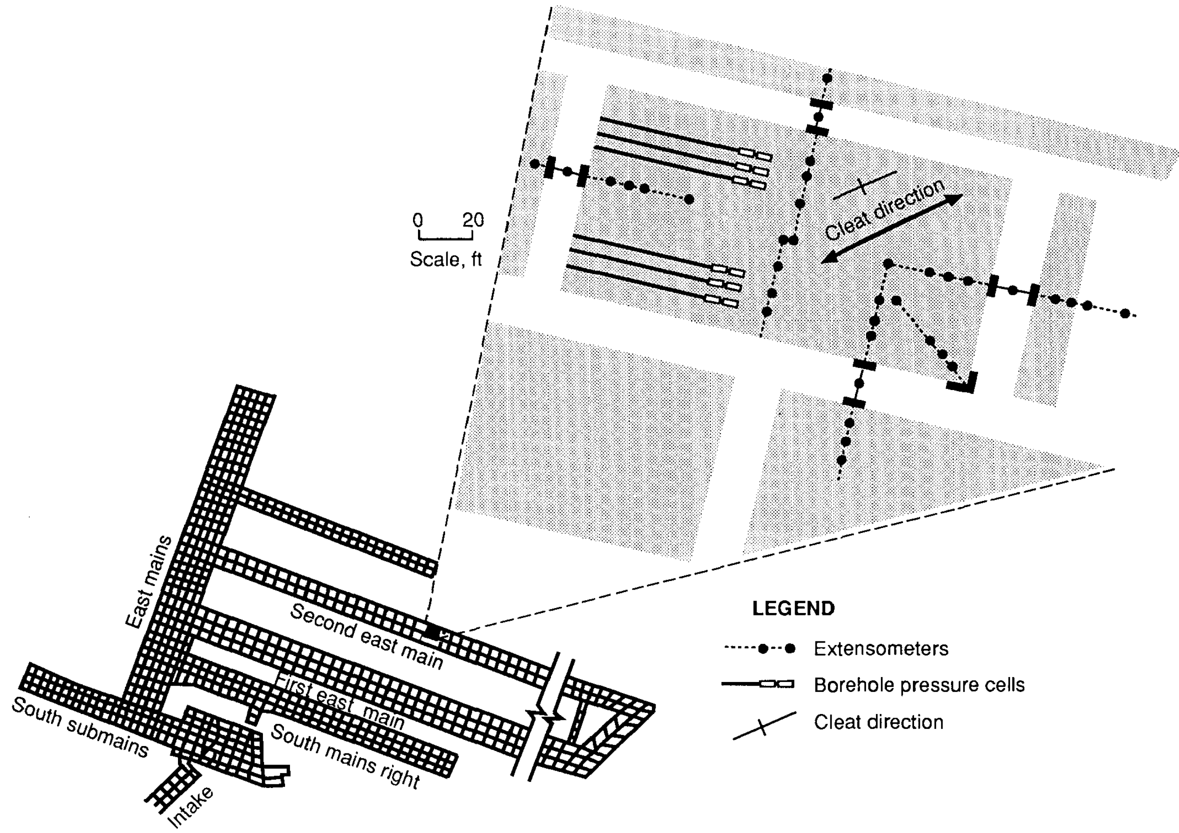

Figure 13.—Example test plan for longwall study.

borehole extensometers (MPBX) into the rib is one way to gauge horizontal rib movement at varying depths into the pillar. Geophysical methods offer another alternative for measuring the rib pillar yield zone to detect changes in coal integrity. One such method that shows promise is capable of obtaining sonic velocity profiles through the coal seam and may be used to detect potentially dangerous rib conditions (*25*). Another technique to detect the degree of rib fracture is an air-injection method that relates the rate of air leakage to fracture intensity (*12*).

Gathering baseline information on general load transfer and pillar yield characteristics along gateroads in underground longwall coal mines would also help quantify rib failure. Such comprehensive field investigations and instrumentation have been implemented by the Bureau to monitor ground control around longwall panels (*26*). One such plan is shown in figure 13. Notice the MPBX installed along the rib periphery and pillar corner. Strategies for installing arrays of borehole pressure cells and MPBX are aimed primarily at testing pillar performance during mining. This supplemental information represents a foundation for understanding the "driving forces" behind failing ribs.

