FUNDAMENTALS OF COAL MINE ROOF SUPPORT

By Christopher Mark, Ph.D.,[1] and Thomas M. Barczak[2]

ABSTRACT

Roof supports can only be understood in conjunction with the rock structure that they support. The strength of the rock depends on geology, and the loads are applied primarily by the in situ and mining-induced stresses. Other factors, such as wider spans and retreat or multiple-seam mining, can also reduce the stability of mine openings. Roof supports are used to help stabilize these openings, but their performance characteristics must be properly matched to the loading environment and ground behavior if they are to succeed. Roof supports include both intrinsic supports, such as roof bolts, and standing supports. The key characteristics of any support include its maximum load-carrying capacity, stiffness, and residual strength. Other important factors are the timing of installation, the stability of the support as it is loaded, and the capability of the support system to provide skin control. This paper explains in practical terms how supports work and the important factors in ensuring that a good support design and application strategy are developed.

---

[1] Supervisory physical scientist.
[2] Research physicist.
Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA.

INTRODUCTION

Roof support is essential to the safety of every underground miner. It has three primary functions:

- To prevent major collapses of the mine roof;
- To protect miners from small rock falls that can occur from the immediate roof skin; and
- To control deformations so that mine openings remain serviceable for both access and escape, as well as for ventilation of the mine workings.

Roof supports interact with the ground to create a stable rock structure. With any structure, an engineering analysis begins with evaluations of two fundamental factors:

- The strength of the different components of the structure; and
- The forces that are loading it.

Rock structures are unique in that the strength of one essential component, the rock itself, can seldom be determined accurately. Similarly, the ground stresses are rarely well understood. Ground control engineers have had to develop novel techniques to compensate for these deficiencies.

This paper begins with a summary of the factors affecting the integrity of mine roof structures. Next, it discusses the function and properties of mine roof support. It concludes with a framework for understanding how the supports and the ground interact with each other to provide a stable mine opening.

FACTORS AFFECTING THE INTEGRITY OF MINE STRUCTURES

An assessment of the integrity of any mine structure must begin with an analysis of (1) the structural integrity and strength of the roof rock, (2) the excavation geometry, and (3) the forces applied to the mine roof.

ROCK STRENGTH

Rock strength traditionally is estimated from laboratory tests. The uniaxial compressive test is the most commonly used. Figure 1 shows the approximate range of compressive strengths observed in U.S. coal measure rock. Triaxial tests, where the rock is confined, more accurately simulate the three-dimensional stress that rock typically encounters underground. Shear tests of bedding planes can be very helpful in evaluating the likelihood of slip, but are rarely performed in the United States. These three types of tests are shown in figure 2.

Rock tests are severely limited in that they are conducted on small samples of intact rock. The strength of the rock mass in mine roof is, however, determined largely by the presence of cracks, bedding planes, and other natural discontinuities. Rock mass classification systems were developed to help quantify their effects.

The Coal Mine Roof Rating (CMRR) focuses on the specific features that commonly occur in coal measure rock. It weighs the individual geotechnical factors that determine roof competence, including—

- The uniaxial compressive strength of the intact rock;
- The spacing and persistence of discontinuities like bedding planes and slickensides;
- The cohesion and roughness of the discontinuities; and
- The presence of ground water and the moisture sensitivity of the rock.

Simple index tests and observations are used to rate each of these parameters, which are then combined into a single rating on a scale from 0 to 100.

The CMRR can be calculated from underground exposures like roof falls and overcasts [Molinda and Mark 1994] or from exploratory drill core [Mark and Molinda 1996]. In the case of drill core, point load tests are used to estimate the compressive strength and the cohesion. A computer program is currently being developed to aid in the collection, interpretation, and presentation of CMRR data.

The CMRR incorporates most of the geologic factors that affect the mine roof. It does not address large-scale features, like faults, sandstone channel margins, or igneous dikes. Such features may cause major disruptions in relatively small areas and should be treated individually.

CMRR values have been obtained from hundreds of coal mines throughout the United States and abroad. Figure 3 shows that the northern Appalachian coalfields typically have the weakest roof in the United States; the strongest roof is found in Utah. Ground conditions and roof bolt densities from three major coal mining countries are compared in figure 4 [Mark 1999b]. Roof bolt design guidelines are presented elsewhere in these Proceedings [Mark 2000].

ROOF SPAN

In underground coal mining, the excavation geometry does not vary much, but the span can be very important. The basic principle that governs the relationship between stability and the span was first formulated by Austrian tunneling engineers [Bieniawski 1989]:

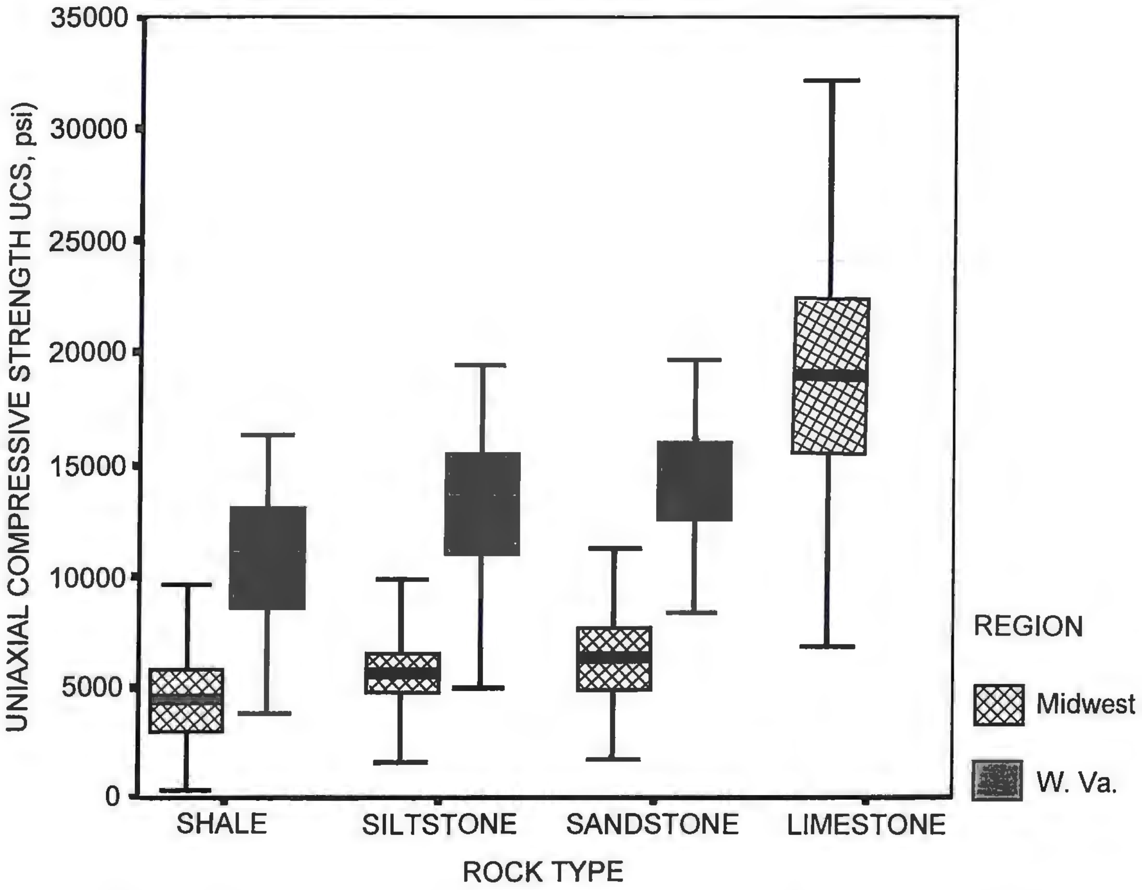


Figure 1.—Range of compressive strength for U.S. coal measure rocks [Rusnak and Mark 2000].

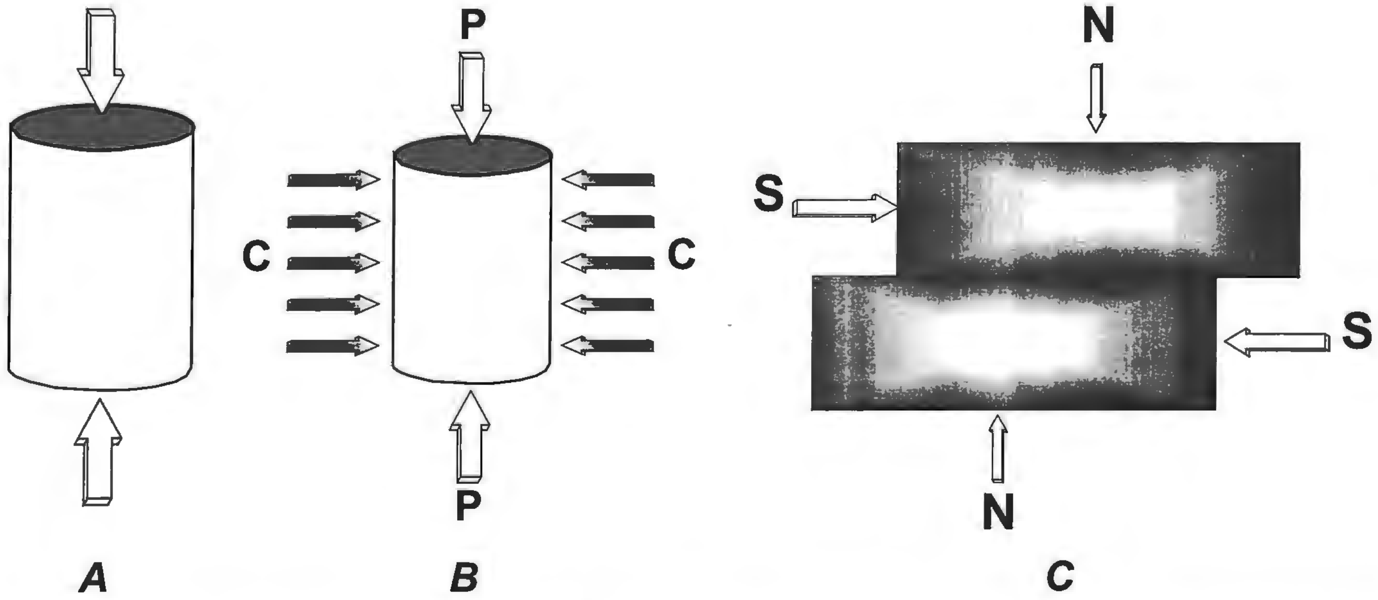


Figure 2.—Three types of laboratory strength tests. *A*, uniaxial compressive strength test; *B*, triaxial compressive strength test; *C*, bedding plane shear test.

