# YIELDING PILLAR GATE ROAD DESIGN CONSIDERATIONS FOR LONGWALL MINING

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## ABSTRACT

With the ever present pressures to both expedite long-wall gate road development and optimize panel entry stability, the use of yield pillars, either alone or in combination with larger, stiff abutment pillars, has become a topic of considerable interest worldwide. To help provide mine operators with a clearer understanding of the successful application of yielding gate road systems, this paper summarizes western U.S. longwalling experiences with yield pillar design, artificial support installation, entry configurations, and the general degree of gate stability achieved for various mining settings. Additionally, the concepts of the "critical pillar" and "optimum-time-to-yield" are discussed, and a brief qualitative analysis of a limited database is presented that demonstrates a potentially high correlation between a number of mining parameters and the stability performance of the yielding entry system. Preliminary conclusions drawn from this cursory evaluation include the following:

- No successful yield pillar designs were achieved in settings where the Coal Mine Roof Rating (CMRR) $(5)$[2] was less than 50 (on a scale of 0 to 100).
- No successful yield pillar designs employed width-to-height ratios (w/h) greater than 5.
- Mining depth and floor quality are largely insignificant where the performance of yielding designs are concerned, but greatly influence whether a critical pillar design will bump violently or damage roof and floor members due to pillar punching.

While U.S. Bureau of Mines (USBM) research continues to develop a proven, comprehensive design methodology for yielding gate road systems, this report serves as a summary reference in support of the emerging acceptance of yield pillar usage in U.S. longwalling.

## INTRODUCTION

The design of safe, productive longwall entry systems in difficult mining conditions has long been a subject of contention among labor, regulatory, and mine operator groups in the Western United States. It has only gained national attention since the Wilberg Mine disaster in 1984 near Orangeville, UT, which involved the controversial use of a two-entry, yield pillar gate road design. In fact, deep, multiseam, severely bump-prone mining conditions and the highly competitive western U.S. coal market have, for nearly 3 decades, made the design of successful, high-performance gate road systems an engineering priority, *critical* to the economic survival of the mine. To overcome these unique mining conditions, full-yielding gate road systems—those solely employing yield pillars—have been routinely used in a majority of the longwall operations in the Wasatch Plateau and Book Cliffs coalfields of central Utah, where abutment pillar gate road systems have largely failed to effect bump-free, economically feasible

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

mining. Several mines in New Mexico, Colorado, and Alabama have also utilized this gate design option and variations thereof to minimize any number of ground control problems without seriously impacting required productivity. By far, the two most common ground control applications of yielding pillar systems are for (1) the mitigation of severe pillar bumps, most commonly experienced in the tailgate entries, and (2) the abatement of destructive, high-stress concentrations surrounding remnant gate road pillars, which seriously affect entry stability during close-proximity, multiseam mining.

A majority of western U.S. longwalls are currently multiple-seam mining operations or plan to be in the near future. Many of these mines are subject to massive sandstone canyon-and-mesa overburden conditions (figure 1), relatively strong roof and floor strata (figure 2), and mining depths routinely ranging over 450 m (1,500 ft)—currently approaching 900 m (3,000 ft) at one mine in central Utah. As a result, western longwallers have experienced among the worst pillar/panel bump and seam interaction problems found in U.S. underground coal mining within the last 30 years.

To cope with these severe mining conditions, the use of stiff, load-concentrating abutment pillars in gate developments was largely abandoned in favor of the less rigid, load-shedding yielding pillar. As these pillars gradually and nonviolently yield, the strata immediate to the entry system are allowed to deform, creating a "softened" zone around the entry system. Weakening the pillar supports and surrounding rock mass transfers high abutment loads away from the entry system onto the adjacent panel(s) and minimizes the load-concentrating potential of the remnant gate pillars during subseam mining.

Additional applications of yielding gate designs include the control of floor heave, cutter roof (an example of horizontal stress-related problems), and less commonly, subsidence problems. Although the performance record has not reflected a marked improvement in ground stability in every case, sufficient success has been achieved by some of the industry's most productive mines to warrant a growing interest in the level of safety that yielding systems may afford operations in other U.S. coal regions.

In addition to ground control, yielding gate systems offer some very distinct advantages over full abutment pillar designs where mining economy is concerned. For example, rapid advancements in support, shearing, and face haulage technologies over the past few years have placed an enormous strain on the ability of development to keep pace with longwalling. Yielding systems require less crosscut development and may marginally improve place-mining efficiency where extended cuts are allowed. Reduced entry development and advantages in miner move efficiency may also be realized for various configurations employing both yield and abutment pillars. Support, labor, and capital equipment costs may also be minimized by less

overall development. Once developed, improvements to gate stability in difficult or multiseam mining conditions translate into less nonscheduled face downtime, recently estimated by one western longwall engineer to average over $350 per minute for a ~9,000-metric-ton (10,000-U.S.-short-ton) per 8-h shift operation.

Nevertheless, as promising as the yielding gate system appears to be, the acceptance of this design option continues to be most greatly hindered by (1) the lack of a proven design methodology that quantifies the performance potential of the entire yielding gate road system, coupled with (2) the somewhat frequent occurrence and severity of failed "misapplications" within the limited experience base attained thus far.

To date, a number of design methods have been developed for these specialized gate systems, but they typically focus on pillar sizing alone and fail to address gate performance once the pillar has yielded. As a result, on-site engineers have primarily relied upon the trial-and-error refinement of traditional pillar designs used within the local mining community. While this "technology transfer" process has worked fairly well within specific western U.S. coal districts, failure to recognize that gate performance depends greatly on such factors as the quality of the immediate roof strata and installed support systems has also resulted in several unsuccessful attempts to import a design from one coal region to another. With relatively few mines utilizing this gate design option in recent years, the consequences of misapplying and/or poorly designing yielding pillar gate roads can only encourage industrywide skepticism and misunderstanding. Today, for example, it is largely held that full-yielding systems are *limited* to the difficult mining conditions found in the West, that extensive secondary tailgate support is required at a minimum, and that multientry systems (more than two) simply provide inferior, unacceptable levels of gate stability performance. As will be illustrated later, yielding gate road systems, and particularly yield pillars in abutment-yield gate configurations, have a much broader application potential in many U.S. coalfields than is currently believed.