RIB MODEL STUDIES

A low-risk procedure for evaluating support needs and behavior of supported rock masses around underground mine openings is the modeling of in situ conditions. As mentioned previously, the interaction of many structural, stress, and geometric parameters affect rib behavior. Modeling is one method to study these interactions.

Regardless of the model method used to study rib instability, a practical approach is to (1) define the problem of rib instability, (2) identify important parameters and processes to be studied, (3) determine the appropriate model based on the expected rib failure, (4) verify and validate the results with field or laboratory data, and (5) if significant, incorporate the results into rib and pillar design.

PHYSICAL MODELS

Limiting the number of parameters in the model is one technique that reduces model complexity while saving time and money. This approach can be most usefully applied in physical modeling, in which the simplicity or complexity of the model is directly related to the number of worker-hours needed for model preparation and execution. Often loading core or small block samples can generate useful information. For instance, cores or blocks of coal can be prepared and tested to investigate the effects of various confinement techniques, such as bolting pattern and mesh, on coal strength and deformation. Bureau research has developed a rib bolt spacing formula based on triaxial test results on rock cores with preconfigured bolt patterns (*17*). The base-friction modeling method has been used to compare supported ribs with unsupported ribs, as shown in figure 14 (*27*). Simple hands-on rib modeling techniques are useful in developing and testing concepts prior to conducting large-scale field tests or running more complex models.

Physical models requiring similitude between what is modeled and the measured field conditions present greater challenges in terms of time and expense. Usually such models have been reserved for global mine control design rather than for local problems such as rib instability. Researchers in England have applied dimensionless analysis to evaluate ribside pack-width effects and rib behavior under different loading conditions (*28*).

NUMERICAL MODELS

Normally, complex-parameter interactions are more efficiently modeled using numerical techniques. A valid numerical procedure for determining progressive rib failure considers changes in the mine-wide static load distributions imposed on underground mine workings during various stages of the mining cycle (*29*). A useful approach is shown in figure 15. Initially, a three-dimensional displacement-discontinuity boundary-element model (*30*), such as MULSIM (*31*), is used to determine global stress distributions above mine workings during any stage of mining. Predictions about pillar and ground control performance are provided by the output of this first program. The next step is to zoom in on a smaller scale portion of the larger mine layout model, such as the region of interest around a single pillar or a slice along a pillar edge. In the second step, loading conditions predicted by the boundary-element code are input into a pseudoelastic, finite-element model such as ADINA (*32*) to observe post-yield behavior patterns of the pillar or rib in greater detail. Establishing boundary conditions in this way can be useful when using other model types.

Supported rib effects under yieldable pillar conditions have been studied using NONSAP finite-element code (*33*), which is similar to ADINA. Findings from that study showed that by using rib support that complies with the deformability characteristics of the rock mass, e.g., coal, the resistance needed by the support to achieve stability can be relatively small (*34*).

When slab or block failures are expected, discrete-element models offer appropriate solutions to rib failure. These programs discretize the rib into discontinuous slabs and blocks that interact, and the programs generate different outcomes depending on material and fracture surface characteristics of the blocks. The discrete model (fig. 16), which takes support elements into account, has been used to test different support strategies for varying rib conditions (*35*).