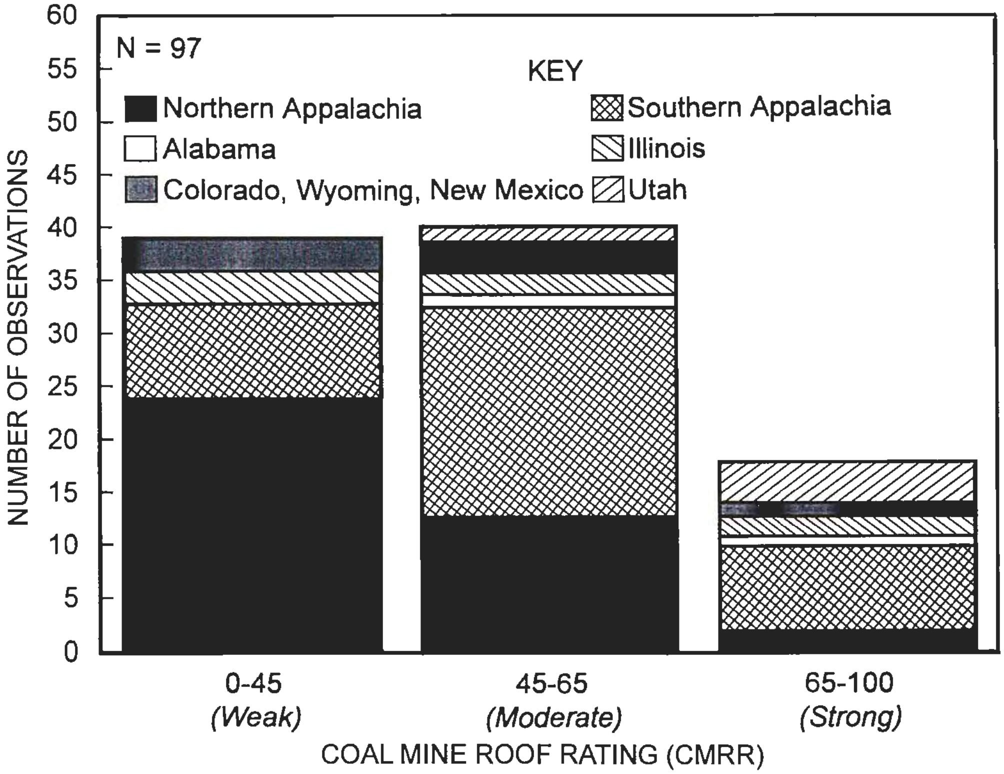


Figure 3.—Range of Coal Mine Roof Ratings (CMRR) observed in the United States [Molinda and Mark 1994].

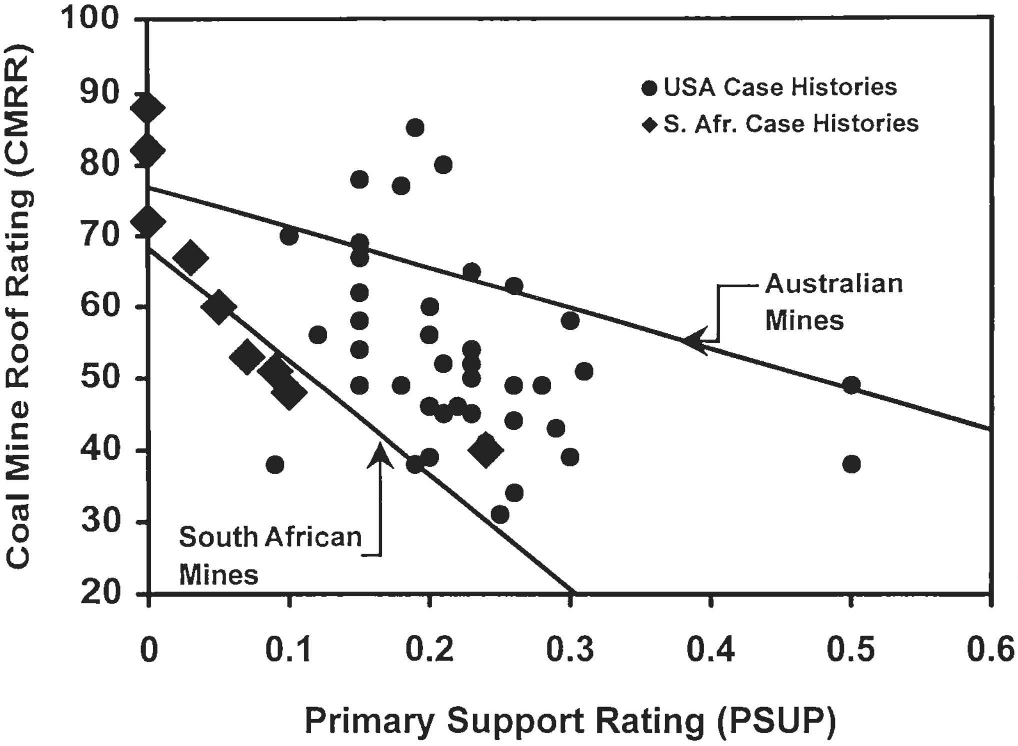


Figure 4.—Roof bolt densities observed in three coal mining countries [Mark 1999b].

- For a given rock mass, a tunnel's standup time decreases as the roof span becomes wider; and
- For a given roof span, a tunnel's standup time decreases as the rock mass quality becomes poorer.

The greatest spans in coal mines are encountered in intersections. While entries are normally limited to 6 m (20 ft), the diagonal spans of intersections are generally in the 7.5-12 m (25-40 ft) range. Approximately 70% of all roof falls occur in intersections, although intersections only account for about 20% to 25% of all drivage. Roof falls are therefore 8 to 10 times more likely to occur in intersections than in an equivalent length of entry [Molinda et al. 1991].

A study by Mark [1999a] looked at standup time during extended (deep) cut mining, where the continuous miner advances the face more than 20 ft beyond the last row of permanent supports. At 36 mines, it was found that when the CMRR was >55, the roof was stable in nearly every case. When the CMRR was <37, the roof collapsed before the cut could be completed. When the CMRR was between 38 and 55, extended cuts were feasible some times, but not others (figure 5). The data also show that extended cuts are less likely to be stable if either the entry span or the depth of cover is increased.

Many studies have documented the effect of roof span on stability. The longwall study cited earlier found a strong correlation between entry width and CMRR (figure 6) [Mark and Chase 1994]. The relationship between intersection span and the incidence of roof falls at six mines was documented by Mark et al. [1994] (figure 7). A similar correlation is reported by Molinda et al. [2000].

FORCES APPLIED TO THE COAL MINE ROOF

Stress is everywhere underground (figure 8). Usually, the external forces applied to rock are all compressive, but they are not equal in all directions. The in situ stresses are normally resolved into three components: (1) vertical stress, (2) the maximum horizontal stress, and (3) the minimum horizontal stress.

Vertical Loads

The most obvious source of loads on mine structures is the weight of the rock itself. It is convenient to analyze two types of vertical loads (figure 9):

- The *roof load*, which is due to the weight of the immediate roof strata as they sag into the mine opening; and
- The *pillar loads*, which are applied by the weight of the overburden.

The roof load is the vertical force that most directly applies to roof support. Various "dead weight" design methods are based on estimating the volume of immediate roof rock that has separated from the more stable overlying rock mass and consequently must be supported [Mark 2000].

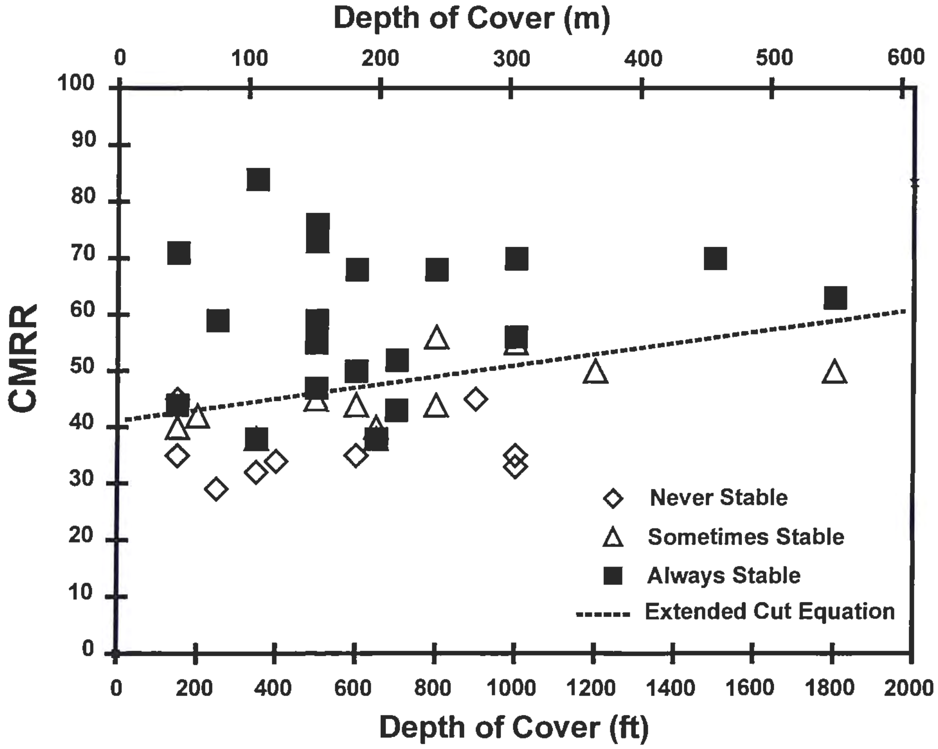


Figure 5.—Relationship between CMRR, depth of cover, and the stability of extended cuts [Mark 1999a].

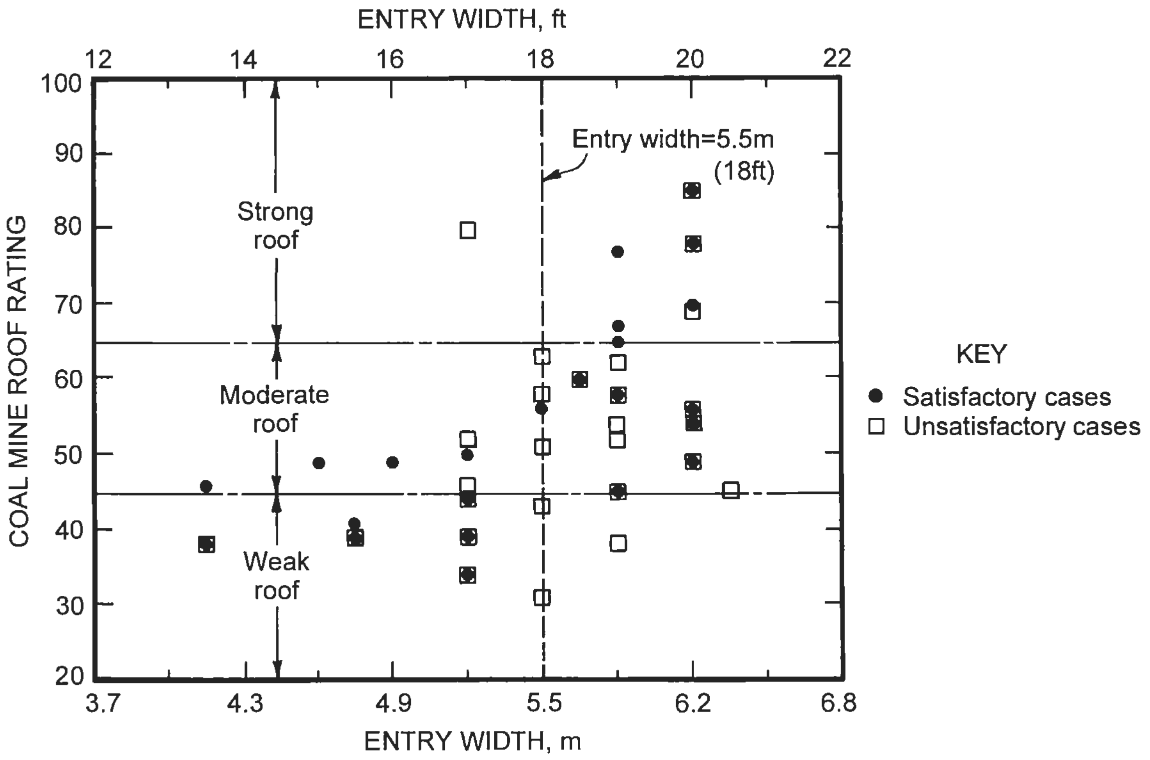


Figure 6.—Entry widths and CMRR in U.S. longwall mines [Mark and Chase 1994].