Regardless of existing perceptions, the challenge of gate development keeping pace with rapidly expanding longwall production capabilities has driven mine operators to minimize both pillar sizes and the number of entries mined. As a result, interest in this design option has been largely mandated by these economic concerns, and now the engineering questions surrounding ground control and operations need to be answered. To assist mine operators in addressing the ground control/gate design aspects of yielding pillar gate systems, this paper presents a general overview of what has been learned thus far from western U.S. mining experiences over the past decade. More specifically, the fundamental concepts of design viability (under which circumstances yielding gates might be appropriate), timing of pillar yielding, and the "critical" pillar are

Figure 1.—Canyon and mesa topography common to the coalfields of central Utah.
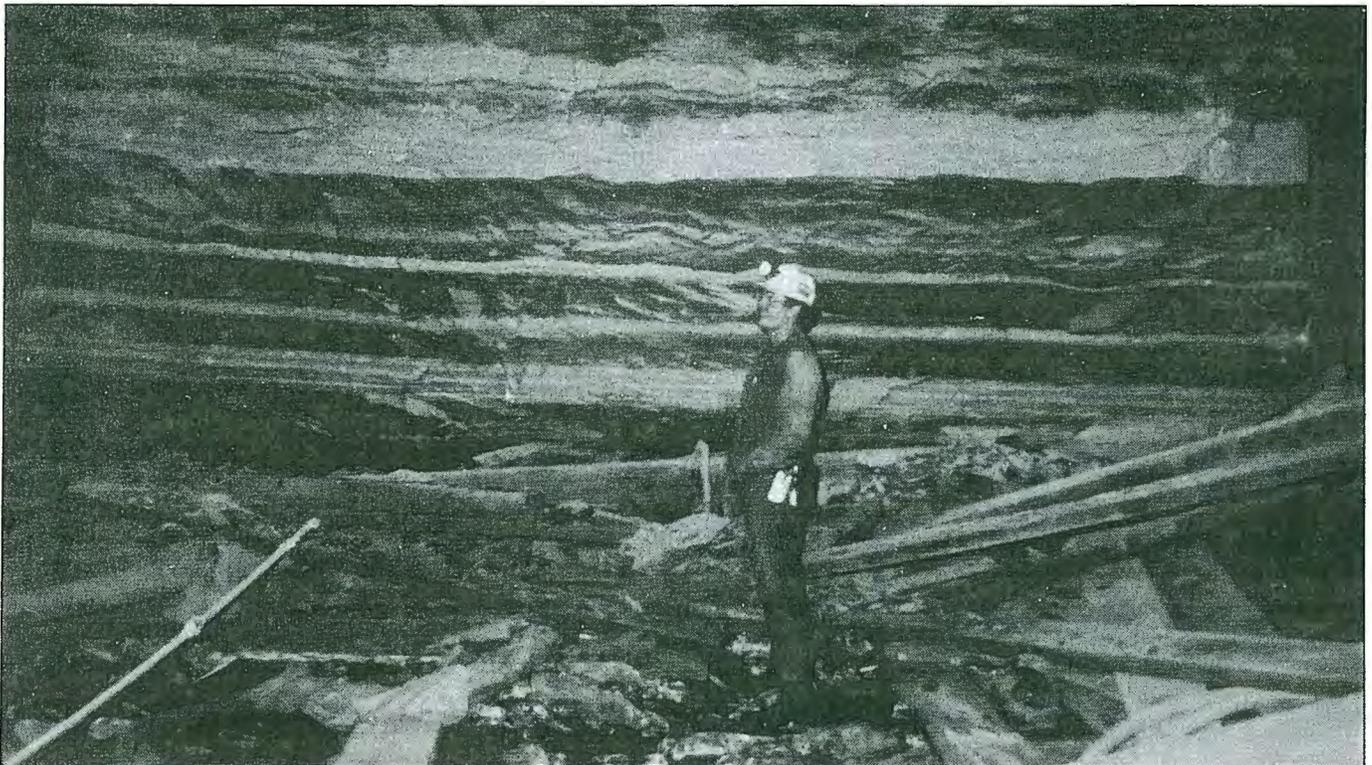


Figure 2.—Typical strong roof strata sequence, found in many western U.S. mines, comprised of fine-grained sandstones, siltstones, and strong mudstones.

discussed in the context of an approach for designing yielding gate systems. A brief, informal analysis of several successful and unsuccessful attempts to use yielding designs in recent years as related to roof and floor quality, pillar dimensions, and mining depth is also presented. While USBM research continues to develop a proven, comprehensive design methodology for yielding gate road systems, this paper serves as a summary reference in support of the emerging acceptance of yield pillar usage in U.S. longwalling.

## ASSESSING THE VIABILITY OF YIELDING GATE ROAD SYSTEMS

With respect to ground control, the viability of yielding gate designs for any particular mining property is a function of the strength or supportability of the immediate mine roof, lateral continuity of both the roof and floor strata, and mining depth. In lieu of being able to currently quantify this relationship mathematically, the basic concept is most simply illustrated in figure 3. Three boundaries—the left, lower, and right sides of the "viable" region—essentially define the following basic requirements of a potentially viable yielding pillar gate design for any specific mining property.

*1. Does sufficient overburden exist to effectively initiate the timely yielding of the minimum pillar size required by the U.S. Mine Safety and Health Administration (MSHA) and/or mine operations?*

Most important to the successful implementation of a yielding gate system is *using pillars that yield*. Although this requirement appears obvious, perhaps the most common factor in unsuccessful cases is the use of pillars that do not yield sufficiently to effectively redistribute pillar/entry loads to the surrounding panel abutments. The stabilizing, load-reducing qualities of the yielding design are instead replaced by severe roof, floor, pillar, and panel instabilities driven by the concentration of high abutment loads across the entry system.