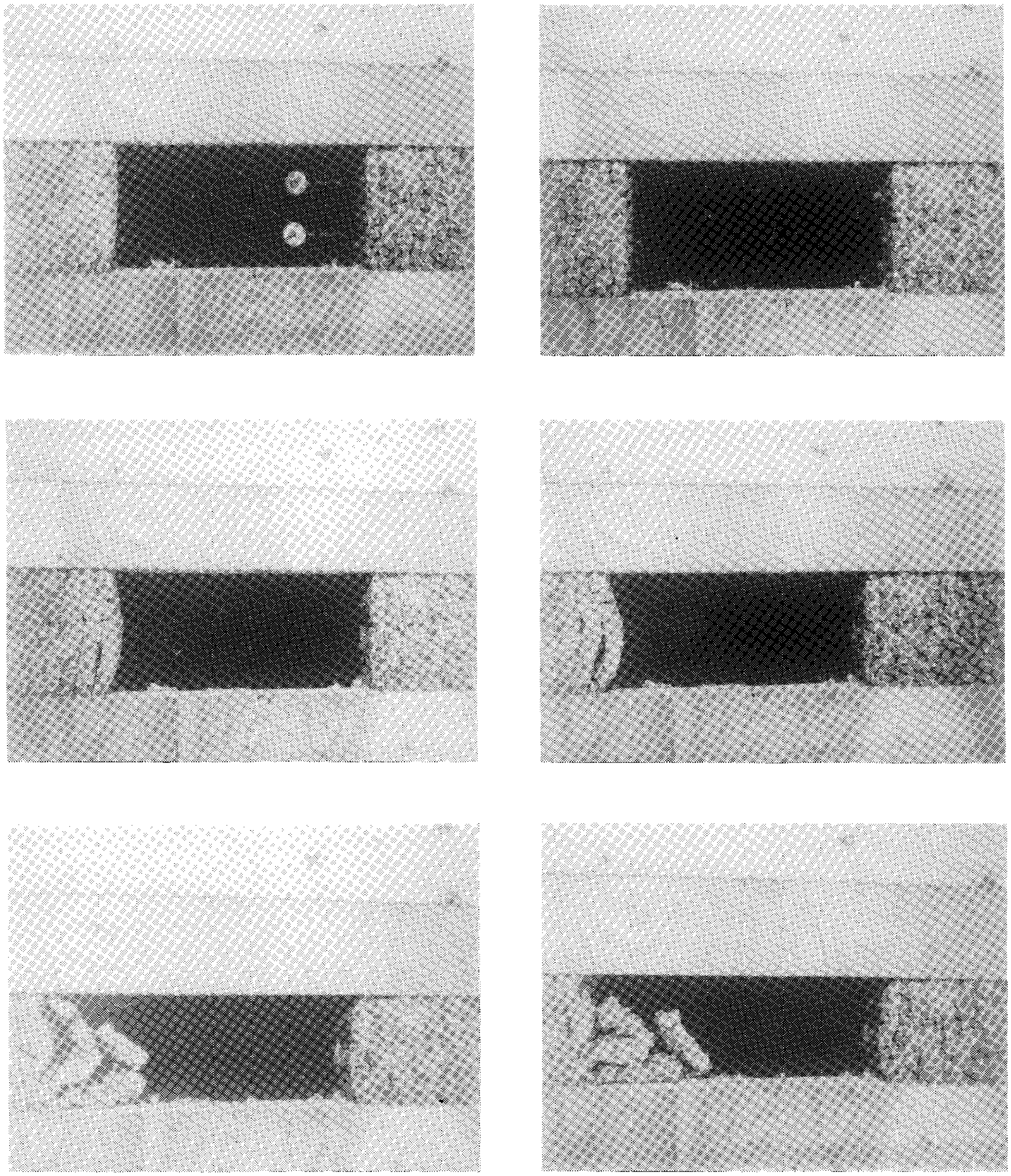

Figure 14.—Comparison of supported versus unsupported ribs using base-friction model. Photographs taken at 10-sec intervals.