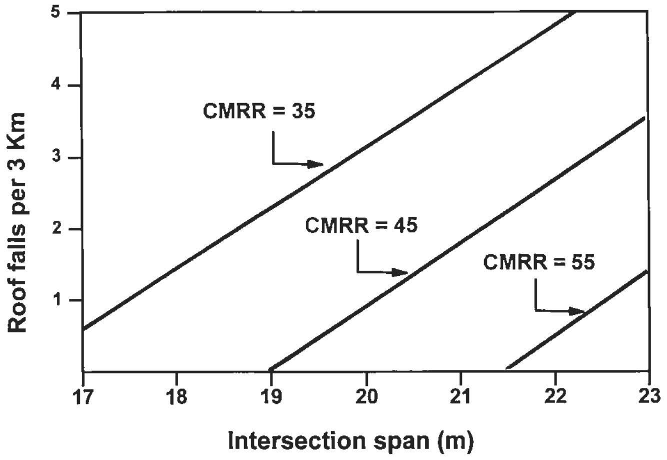
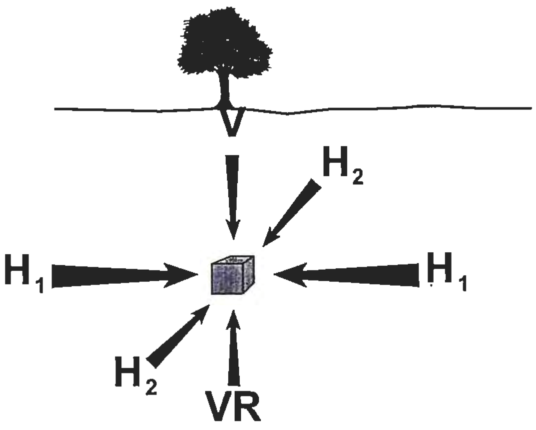


Figure 7.—Relationship between CMRR, intersection span, and roof fall rate at six U.S. mines [Mark et al. 1994].

The overburden load, on the other hand, is primarily carried by the pillars, but it can affect the immediate roof stability (and thus support loading) by—

- Causing sloughage of the pillars, thereby increasing the roof span in the mine entry;
- Excessively loading or yielding the pillars or the mine floor, resulting in differential movements that can damage the immediate roof rock;
- Stressing the pillars, which causes them to squeeze out and apply a horizontal force to the immediate roof rock above the mine entry.



V = Weight of Rock
H_1 and H_2 = Horizontal Stresses
VR = Reaction Counteracting Weight of Rock Above

Figure 8.—Stress on a typical element of mine roof.

Horizontal Stress

The horizontal stresses are normally more important to roof stability than the vertical stresses. The reason is that most vertical stress is applied to the pillar, whereas the roof must bear the full brunt of the horizontal stress. Moreover, the magnitude of the horizontal stress is usually greater than the vertical stress. The effects of horizontal stress are—

- Compressive-type roof failures (commonly called cutter roof, guttering, shear, snap top, and pressure cutting). In thinly bedded roof, the failure develops as the progressive layer-by-layer crushing of the individual beds.

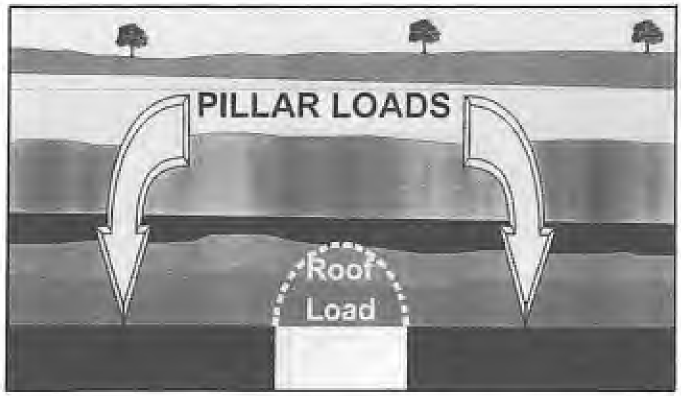


Figure 9.—Vertical loads in underground coal mines.

- Directional effects, because roof damage is generally much greater in entries oriented perpendicular to the maximum horizontal stress than in entries driven parallel with it.

During the past 15 years, horizontal stress has become central to an understanding of coal mine ground control. An important breakthrough was the recognition that the stresses observed in coal mines are caused by global plate tectonic forces [Mark 1991]. The World Stress Map Project [Zoback and Zoback 1989] identified stress regimes in many parts of the world by analyzing active faults, borehole breakouts, and hydraulic fracturing stress measurements (figure 10).

An evaluation of stress measurements made in underground coal mines confirmed that the stress map applies to underground coal mines [Mark and Mucho 1994]. In the Eastern United States, 76% of the measurements fell within 25° of N. 75° E.

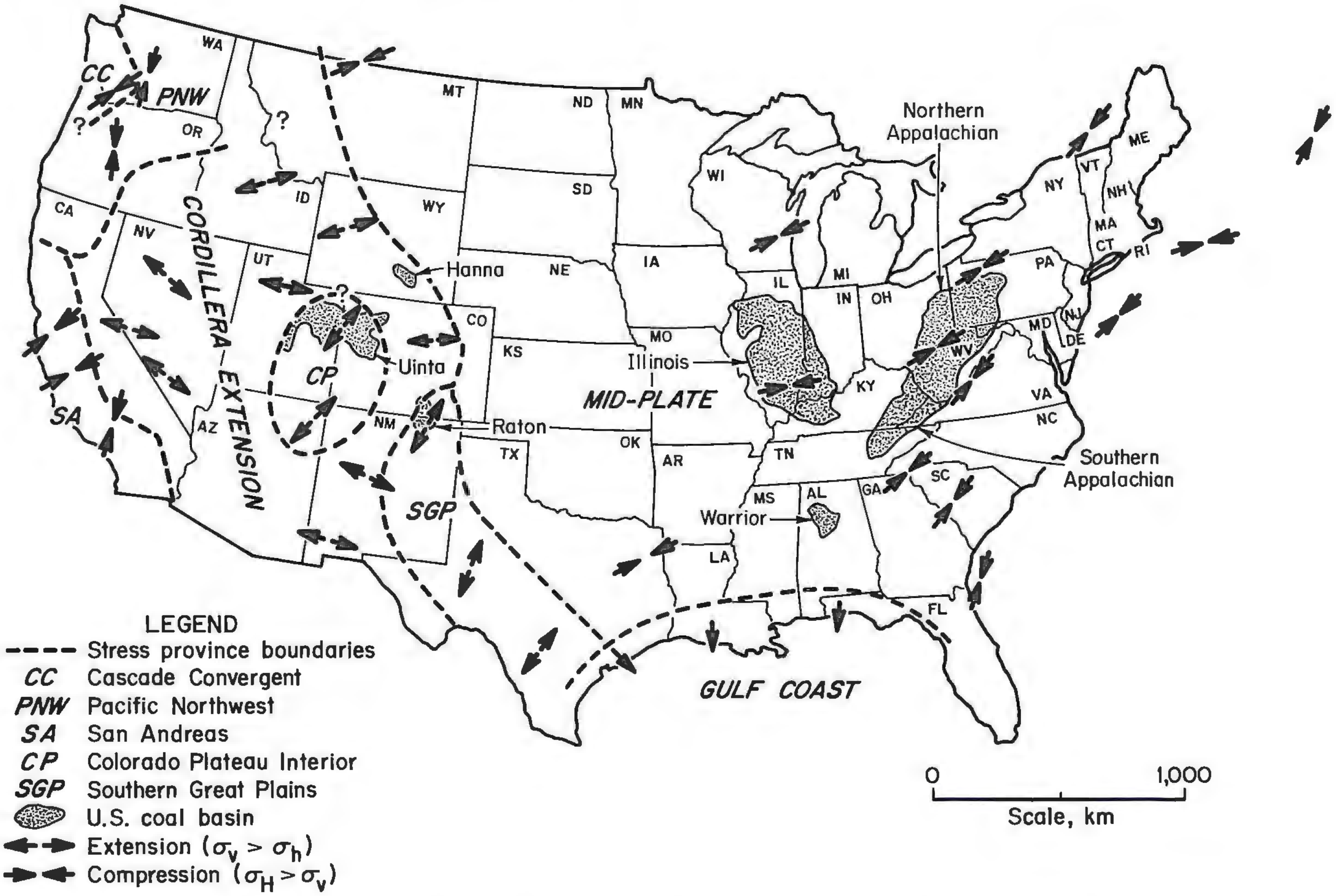


Figure 10.—Stress fields in the continental United States [Zoback and Zoback 1989].

In magnitude, the horizontal stresses were generally two to three times the vertical (figure 11). In the Western United States, there seems to be much more variation from mine to mine and even within individual mines. The horizontal stress is also approximately equal in magnitude to the vertical stress in the West (figure 12). In both sets of measurements, the maximum horizontal stress was usually about 40% greater than the minimum.

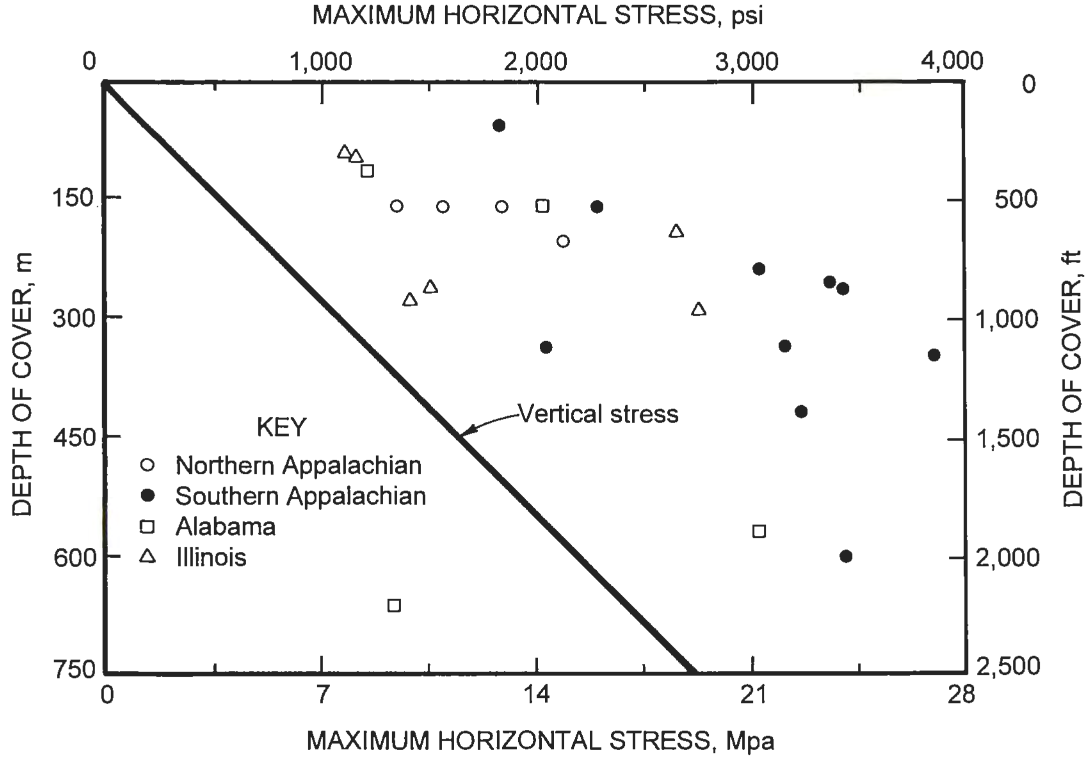


Figure 11.—Horizontal stresses in measured eastern U.S. coal mines [Mark and Mucho 1994].