Failure to achieve pillar yielding in moderate to deep settings is generally a design-related problem involving pillar oversizing or attempts to customize the timing of pillar yield to accommodate marginal ground conditions (discussed in more detail in the next section). Conversely, pillar yielding in relatively shallow operations (the left side of the "viable" region in figure 3), may be unavoidably restricted by both the minimum pillar width allowed and the minimum overburden depth then required to initiate timely yielding.

Based on an informal survey of many western U.S. operations, the smallest pillar width deemed operationally feasible, as well as allowed without an MSHA exemption, is 6.1 m (20 ft), and in some cases no smaller than 9.1 m (30 ft). Most of the operations queried used two-entry systems, so it may be possible to utilize smaller widths for the adjacent pillars in multientry applications. Experience with pillar sizes less than 6.1 m (20 ft), used in conjunction with abutment pillars and/or in thin-seam settings where rib stability is not a problem, suggests this is a feasible consideration.

*2. Is the mine roof quality sufficient to withstand potentially large entry deformations without the use of excessive artificial support?*

Yielding gate systems by definition involve significant entry deformations ranging from several centimeters to over a meter depending on the height of the opening, width of the gate, caving characteristics, support type, pillar behavior, etc. The ability of the immediate, supported interval of roof strata to withstand the bending and shearing stresses that accompany pillar yielding is paramount to achieving gate stability throughout panel mining. Weak strata in the immediate mine roof can be tolerated with the use of wire or plastic mesh if the unit is not too thick, but competent strata must comprise the majority of the bolted interval. Unconsolidated, highly structured, weak, thinly bedded roofs, without adequate support, are destined for failure in yielding systems (figures 4-5). Some allowance for roof weaknesses can be made depending on
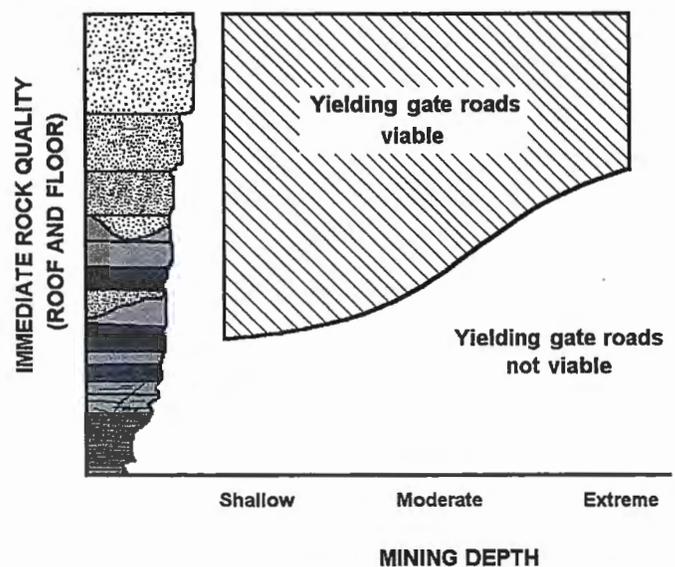


Figure 3.—Conceptual relationship between immediate roof quality, mining depth, and the potential viability of a yielding gate road system.

Figure 4.—Weak, unconsolidated, highly laminated roof sequence that is not conducive to successful applications of yielding gate road designs.

the amount and type of support to be used, persistence of weak roof zones along the gate, and perhaps the stand time required of the opening (mostly due to panel lengths). In general, however, additional (heavy) support should not be viewed as an alternative for making yielding systems viable in marginal conditions; the risk of failure is high.

As mining depths increase, the quality of the bolted roof necessary to ensure gate stability should also improve to accommodate potentially higher and more sudden gate deformations. Although it can be argued that yielding of the gate pillars and softening of the immediate few meters of overlying roof strata essentially isolate the entry system from overburden loading, the potential for higher abutment loads at greater depth is not a subject best left to theory. Abutment loading mechanisms, both ahead of the face and along the caving gob, are not easily characterized for nonyielding gate systems, let alone the more complex yielding systems.

Consideration should also be given to strong mine roof conditions where the possibility of sudden loads being imparted to partially yielded pillars exists during first face

passage. Strong, stiff roof units (beds, channels, etc.) can effectively bridge small gate widths (typical of two-entry designs) prior to first panel mining, thereby shielding the entry system from a majority of the overburden loading necessary to initiate full pillar yielding. Once the face passes, removing a primary support abutment for the gate road roof strata, the full weight of the panel side abutment is imparted to the partially yielded coal pillar. The result is commonly severe pillar bumping and/or damage to the immediate headgate floor near the face. In this case, the roof is sufficient to withstand considerable entry deformation, but may actually contribute to serious pillar and floor instabilities if pillar yielding is significantly impeded.

The USBM-developed CMRR, described later, is an efficient, practical rock mass classification system that the mine design engineer can employ to assess the structural integrity and supportability of the mine roof when considering yielding gate designs (5).

*3. Is the floor quality sufficient to not engender problems related to specific roof conditions and mining depths?*

Although mine roof quality is by far the most important factor affecting entry stability once pillar yielding has begun, the quality of the floor can create two extreme circumstances in which yielding entry systems become hazardous under otherwise viable roof conditions. First, in moderate, yet supportable roof conditions, where delayed pillar yielding (using a larger pillar) is being considered to minimize total roof deformations, the floor must be strong enough to resist pillar punching. Weak floor strata cannot withstand sustained loading from highly loaded pillars, resulting in serious, progressive entry heave and, occasionally, sudden, violent failures of the immediate floor strata (figure 6). Second, in strong roof conditions, the floor must not be so strong that pillars cannot be designed small enough to ensure nonviolent yielding and still meet operational and mining law requirements.