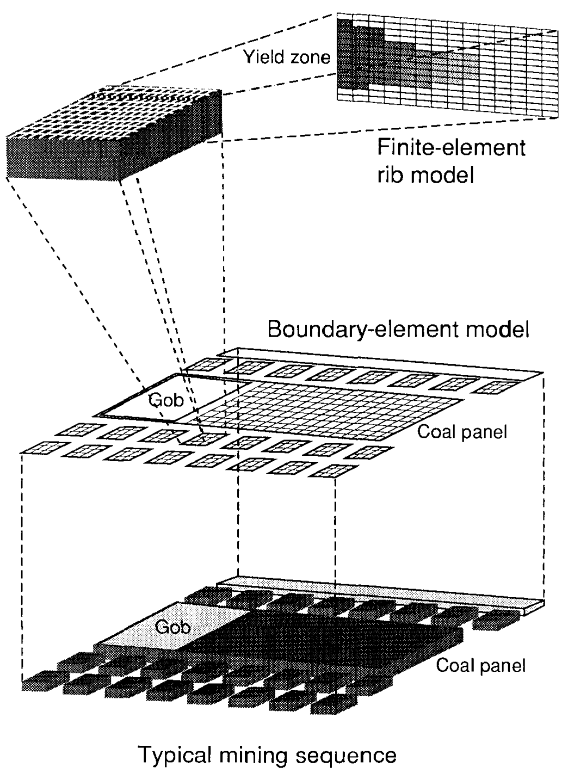

Figure 15.—Numerical procedure for studying rib behavior.

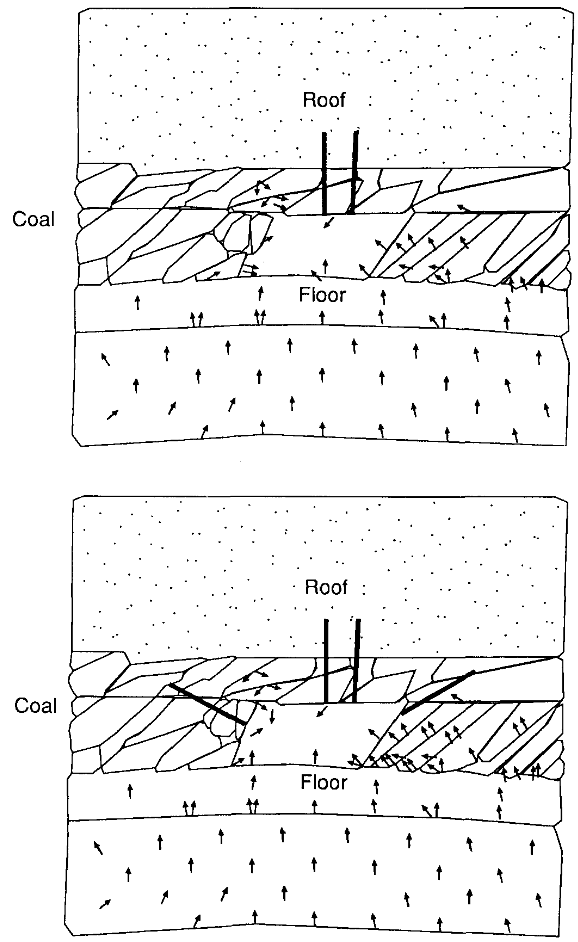

Figure 16.—Discrete model of mine opening for rib study. Thick lines indicate roof bolts. Arrows indicate displacement direction.

CONCLUSION AND RECOMMENDATIONS

In conclusion, this report presents a practical view toward the study of rib failure and discusses steps that can be taken to reduce the incidence of failing ribs. Once the potential for rib fall has been established, the mechanics of rib behavior should be adequately identified. Other contributing causes such as geology, material and fracture properties, and stress anomalies should be evaluated and determined. The design of remedial support strategies should be based on the mode of expected rib failure from past mine experience and recent data obtained from a field ground control monitoring program. Physical and numerical modeling can provide additional information on rib behavior based on global and local parameter interactions not easily quantified in field measurements. Decisions for improving stability through secondary support can involve more strategy and understanding of the problem than to simply install bolts when rib failure occurs.

It is suggested that further studies be undertaken to—

1. Develop the methodology to match rock and support deformability characteristics. Coal seam interactions and support effects need further evaluation.

2. Assess the relationship between time-dependent behavior of rib and the time factors involved with the installation of support.

3. Apply current support technology and develop new rib support technology using innovative systems, materials, and procedures.

4. Develop more user-friendly computer software to evaluate rib support design using empirical and analytical data.

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