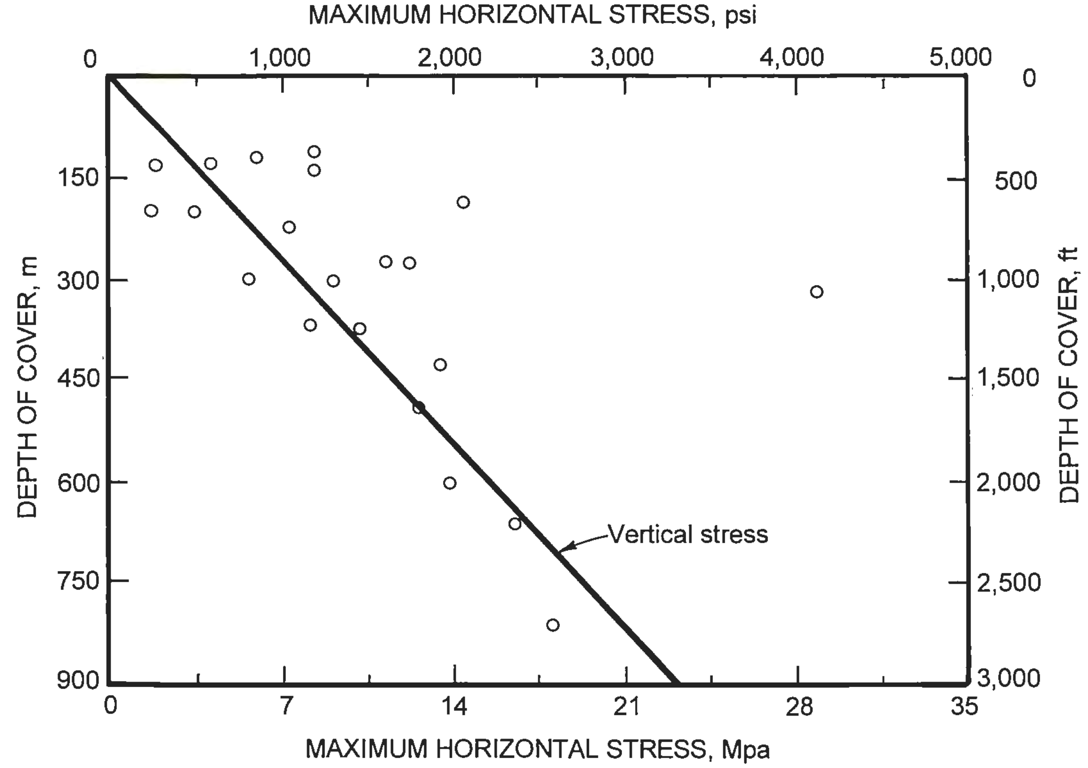


Figure 12.—Horizontal stresses measured in western U.S. coal mines [Mark and Mucho 1994].

Two other factors also determine the degree to which horizontal stress will affect ground control:

- *Roof type:* Weak roof is more likely to suffer damage than strong rock, and laminations or thin bedding (as in shales or stackrock sandstones) greatly reduce the ability of rock to resist horizontal stress.

- *Surface topography:* Stream valleys can concentrate horizontal stresses and have often been associated with particularly difficult horizontal stress conditions. Stream valleys can also reorient the maximum horizontal stress away from the regional direction [Molinda et al. 1991].

Stress measurements are too expensive for most mines to use routinely. As a substitute, procedures have been developed to estimate the orientation of the maximum principal stress [Mucho and Mark 1994; Fabjanczyk 1996]. Such features as roof "guttering" or roof "pots" are mapped underground, and the stress direction is inferred from their orientation and severity.

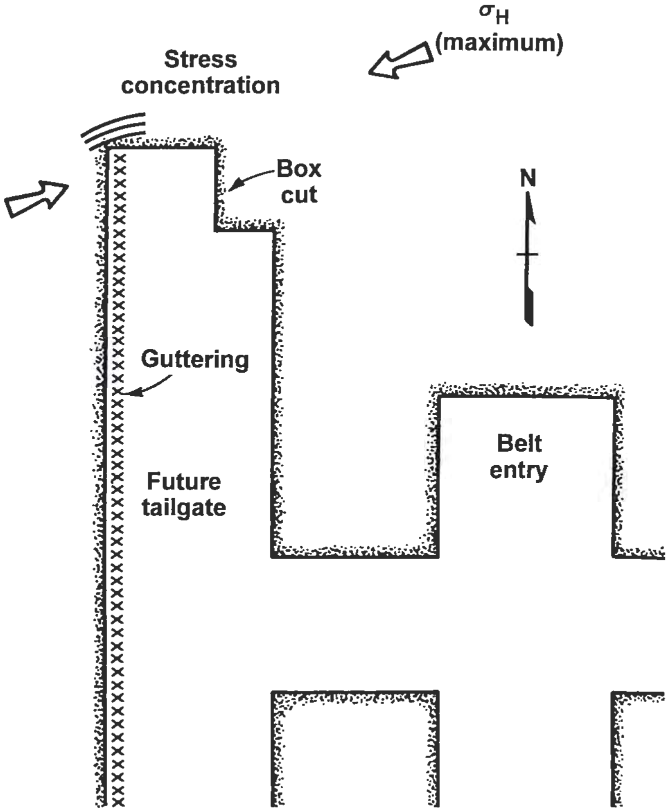


Figure 13.—Horizontal stress concentration in leading entries [Mark and Mucho 1994].

Mining-Induced Stresses

The act of mining can concentrate and reorient the original in situ stresses. Whenever coal is removed, the overburden weight that it had carried is transferred. Vertical stresses are therefore increased on the adjacent unmined coal. Horizontal stresses are similarly affected when the roof is deformed or fails. Horizontal stress cannot pass through broken ground, so it becomes concentrated where the roof is still intact.

- *Development mining:* Entry development creates pillar loads, and "transient stress abutments" have been observed [Karabin et al. 1982]. Horizontal stress creates more serious roof control problems. In some mines, "leading entries" are heavily damaged and require extensive support. Adjacent entries can be stress relieved [Mark and Mucho 1994] (figure 13). Outby the face, a roof fall can create a horizontal stress concentration, which can then propagate itself hundreds of feet.

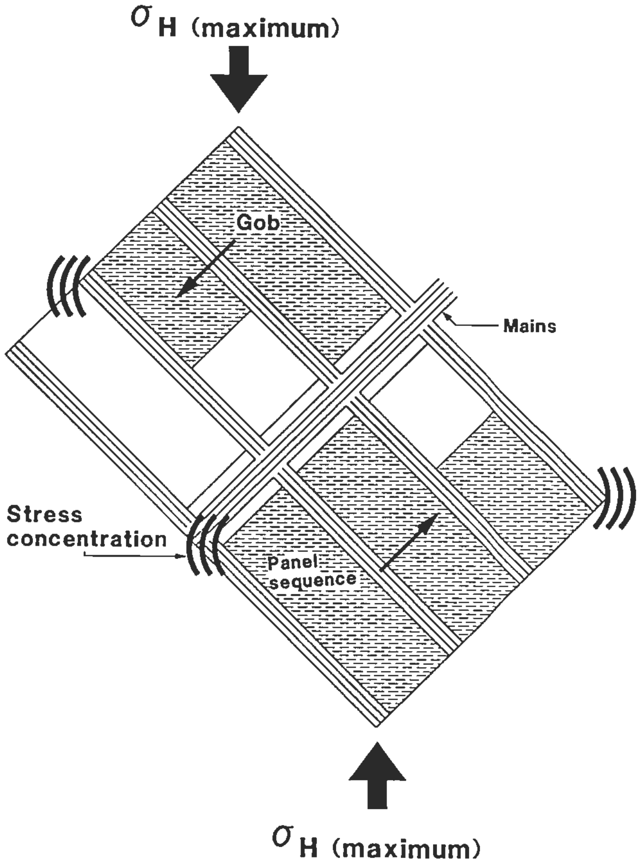


Figure 14.—Horizontal stress concentrations in longwall headgates [Mark and Mucho 1994].

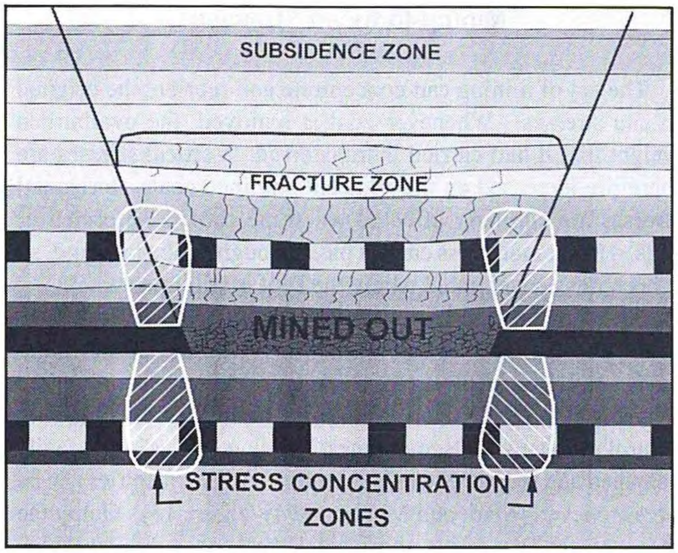


Figure 15.—Multiple-seam mining and its effects on ground control [Mark 1990].

- *Retreat mining:* Longwall mining and pillar recovery can concentrate large vertical loads on gate entries and pillar lines. Proper pillar sizing is essential for limiting the roof stresses and deformations to levels that can be handled by roof support [Mark and Chase 1994, 1997; Colwell et al. 1999]. Secondary support is generally necessary to help control the additional loads. Recently, the importance of horizontal stress abutments has also been documented [Mark et al. 1998] (figure 14). Proper panel layout can greatly reduce the loads applied to the roof.

- *Multiple-seam mining:* Overmining and undermining are responsible for some of the most severe conditions found underground. Both can concentrate vertical loads, and undermining can cause subsidence that damages the roof above overlying coalbeds (figure 15) [Chekan and Listak 1994].

THE FUNCTIONS OF ROOF SUPPORT

Support systems work best when they enhance the inherent strength of the mine roof [Hoek and Wood 1988]. They can do this by—

Providing confinement. Rock is much stronger when it is confined. Since roof rock is usually being loaded by horizontal stress, even a small amount of vertical confinement can have a big effect. The frictional strength of bedding planes may also be strengthened by confinement.

Limiting deformation and preventing unraveling. By maintaining the integrity of the roof line, supports help the upper layers maintain their strength.