*4. Is the mining depth so great or complicated by unique seam conditions that a yield pillar cannot be developed?*

This situation (illustrated by the right side boundary of the "viable" region in figure 3) has only been partially demonstrated by one U.S. mine in recent years. In this case, mining depths approaching 900 m (3,000 ft) and high gas concentrations within the seam produced severe face bumping in gate development drivages, forcing the mine to use an advancing longwall system. Although the inability to develop panel entries was not the direct result of a failed yield pillar design, the existence of an application limit was nevertheless demonstrated. This limitation does not appear to be of immediate concern in today's longwall industry, but will certainly impact future operations as mining proceeds to greater depths in search of quality deposits. To date, correlations between gate performance and such factors as widely ranging, sudden changes in overburden depth, seam dip, and extreme mining depth have been inconclusive. These topics will be addressed in more detail when a much larger database has been compiled.

Aside from these most basic considerations, there are many additional factors that influence whether a yielding gate design is actually appropriate for a particular mine setting or not. Factors such as the number of entries to be used (total gate span), pillar sizes, entry spans, types of supports, cavability of the gob, geologic anomalies, etc., all influence the potential success of these designs as well, as they do any type of gate configuration. However, the historical experience base with yielding gate systems in the United States is fairly limited and often does not clearly define the boundaries of success/failure for the many possible cases that could exist. Nevertheless, completing this first step in the design process can roughly estimate the success potential of a yielding pillar design as high,

marginal (risky), or low (extremely risky) and, more importantly, is an absolute requirement to avoid the oversights common to available yield pillar design methods.
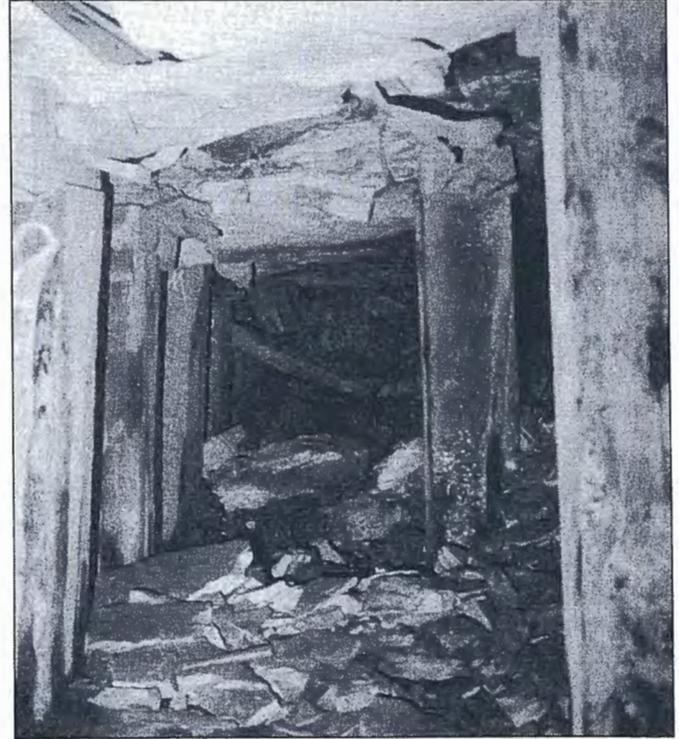


Figure 5.—Poorly laminated, minimally supported mine roof typically cannot withstand the deformations of yielding gate designs.



Figure 6.—Severe floor heave resulting from improper pillar design.

# YIELDING GATE ROADS:  SOME PRACTICAL CONSIDERATIONS

Despite the fact that a thorough design methodology does not currently exist for the yielding gate road *system*, past experiences with this design option in the United States have given a good deal of insight into its successful application, as well as some of the key concepts governing its use.  Until proven guidelines are available for defining appropriate mining conditions for successful applications, one should consider the following characteristics common to many western U.S. experiences when further evaluating the viability of yielding gate designs for a specific property.

## PILLAR SIZING

Pillars are generally 6 to 9 m (20 to 30 ft) wide in 1.8 to 3.0 m (6 to 10 ft) seams (w/h ratio of 3 to 5) and are typically intended to yield shortly after development or with the approach of the first panel face at depths averaging around 455 m (1,500 ft).  In practice, measurements of pillar load histories (2) suggest that *full* yielding seldom occurs until after first panel mining is well outby and the majority of the peak side abutment has been attained. Although substantial, sometimes slightly increasing loads are often seen within the pillar core region long after first face passage, it is clear from elevated load measurements taken within the adjacent panel that the maximum load-bearing capacity of the pillar has been surpassed and a yielding gate system is in place.  Aside from the various stages and degrees of loading during mining, the rate of pillar yielding is a function of such factors as coal strength, seam height, pillar and entry width, and roof and floor strata properties.  The influence of each, or a combination, of these parameters varies considerably with conditions.  For example, strong, unstructured coal confined by massive sandstone roof and floor members has been encountered by at least one western U.S. mine in recent years, where a 9-m (30-ft) pillar design failed to yield properly under 365 m (1,200 ft) of mesa-forming sandstone strata, which resulted in consecutive, violent pillar bumps as second panel mining approached.  A much smaller pillar might have yielded under these conditions; however, as previously noted, it is both mining law and the general consensus among western mine operators that 6 m (20 ft) is a minimum limit based on operational feasibility considerations (power center storage, face equipment manipulation, place-mining scheduling, etc.).  Likewise, larger pillars have been used, up to 14 m (45 ft) wide, with the intention of early yielding, but significant problems have been reported owing to inconsistent pillar yielding along the gate length (2).

The database of case history experience described later in this report indicates that no successful yield pillar designs were achieved with w/h ratios >5. Although the database compiled for this discussion is quite limited, it does represent the general experiences of most western U.S. mines employing yielding pillar systems.