Tying weaker rock units to stronger ones. Coal mine roof often consists of several layers of rock with different strengths. Roof bolts are particularly effective in tying weak or broken rock to beds that are more self-supporting.

When the rock is completely broken and has lost all of its strength, supports can also carry the dead-weight load.

PROPERTIES OF ROOF SUPPORT SYSTEMS

Roof supports can be divided into two categories:

- *Intrinsic support*, where the supporting elements are installed within the roof; and
- *Standing support*, where the supporting members are installed between the roof and floor.

Roof bolts are the best example of intrinsic supports. Roof bolts are loaded as the roof deforms, and they interact with the rock to reduce bed separation by confinement much as reinforcing steel does with concrete. Standing supports, like cribs, posts, or longwall shields, develop loads in response to the convergence between the roof and floor.

CAPACITY OF ROOF SUPPORTS

The first question usually asked regarding a support system is: "How much load can the support carry; what is its capacity?" For roof bolts, two types of capacity are normally given: the *yield* and the *ultimate* (figure 16). In general, these can be calculated from the properties of the steel and the diameter of the bolt. However, as discussed by Mark [2000], poor anchorage can substantially reduce the effective capacity of roof bolts.

The capacities of standing supports depend on several factors, including the materials, configuration, and height. In general, the capacity of each particular support type must be determined by controlled load testing. The Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) has tested a large number of supports in its unique Mine Roof Simulator. From these tests, the performance characteristics of these various support systems have been determined. By matching the support characteristics to the ground behavior, an optimum support design can be achieved. To facilitate this approach, NIOSH developed the Support Technology Optimization Program (STOP). This program allows the user to determine the optimum installation parameters for any support technology and compare the installation of one support system to another in terms of installed support load density and the convergence control provided by the support [Barczak 2000c].

In many cases, however, the capacity may not be the most meaningful way to define a support. Consider the example shown in figure 17. The second support (support No. 2) has twice the ultimate capacity of the first support, but it takes four times the convergence to reach this capacity. Furthermore, at one unit of displacement, the second support has only one-half the capacity of the first support. Figure 18 is another example of the importance of defining the support capacity in relation to the displacement. Although this support has an ultimate capacity of >1,000 tons, is that really meaningful? Before this capacity is mobilized, nearly 5 ft of convergence must occur. By that time, most entries would be entirely unserviceable. Clearly, a better question is: "How much load can the support carry *at a specified amount of displacement*?" This leads directly to the issue of support *stiffness*.

STIFFNESS OF ROOF SUPPORTS

Stiffness is simply a measure of how quickly a support develops its load-carrying capacity in response to convergence. Stiffness is a measure of performance before a support reaches its maximum capacity. Stiffer supports develop capacity more quickly (with less displacement) than softer supports. The support elements can be thought of as large springs. A softer spring will compress a greater amount to provide the same resisting force as a stiffer spring. A good analogy is to think of a ½-ton and 3/4-ton pickup truck. The 3/4-ton truck has stiffer springs on the bed of the truck. Thus, if these two trucks were placed side by side and each was loaded with a cord of firewood, the bed in the ½-ton truck would be lower than the bed in the 3/4-ton truck (figure 19).

While some roof supports are installed with an initial preload, they all develop their load-carrying capacity only through movement of the roof. This creates a fundamental paradox in roof support design. The roof must deform to mobilize the support capacity, but it is this very movement that the support is trying to prevent. Thus, a critical design issue is the stiffness of the support system.

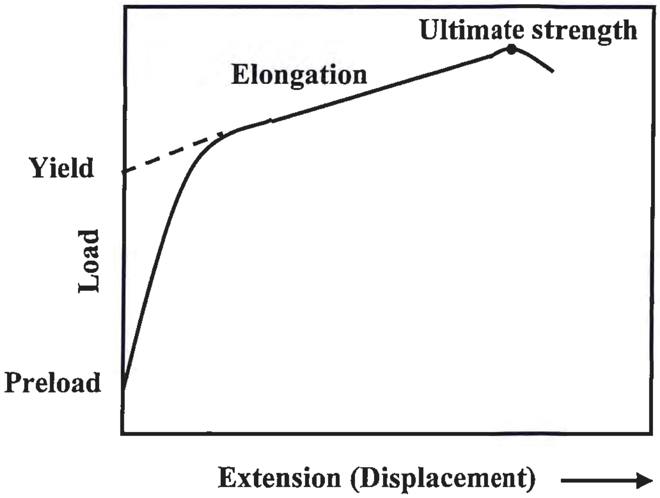


Figure 16.—Yield and ultimate strengths of a roof bolt.

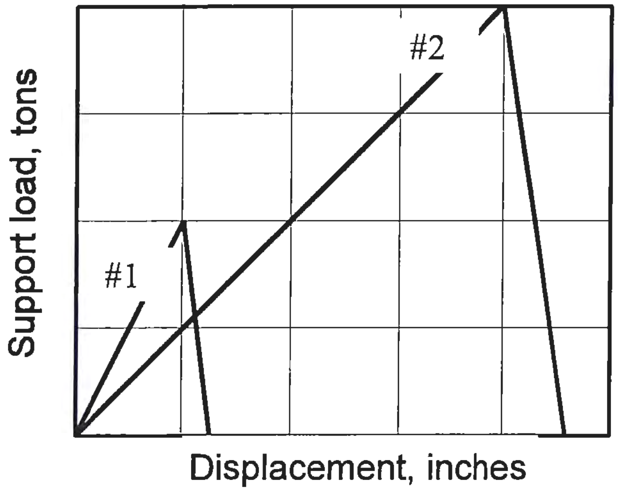


Figure 17.—Example showing that the capacity of a support should be defined in relation to its displacement.

Since stiffness is such an important design parameter for roof supports, let us examine some of the things that impact the stiffness of a support structure. Stiffness (K) is a function of the area (A), material modulus of elasticity (E), and the length or height of the support (L), as expressed in equation 1.

$$K = \frac{A * E}{L} \qquad (1)$$

Thus, as seen in equation 1, stiffness increases with area and material modulus and decreases with increasing support height. The significance of these parameters can best be understood by looking at some practical examples.

Intrinsic Support

Let us first examine the implication of these parameters on roof bolt stiffness. First, since roof bolts are made from steel and the modulus of elasticity of steel varies little, the stiffness

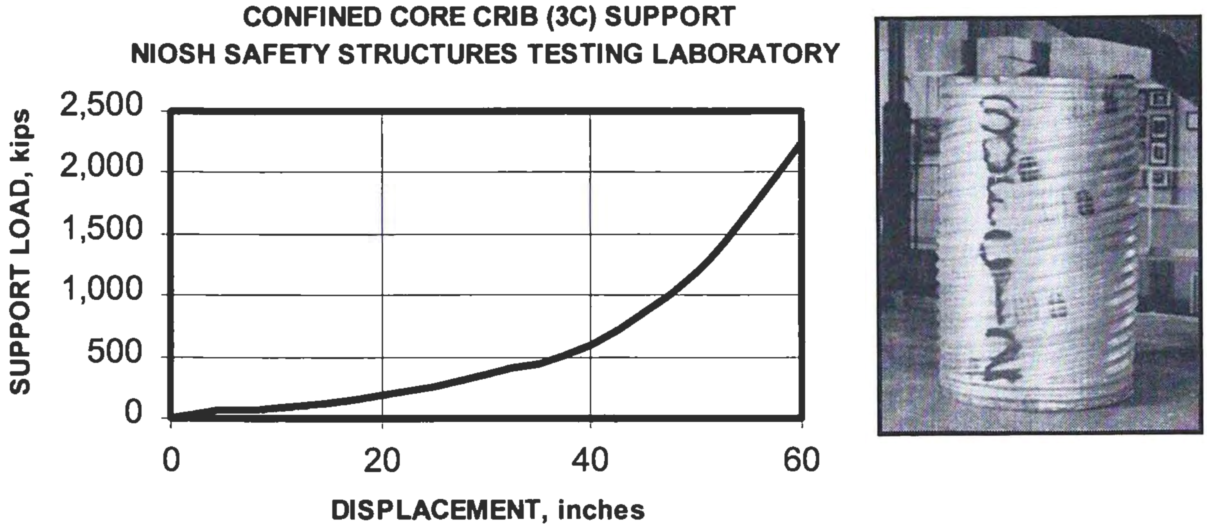


Figure 18.—A support that requires 5 ft of convergence to reach peak load.

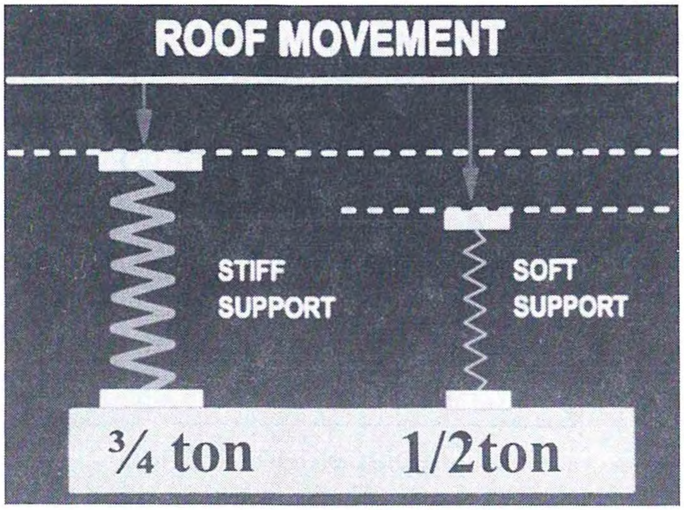


Figure 19.—Pickup truck analogy illustrating support stiffness. The heavy spring in the 3/4-ton truck deflects less than the light spring in the ½-ton truck when both are loaded with the same cord of firewood.

of roof bolts is not affected by the grade of steel used in fabricating the bolt. However, since the stiffness increases in direct proportion to area or the square of the bolt diameter, bolt stiffness increases dramatically with increasing bolt diameter. Thus, a 7/8-in-diam bolt is twice as stiff as a 5/8-in-diam bolt, all other things being equal.

Bolt length also affects stiffness. With a conventional point-anchor mechanical roof bolt (figure 20), the bolt is anchored only at the top, and the "free length" of the bolt is defined as the length of bolt below the anchor. Thus, as the bolt length increases, the stiffness of the bolt decreases, meaning that longer bolts have a softer response and allow more roof movement to occur for the same increase in bolt load. Fully grouted bolts, on the other hand, do not initially have a "free length" and usually become highly stressed in localized areas in response to roof movements. For this reason, fully grouted bolts are normally considered to be stiffer than point-anchor bolts. Cable bolts and trusses are the least stiff of the intrinsic supports [Dolinar and Martin 2000].

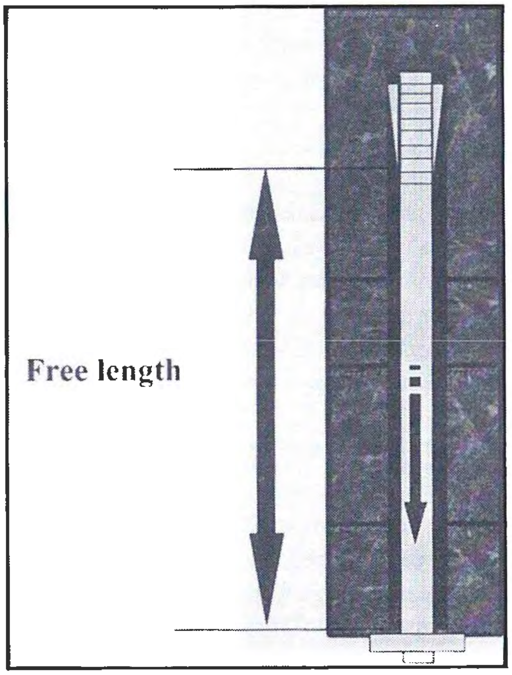


Figure 20.—The free length of a point-anchor roof bolt affects its stiffness.