## Critical Pillars

Where the use of pillars with w/h ratios greater than 5 is concerned, the concept of the *"critical pillar"* has often governed the performance experienced.  A critical pillar can most simply be defined as one that is too large to yield sufficiently, resulting in load transfer to nearby panel abutments, yet remains too small to fully support panel abutment loads safely.  Figure 7 illustrates the relationship of the critical pillar to both appropriate applications of the yield and abutment pillar gate systems.  The horizontal axis represents the minimum performance standard that separates a successful system from an unsuccessful application.  The curve is an idealistic representation of how the level of confidence in a design passes from working abutment systems to working yielding systems, passing through the critical pillar zone along the way.

An important aspect of this concept is the rate at which a successful gate design can become unsuccessful.  For abutment pillar systems, changes in performance are generally more gradual, and are witnessed by the onset of minor floor heave, an increase in audible coal popping and minor bumping, and increased frequency in roof-related problems.  These changes generally develop more slowly
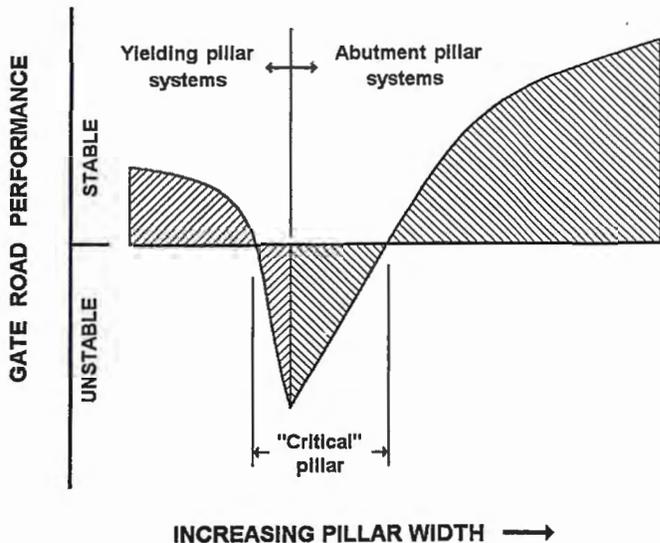


Figure 7.—Conceptualization of the "critical pillar" relationship showing the transition from successful yield pillar systems, through unsuccessful critical designs, to successful abutment pillar systems.

since pillar sizes are not typically subject to drastic downsizing at operations using this design option; nor do mining conditions typically change quickly enough to affect the full definition of the critical pillar on a design that has worked well for several panels. Conversely, for yield pillar applications the difference between a fully successful yielding gate and the worst possible critical pillar conditions can often be measured in a matter of a few meters of additional pillar width.

A USBM study currently underway in Utah involving pillar sizes ranging from 9 to 17 m (30 to 55 ft) under cover depths approaching 900 m (3,000 ft) has already witnessed the extremes over this relatively short range of pillar sizes, and first panel mining has only recently passed the largest of the pillars being investigated. At this time, the 17-m (55-ft) design has bumped violently in the headgate just after passage of the first face. The 9-m (30-ft) pillars, still 600+ m (2,000+ ft) outby the face, have exhibited signs of sufficient yielding to inhibit this type of pillar failure entirely, as considerable past experience at this mine would also support. Although pillar bumping subsided as face advance has temporarily moved under more moderate cover, it is very likely that renewed bumping will occur in the pillars ranging 12 to 15 m (40 to 50 ft) once the second panel face approaches.

This study graphically emphasizes the importance of keeping pillar sizes small enough to yield at all times. Increasing yield pillar widths to accommodate deepening cover, in the same manner abutment pillar widths may be increased, is a notion to be avoided. The very nature of the yielding gate road—the softening of the localized ground mass—makes the degree of entry stability attained largely independent of mining depth once pillar yielding has been achieved. Maintaining this weakened zone around the panel entry system is paramount to gate stability.

It cannot be overemphasized that increasing the pillar width toward the critical pillar range only invites the full weight of the overburden to be imparted upon a gate system that cannot possibly support it. As a result, critical pillars are to be considered *extremely* bump-prone (figures 8-9), even at shallow depths when strong mine roof and floor conditions exist. Unlike the abutment-to-critical pillar transition, where coal bumps are generally first witnessed in the tailgate, the yield-to-critical pillar transition provides for severe bumping in the headgate entries immediate to the face. In settings not readily conducive to pillar bumping, prolonged loading of the gate pillars will certainly result in severe roof, floor, and/or rib instabilities (figure 10), requiring extensive supplemental support along the entire tailgate entry at a minimum (figures 11-12), if gate closure can be avoided at all.



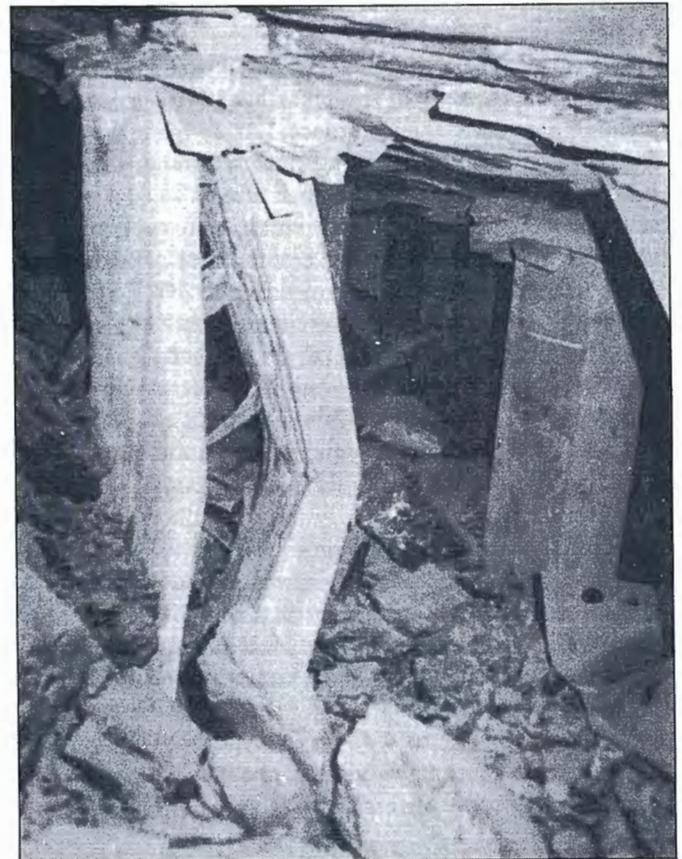Figure 8.—Critical pillar bump at the tailgate corner.