Standing Support

The same principles apply to standing support. Using wood cribs as an example, 9-point cribs are stiffer than 4-point cribs because the timber contact area of a 9-point crib is 2.25 times that of a 4-point crib. Likewise, a 10-in-diam post will have a stiffer response than a 6-in-diam post. Wood cribs can be made stiffer by using different wood species. For example, the elastic modulus of oak is greater than that of poplar wood; thus, oak cribs will be stiffer supports than equivalent cribs constructed from poplar timbers. The stiffness of standing supports is also height-dependent, decreasing with increasing height. For example, a 4-point wood crib constructed from 6×6×30-in, mixed hardwood timbers in a 6-ft seam height will provide 41 tons of support capacity at 2 in of convergence, whereas the same crib design constructed in a 10-ft seam will provide only 32 tons (a 25% reduction) at 2 in of convergence.

Both intrinsic and standing support systems can made stiffer by increasing the density of the supports. An example is shown in figure 21, where two rows of wood cribs are increased to three rows, with the middle row staggered with respect to the two outer rows. Another approach to increase the system stiffness is to reduce the spacing between supports.

Supports can also be softened by adding additional material on top of the support or within the support during its construction. The rule to remember here is that of the weak-link principle—the softest material will control the initial stiffness of the support. The load-displacement response of a concrete crib topped off with a row of wood timbers is shown in figure 22. It is seen in this figure that the wood, which is the softer of the two materials, controls the initial load development of the support. The same principle applies to timber posts where cap boards and/or wedges are used on top of the post. Here, the material may be the same, but wood is much stronger and stiffer when loaded parallel to the grain as in the post section compared to perpendicular to the grain, as would be the case for the cap blocks or wedging material.

RESIDUAL STRENGTH

What happens to a support after it reaches its maximum capacity can be just as important as what happens before. Consider the concrete crib constructed from concrete block typically used in stopping walls and the 24-in-diam Can support shown in figure 23*A*. Both have approximately the same initial stiffness and capacity. However, once the concrete crib reaches its maximum load, it fails completely, leaving the roof entirely

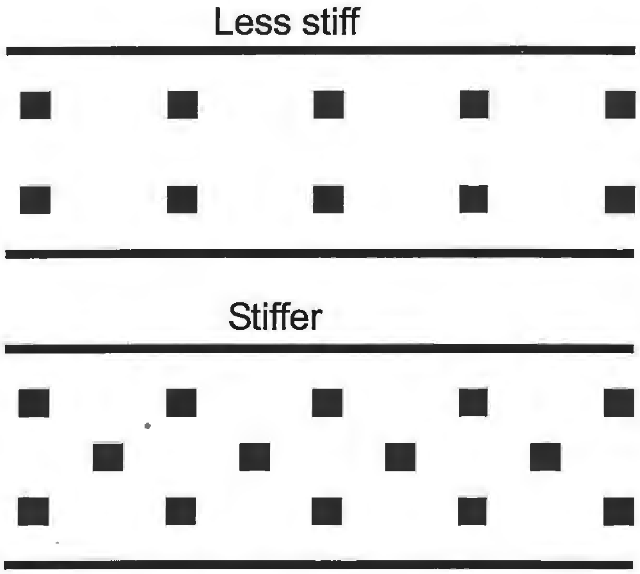


Figure 21.—The stiffness of a wood crib support system is increased by increasing the support density.

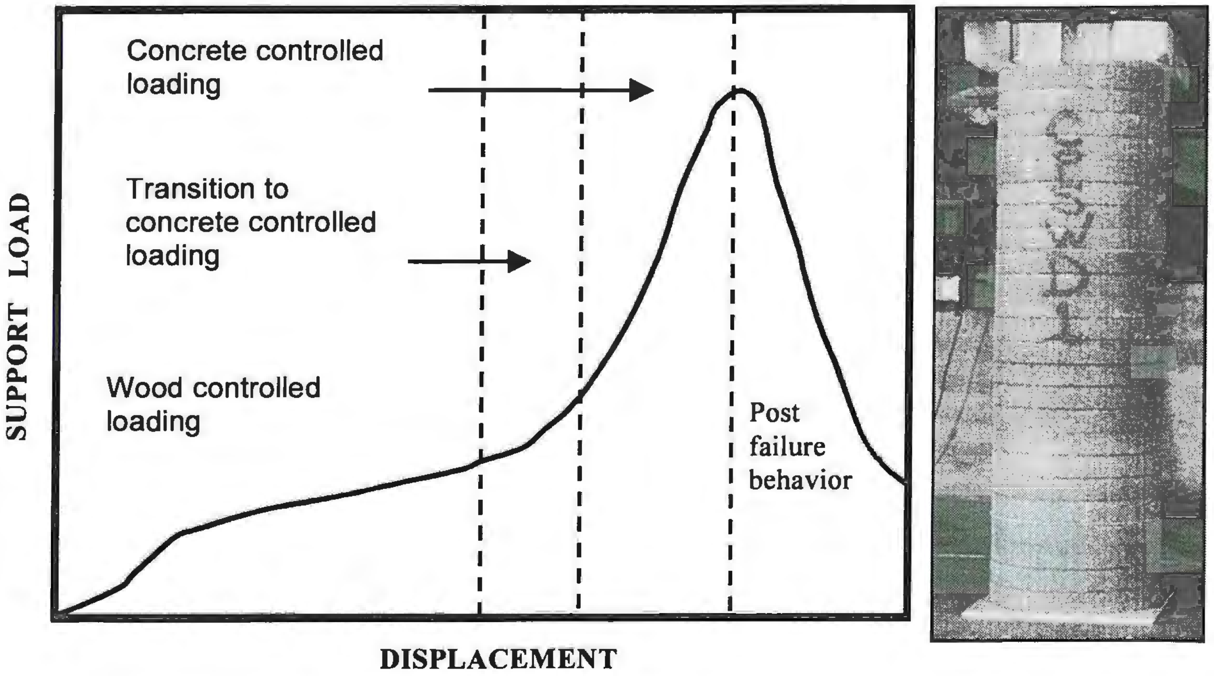


Figure 22.—The stiffness of a concrete crib is reduced by placing wood timbers on top.

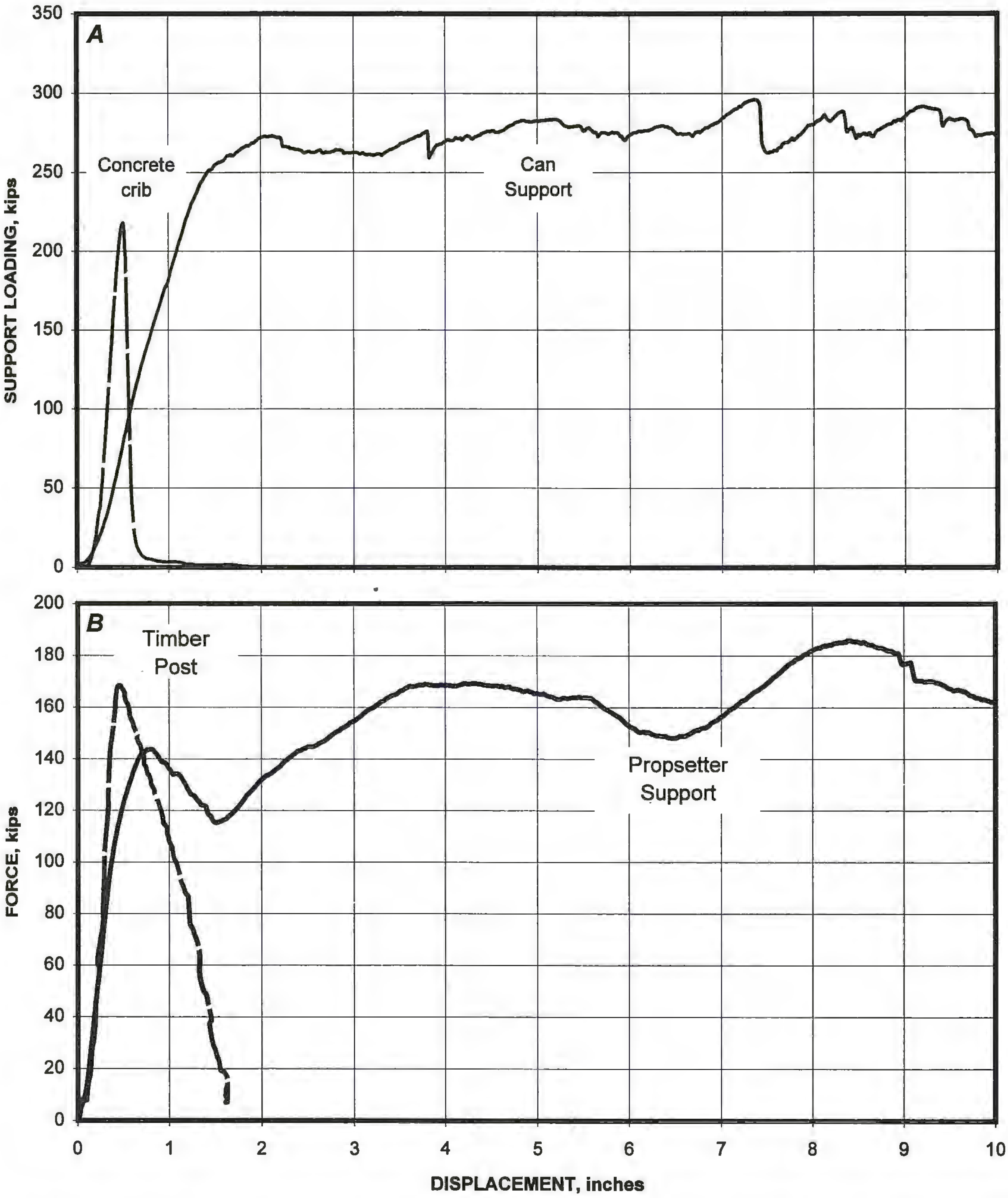


Figure 23.—Residual strength. *A*, The Can has better residual strength than the concrete block crib. *B*, The Propsetter has better residual strength than the timber post. (Note: 1 kip = 1,000 lb).

unsupported. The Can, on the other hand, continues to carry nearly all of its load as the roof continues to move down as much as 2 ft. A similar comparison can be made between a conventional timber post and a Propsetter support (figure 23*B*). The residual strength of supports like the Can and Propsetter make them much more useful in moderate to high convergence such as longwall tailgates than brittle supports like the conventional concrete crib and timber post.