Figure 9.—Critical pillar bump near the headgate corner.

Figure 10.—Severe rib failures accompanying floor heave conditions in a critical pillar application.



Figure 11.—Intensive mine roof support used to control entry closure in a critical pillar tailgate setting.

28



**Figure 12.—Additional example of tailgate support requirements when critical pillar is used.**

## Timing of Pillar Yielding

The ability to reliably design pillars to yield at specified points in mining would greatly increase the utility of this gate design option, but at the same time would require a much better understanding of ground response to pillar yield than currently exists. Timed yielding would be most beneficial in cases where a yielding system is deemed desirable for any number of reasons (bumps, multiseam, subsidence issues, etc.), but poor mine roof conditions necessitate minimizing entry deformations to ensure gate stability. For example, delaying pillar yielding until late in the mining cycle, or even until gob isolation, may minimize tailgate roof strains to within stable limits and still relieve stress transfer problems when mining subjacent seams.

However, the risks associated with attempting to customize designs to account for marginal or weak ground conditions as a function of mining advance are considerable. In weak conditions, where pillar yielding is designed to occur with the onset of second panel face approach, or after, during isolation in the gob, the risk of inducing bumps may be low, but critical pillar sizes are likely to create detrimental roof and floor conditions. Conversely, yielding too early in weak ground will undoubtedly encourage severe roof falls ahead of the face. The greatest risks are often when attempting to customize designs in moderate ground conditions to yield later in mining. Here, both roof and floor failures and severe

pillar bumping can become serious issues, with little margin for design error.

## ARTIFICIAL SUPPORT

Primary tailgate support varies greatly depending on the quality and continuity of the roof strata. Strong roof conditions generally warrant little more than conventional, planned bolting. Moderate roof quality typically requires a higher-cost primary support system commonly consisting of high-strength combination bolts and straps, angle bolting, slings or trusses, and steel mesh installed during bolting, not during cribbing. Generally, poor mine roof quality cannot be effectively supported without the use of multiple-support systems, as has been the case in a number of western U.S. mining experiences.

Longwalls are currently operating in the United States under poor roof conditions with yielding pillar gate designs, but tailgate stability is marginal on a day-to-day basis, with occasional entry closures immediate to the face-end responsible for significant delays in mining. In such cases, the performance of the support system is typically less than effective regardless of the type or quantity installed. A promising type of support for improving moderate roof performance, and possibly some weak roof situations, is the cable bolt. The USBM is currently conducting research to determine the effectiveness of this support in holding the severe loads often witnessed in tailgate roof strata.

Wire or plastic mesh, generally installed during gate road advance or with tailgate cribbing, is a standard practice to control the inevitable roof rash occurring within the first few centimeters of the immediate roof. In cases where roof quality is above average and minimal deterioration is anticipated, mesh installation can be done during cribbing and may be limited to lightweight plastic varieties. Marginal roof conditions require strong, steel mesh bolted tightly against the roof to inhibit progressive strata failures (figure 13). Particular care should be taken to adequately mesh along the tailgate panel roof-ribline, as this will be a difficult area to control when at the face-end.

Secondary support is critical to the success of most yielding systems, primarily those with moderate roof conditions, and generally consists of double-row, soft-wood cribbing to accommodate large deformations and provide a protected escapeway. Four-point cribbing is often preferred for its softer, consistent response to entry deformations, but nine-point cribbing is not uncommon when conditions warrant (figure 14). As roof qualities weaken, approaching the point where yielding systems should be re-evaluated for their effectiveness, it is not unusual to see solid wood packs begin to replace the larger nine-point cribs. In extreme conditions, various steel-set systems have been trialed for their effectiveness (figure 15), but abandoned due to cost.