OTHER SUPPORT CHARACTERISTICS

Stability

Stability can be defined as the capability of a support to sustain its load-carrying capacity through a useful range of convergence without failing prematurely. Instability that results in premature failure can be caused in several ways, the most common of which are—

- Buckling, which is common in timber posts and most prop-type supports (figure 24*A*);
- Material failure, where the load applied to the support causes the material to fail in all or part of the support such that the integrity of the support is compromised (figure 24*B*);
- Eccentric loading, which can be caused by wedging of the support in place or uneven roof and floor contact (figure 24*C*); and
- Lateral roof-to-floor loading, usually caused by differential floor heave, which causes the support to lean or tilt off axis (figure 24*D*) [Barczak 2000b].

Material Handling Requirements

Each year, 5,000 workdays are lost by workers in underground coal mines from timber handling injuries alone. In recent years, new support technologies have been developed, including engineered timber support systems, that dramatically reduce the material handling requirements for standing roof support systems [Barczak 2000a].

Installation Quality

In order to get the full benefit of the support, it must be installed properly. Improper installation of support is a major cause of premature support failure. Each support is different, thus the critical parameters for proper installation vary from support to support. Some examples are—

- *Wood cribs:* The performance of wood cribs can be degraded in several ways due to poor installation. For example, the timbers should be overhung to allow the timbers to interlock more effectively, thereby improving the crib stability during loading (see figure 25*A*). Constructing the crib with the wide side of the timber place up will reduce the capacity and degrade the stability of the support. Rounded support timbers will also reduce crib stability and capacity (figure 25*B*). If possible, these timbers should be replaced by square timbers during the construction process. Timbers should also be of consistent quality. One weak or poor-quality timber can severely degrade a 4-point wood crib, since each timber must function to provide the full support capability (figure 25*C*).
- *The Can:* The Can Support is a thin-walled steel container that is prefilled with air-entrained concrete before the unit is transported into the mine. Proper installation requires a layer of good-quality timbers that provides full coverage of the top of the Can to preserve the design load profile. If this is not done, the timbers will not have adequate strength to transfer the loading to the Can; instead, the initial load profile of the support will be unintentionally softened by the wood timber response (figure 26).
- *Roof Bolts:* Obviously, roof bolts depend on proper anchorage to achieve the rated bolt capacity. For grouted bolts, proper mixing and hold time during the bolt installation are critical. Grout performance is affected by several factors, including temperature, age, and conditions of storage.

Timing

Another way to define supports is by the time of installation. *Primary* supports are installed immediately upon development. In the United States, primary supports are almost always roof bolts. *Secondary* supports are placed in anticipation of additional loading, as in a longwall tailgate. *Supplemental* supports are used when the original supports are insufficient.

Skin Control

Skin control is the ability of a support system to prevent injuries from small pieces of falling rock. With roof bolts, skin control may be supplied by plates, headers, straps, or mesh [Bauer and Dolinar 2000]. Skin control is also the reason why many miners would prefer two rows of 4-point wood cribs to a single row of 9-point cribs, even though the load-bearing capacities are nearly the same for both support systems.

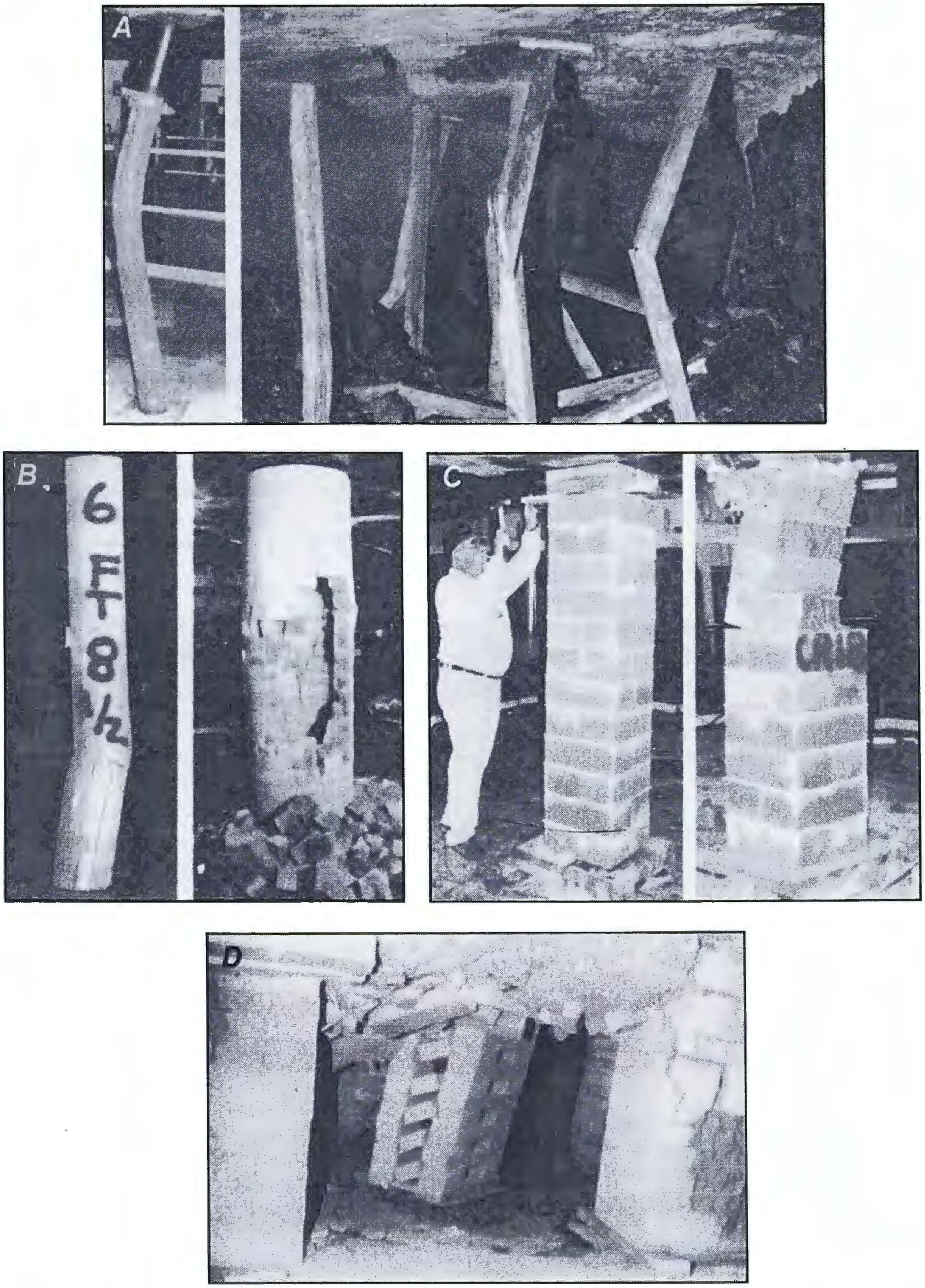


Figure 24.—Examples of support instability. *A*, buckling; *B*, material failure; *C*, eccentric loading; *D*, lateral roof-to-floor movement.

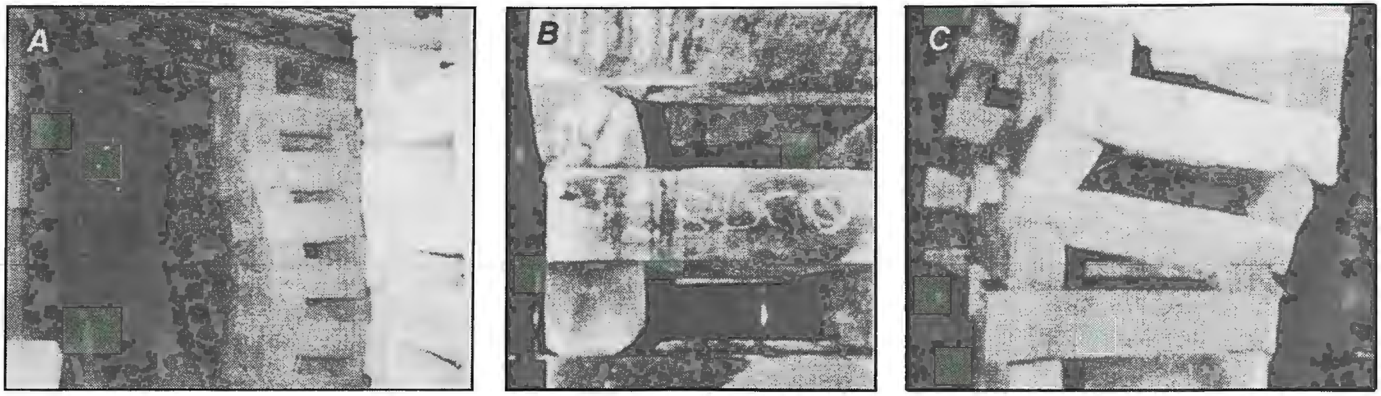


Figure 25.—Examples of poor crib construction. *A*, rollout of crib blocks due to inadequate overhang; *B*, rounded timbers degrade support; *C*, a single weak crib block causes premature failure of a "mixed hardwood" crib.

Figure 26.—Poor-quality timber on top of Can degrades support.

SUPPORT AND STRATA INTERACTION

The goal of roof support is to create a stable rock structure. The properties of the roof and the magnitude of the rock stresses determine the quantity of roof support that is required. The support must also withstand the deformation that occurs in the roof.

The concept of the "ground reaction curve" was developed to illustrate the interaction between the load and the roof movement [Scott 1989]. A ground reaction curve may be defined as "the set of possible support loads required to achieve stability for a given roof." The ground reaction curve depends on the rock mass quality, the span, the in situ stress, and the mining-induced stress. A change in any of these variables can cause the ground reaction curve to shift, thereby increasing or decreasing the support load required (figure 27).

The ground reaction curve forcefully shows that deformation, as well as load, is critical to proper roof support design. The importance of support characteristics can be illustrated using the ground reaction curve. If the support is too soft, it may not be able to develop the necessary support capacity to prevent excessive deformation from occurring (figure 28). A support with little residual strength may fail prematurely if the curve shifts because of additional mining stresses. Mucho et al. [1999] describe how a tailgate ground reaction curve can be measured and used to select the proper support density for a