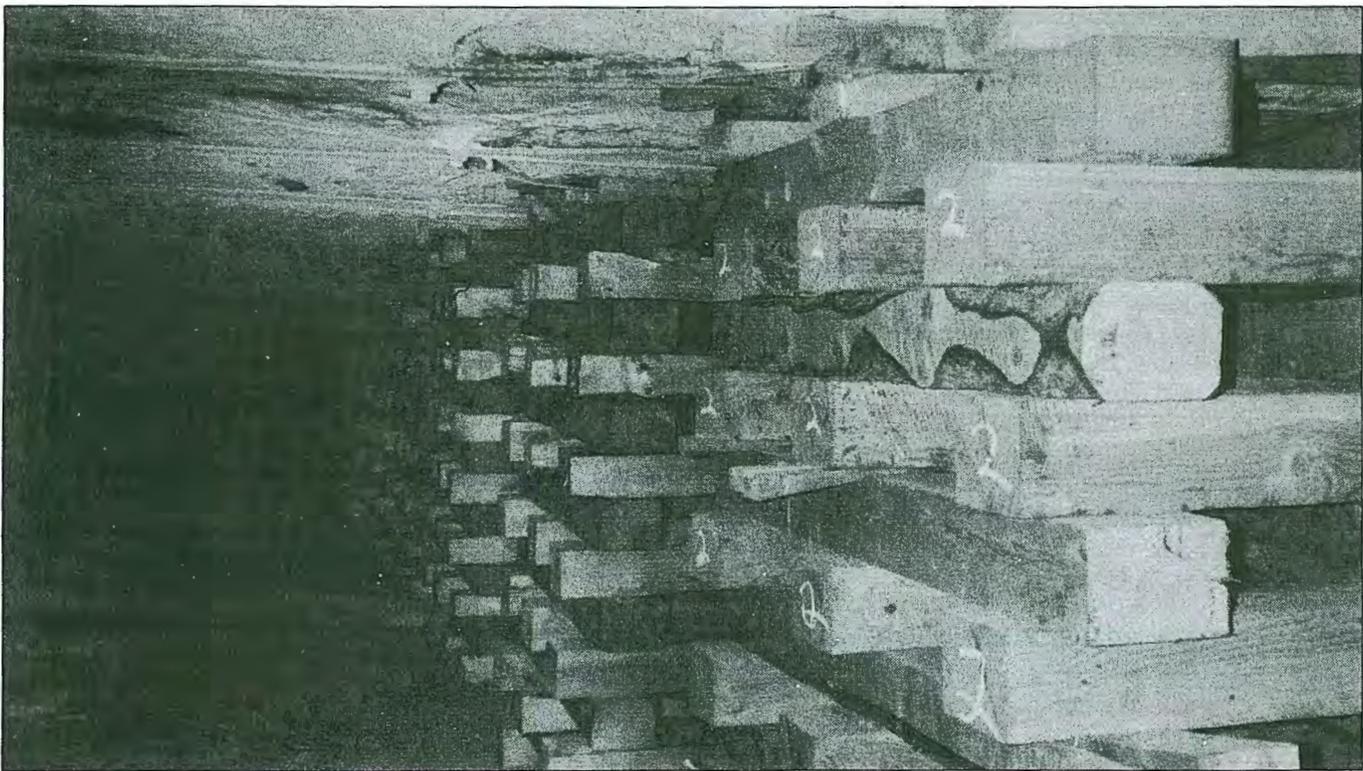Figure 13.—Insufficient support system for holding weak, poorly laminated roof.



Figure 14.—Nine-point cribbing application in a yielding gate road.

**Figure 15.—Steel-set support system, which is no longer used except in the most severe conditions.**

Stiff supports, such as concrete donut cribs and "Big John" timbers, are generally incompatible with the substantial entry closures found in yielding systems, often inducing localized roof and/or floor problems or failing early in the mining cycle. Incorporating "soft" elements within the stiff support structure has been successful in some cases at getting the best of both worlds, i.e., soft enough to survive the initially high entry closures common to yield pillar systems, yet stiff enough to effectively support the mine roof once it has relaxed over the gate (figure 16). Customizing stiff supports in this manner is not a simple engineering task, however, and requires regular design modification to address changing ground conditions.

## ENTRY CLOSURE

Entry closure for yielding systems is often considerably greater than that typically experienced in abutment- or yield/abutment-pillar systems. However, where strong roof and moderate/strong floor conditions prevail, primary support is well engineered, and the pillars are designed to yield properly, tailgate entries may actually experience relatively minor degrees of closure, with the most noticeable effects witnessed within 30 to 60 m (100 to 200 ft) of the face. At one of the deepest western operations, where mining depth has progressed from 455 m (1,500 ft) to nearly 915 m (3,000 ft), little or no change in cribbing

practices has been required to support the relatively strong roof strata present across most of the property. Closures of less than 5% of the entry height after first-panel mining are common at this operation, reaching 10% to 15% with second face approach. Despite the routine use of double-row cribbing at this and other local operations, significantly less cribbing could likely be used with little or no impact to entry stability. To this end, several western operations are currently experimenting with lower-density crib patterns and new types of yieldable supports that can be employed less frequently and somewhat more inexpensively.

In mines where the roof is weaker, greater degrees of entry closure should be anticipated due to bed separations (sag) and failed strata migrating into the entry. Recent observations in one operation under poor roof (weak, highly laminated stack rock conditions) showed tailgate closures averaging 35% in a 1.8- to 2.4-m (6- to 8-ft) seam, with closures often reaching as high as 50% within 60 m (200 ft) of the second panel face. Detached strata well above the bolt horizon was clearly responsible for these excessive crib deformations.

Excessive entry closure becomes a major concern where MSHA-mandated minimum escapeway dimensions come into play, where face-end/tailgate junction blockages can become problematic, and where restricted ventilation problems may be encountered as panel lengths are significantly increased.
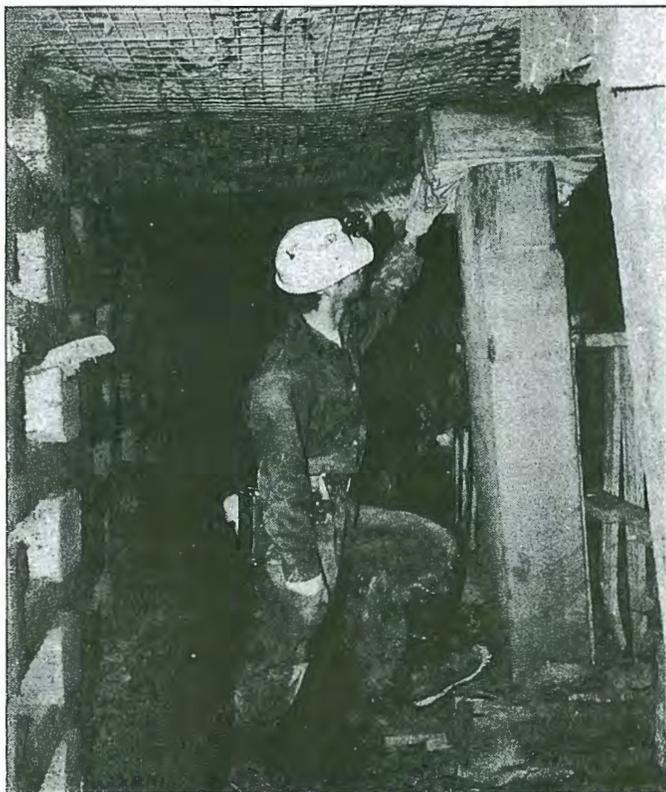
Figure 16.—Capped "Big John" timber allows additional entry closure to occur before failure of the support.