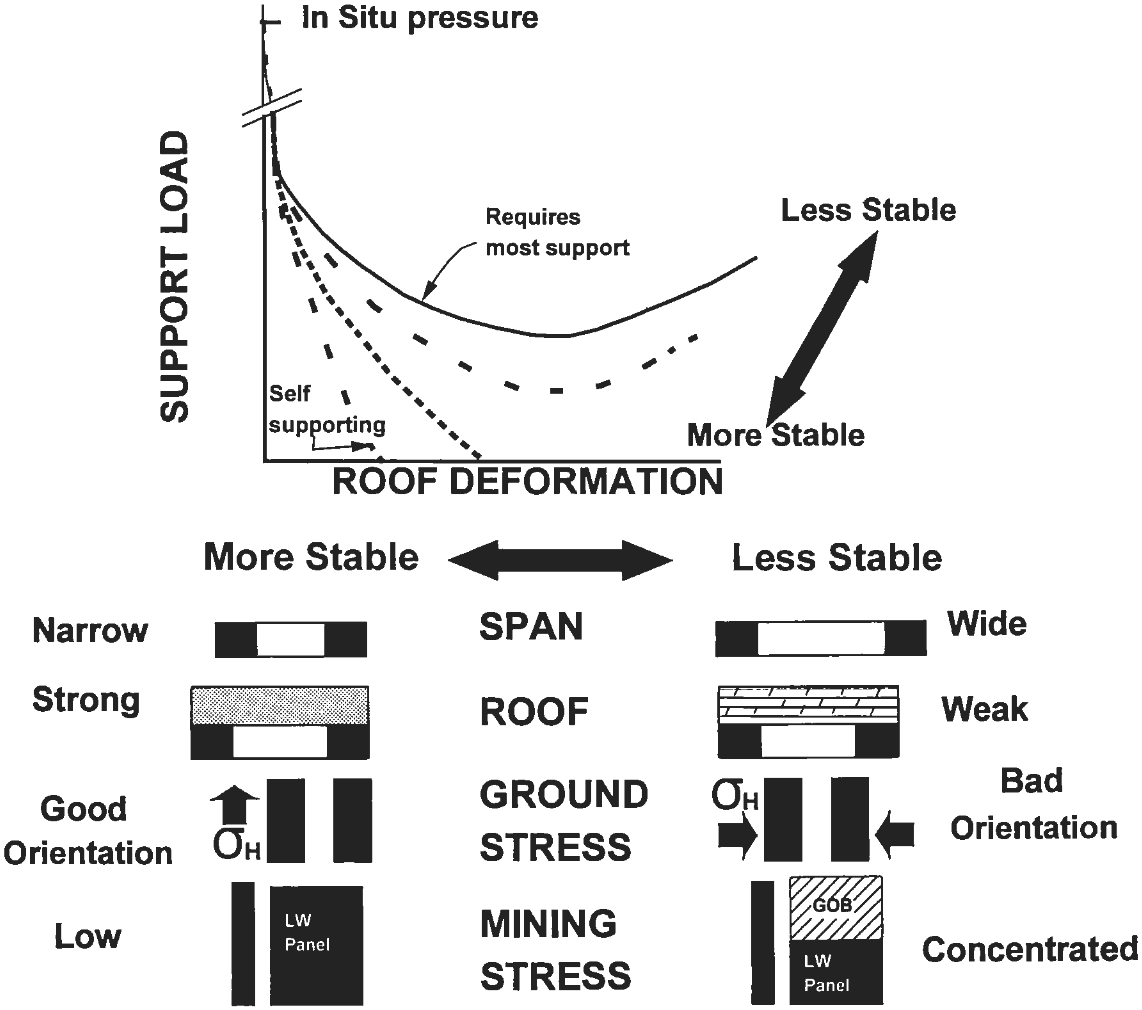


Figure 27.—Ground reaction curves and the factors that affect them.

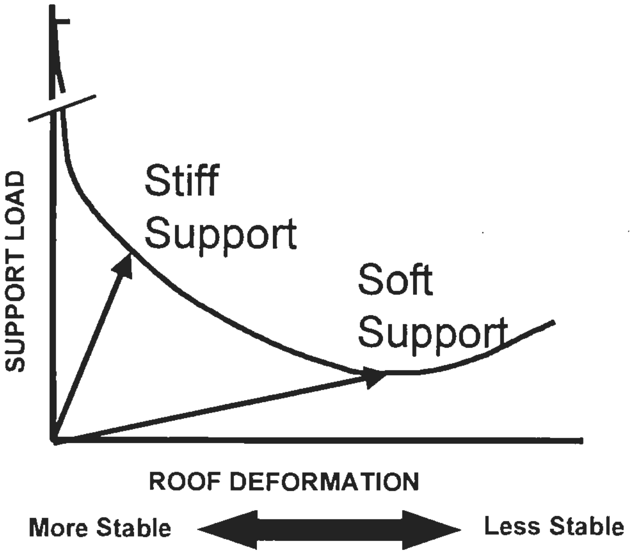


Figure 28.—Effect of support stiffness on the ground reaction behavior.

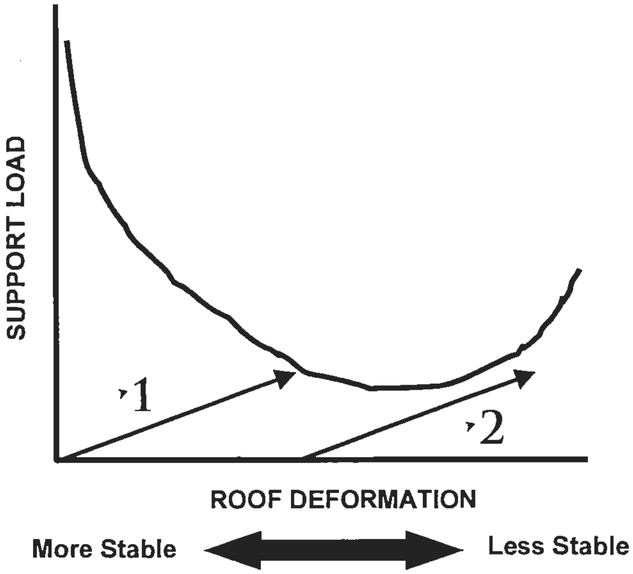


Figure 29.—Effect of installation timing.

particular support design. This capability is also provided by the Support Technology Optimization Program (STOP).

As illustrated by the ground reaction curve, the "ideal" roof support has the following properties:

- High initial stiffness, so that only small ground movements are needed to mobilize the capacity of the support;
- Large load-bearing capacity; and
- High residual strength over a large range of displacement.

Many of the engineered timber and concrete supports have largely succeeded in displaying these characteristics. Traditional wood supports have somewhat less desirable characteristics. Simple timber posts have little residual strength, while wood cribs have a low initial stiffness.

Since passive supports must be compressed to develop their load-carrying capacity, if they are installed too late, they might not develop sufficient capacity in time to put the roof into equilibrium. This is shown in figure 29. Both supports in this example have the same stiffness, but the second support was not installed in time to prevent critical roof deformation and thus could not prevent a roof fall.

CONCLUSIONS

Roof supports work best when they are matched to the ground conditions in which they are used. The performance characteristic of each support is unique. A support system may perform well in one application, but not in another. Understanding the ground, applied loads, and support characteristics are the keys to optimizing support design and application. The goal of the papers in these Proceedings is to provide the best available information and design guidelines to help mine planners in this task.

REFERENCES

Barczak TM [2000a]. Material handling considerations for secondary roof support systems. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Barczak TM [2000b]. NIOSH safety performance testing protocols for standing roof supports and longwall shields. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Barczak TM [2000c]. Optimizing secondary roof support with the NIOSH Support Technology Optimization Program. In: Peng SS, Mark C, eds. Proceedings of the 18th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 74-83.

Bauer ER, Dolinar DR [2000]. Skin failure of roof and rib and support techniques in underground coal mines. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Bieniawski ZT [1989]. Engineering rock mass classifications. New York, NY: John Wiley & Sons.

Chekan GJ, Listak JM [1994]. Design practices for multiple-seam room-and-pillar mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9403.

Colwell MG, Frith R, Mark C [1999]. Analysis of longwall tailgate serviceability (ALTS): a chain pillar design methodology for Australian conditions. In: Mark C, Heasley KA, Iannacchione AT, Tuchman RJ, eds. Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 99-114, IC 9448, pp. 33-48.

Dolinar DR, Martin L [2000]. Cable support in longwall gate roads. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Fabjanczyk MW [1992]. Directional drivage influences and the application of mechanistic mapping techniques. In: McNally GH, Ward CR, eds. In: Proceedings of the Symposium on Geology in Longwall Mining. Sydney, Australia: Coalfields Geology Council of New South Wales, pp. 137-142.

Hoek E, Wood DR [1988]. Rock support. Mining Magazine *Oct*:282-287.

Karabin G, Cybulski JA, Kramer JM [1982]. The formation and effects of transient abutment stresses during non-uniform face advance. In: Peng SS, ed. Proceedings of the Second International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 233-240.

Mark C [1990]. Pillar design methods for longwall mining. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9247.

Mark C [1991]. Horizontal stress and its effects on longwall ground control. Min Eng *Nov*:1356-1360.

Mark C [1999a]. Application of coal mine roof rating (CMRR) to extended cuts. Min Eng *51*(4):52-56.

Mark C [1999b]. Ground control in south African coal mines: a U.S. perspective. In: Peng SS, Mark C, eds. Proceedings of the 18th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 186-193.

Mark C [2000]. Design of roof bolt systems. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Mark C, Chase FE [1994]. Design of longwall gate entry systems using roof classification. In: New Technology for Longwall Ground Control; Proceedings—USBM Technology Transfer Seminar. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, SP 94-01, pp. 5-18.

Mark C, Chase FE [1997]. Analysis of retreat mining pillar stability (ARMPS). In: New Technology for Ground Control in Retreat Mining. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 97-122, IC 9446, pp. 17-34.

Mark C, Molinda GM [1996]. Rating coal mine roof strength from exploratory drill core. In: Peng SS, ed. Proceedings of the 15th International Conference on Ground Control in Mining. Golden, CO: Colorado School of Mines, pp. 415-428.

Mark C, Mucho TP [1994]. Longwall mine design for control of horizontal stress. In: New Technology for Longwall Ground Control; Proceedings—USBM Technology Transfer Seminar. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, SP 94-01, pp. 53-76.

Mark C, Molinda GM, Schissler AP, Wuest WJ [1994]. Evaluating roof control in underground coal mines using the Coal Mine Roof Rating. In: Peng SS, ed. Proceedings of the 13th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 252-260.

Mark C, Mucho TP, Dolinar DR [1998]. Horizontal stress and longwall headgate ground control. Min Eng *Jan*:61-68.

Molinda G, Mark C [1994]. The Coal Mine Roof Rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: U.S. Department of the Interior, Bureau of Mines, IC 9387, 83 pp.

Molinda GM, Heasley KA, Oyler DC, Jones JR [1991]. Effects of surface topography on the stability of coal mine openings. In: Peng SS, ed. Proceedings of the 10th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 151-160.

Molinda GM, Mark C, Dolinar DR [2000]. Assessing coal mine roof stability through roof fall analysis. In: New Technology for Coal Mine Roof Support. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2000-151, IC 9453.

Mucho TP, Mark C [1994]. Determining the horizontal stress direction using the stress mapping technique. In: Peng SS, ed. Proceedings of the 13th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 277-289.

Mucho TP, Barczak TM, Dolinar DR, Bower J, Bryja JJ [1999]. Design methodology for standing secondary roof support in longwall tailgates. In: Peng SS, Mark C, eds. Proceedings of the 18th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 136-148.

Rusnak J, Mark C [2000]. Using the point load test to determine the uniaxial compressive strength of coal measure rock. In: Peng SS, Mark C, eds. Proceedings of the 19th International Conference on Ground Control in Mining. Morgantown, WV: West Virginia University, pp. 362-371.

Scott [1989]. Roof bolting: a sophisticated art. Coal *Aug*:59-69.

Zoback ML, Zoback MD [1989]. Tectonic stressfield of the United States. In: Geophysical Framework of the Continental United States. Geological Society of America, Memoir 172, pp. 523-539.

Information Circular 9453

Proceedings: New Technology For Coal Mine Roof Support

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Pittsburgh Research Laboratory
Pittsburgh, PA

October 2000

ORDERING INFORMATION

Copies of National Institute for Occupational Safety and Health (NIOSH)
documents and information
about occupational safety and health are available from

NIOSH—Publications Dissemination
4676 Columbia Parkway
Cincinnati, OH 45226–1998

Fax: 513–533–8573
Telephone: 1–800–35–NIOSH
(1–800–356–4674)
E-mail: pubstaft @cdc.gov
Web site: www.cdc.gov/niosh

DHHS (NIOSH) Publication No. 2000-151