Figure 17.—Although generally successful in controlling rib sloughage, fencing methods must account for rib toppling in high seams.

## RIB STABILITY

Extensive pillar rib sloughage is to be expected, particularly along the entire length of the tailgate, and is commonly treated with wire mesh or some form of fencing. Artificially confining the rib to help control sloughage, a practice often used by mines employing abutment pillar gate designs, has used successfully in several situations. Generally, however, the volume of rib material moving into the entry is too great to rely solely on rib bolting or doweling. Entry cribbing alone usually provides a sufficient barrier to retard excessive rib migration into the entry, as long as a closely spaced pattern is maintained. Some form of fencing, such as plastic mesh or chain link, has also proved to be very effective when used with a variety of entry supports (figure 17). Where entry heights approach or exceed 3 m (10 ft), the problems of rib slabbing (toppling into the entryway) and crib damage (rollout due to rib loading) often require further support measures.

## NUMBER OF ENTRIES

Theoretically, two-entry systems should outperform three-entry systems based on the principle that the less ground opened up the better. This assertion was emphasized by Carr, where in an analysis of the applications of yield pillars at the Jim Walter Resources, Inc., mines in central Alabama, he states, "The general application of the yield pillar principle is limited to a two-entry yield pillar system. A good spanning main roof is essential if three- or four-entry systems are required." (1, p. 176). This has generally been true in western U.S. mines as well and certainly applies to all multiseam applications (i.e., where abutment structures overlay the current gate road system).

Gate loading can be shown to be higher with the wider multientry spans at various points in the mining process, but no definitive reason exists to rule out multientry gates in all conditions. For example, a three-entry full-yielding system is currently being successfully used in a Utah operation under low cover conditions (<180 m (<600 ft)) to effect improved ground control during subseam mining. Also, at a nearby operation, adequate entry conditions have been recently observed in three-entry end-panel-section bleeder systems at depths reaching nearly 610 m (2,000 ft) (2).

## PILLAR BUMP APPLICATIONS

Gate road systems employing yield pillars, whether alone or in conjunction with abutment pillars, are highly recommended design options for all longwall operations experiencing or anticipating coal bump events in the headgate and/or tailgate entries. Fully yielded pillars simply cannot store the strain energy that drives the dynamic explosiveness of coal bumps, thereby effectively eliminating their occurrence altogether. The historical record of successful longwalling in western U.S. mines,

which presently include some of the most productive operations in the world, would certainly be greatly abbreviated were it not for the bump mitigation attributes of yielding gate systems.

Nevertheless, while it is true that tailgate pillar bumps in yielding entry systems are virtually nonexistent in western U.S. operations today (critical pillar bumping in the headgate, however, remains a serious problem), legitimate concerns have been raised regarding the influence these gate designs may have on end-panel face bumps. Because overburden loads are largely diverted away from the softened groundmass about the entry system and onto the nearby, stiffer panel abutments, one can reasonably conclude that the frequency and severity of face bumps near the tailgate will also increase. This has not been the experience of most western operations, however, suggesting that the degree of face bumping induced by the yielding entry system is a function of numerous mining parameters.

In moderate roof and floor conditions, where the coal strength and seam structure accommodates yielding, peak side-abutment loads are typically lower and more evenly distributed within the tailgate panel periphery. Early pillar yielding maximizes total panel loading before the arrival of the face, which furthers the development of the yield zone within the panel ribline. The deeper the yield zone, the less likely small-scale bumping along the tailgate ribline is to occur or become a frequent problem. Also, the peak stress abutment within the panel will be further minimized and, thereby, less of a contributing factor to face bumping.

This supposition was recently supported at a western operation where panel drilling along the tailgate delineated the yield zone at 9+ m (30+ ft) within the ribline. Face bumping was minimal and did not appear to be related to the side abutment as much as to the rate of face advance. This suggests that, for this particular operation, face bumping occurs when the rate of mining overtakes the peak face abutment and is not the result of using a yielding gate system.

The existence of a deep yield zone does not, however, preclude the occurrence of large-scale bump events. It only indicates a tendency for the seam to yield nonviolently, rather than confine high, bump-prone stresses at or near the face/ribline.

In particularly strong roof and floor settings, where the coal strength and lack of seam structure inhibits yielding around mine openings, yielding gate designs may very well enhance face/panel bumping by enabling a greater expanse of intact roof to cantilever off the panel ribline. The confinement offered by the roof and floor strata typically minimizes the depth of yielding that occurs within the panel rib and concentrates the abutment loads within a relatively short distance of the panel edge.

Where these types of conditions exist over a significant portion of the panel, an abutment-yield system is an alternative worth considering. The yield pillar would not only act as a bump-proof gate support, but also serve as a "bump curtain," shielding the tailgate escapeway from the possibility of explosive abutment pillar failures. Where these conditions are of limited extent (e.g., localized sand channels in most western mines) and a full-yielding gate system is desired, a minimum number of entries is recommended to reduce the span of the cantilevering strata and the resultant abutment load imparted to the tailgate corner of the panel.

## MOVING TOWARD A DESIGN METHODOLOGY

Addressing the general performance standard in a *quantitative* manner requires a specific design criterion that discriminates success/failure in terms of available engineering parameters. For example, the traditional concept of the safety factor is commonly used by many engineering design criteria to express the relationship between the operating environment and the functional requirements of the structure being designed. However, this concept works most easily in mine design applications when static conditions prevail, or can be assumed for reasonably few points in the mining process, and considerable simplification of the setting parameters can be tolerated. As previously discussed, the yielding gate environment is far from static, and the interrelationship of setting elements does not readily lend itself to simplification in the context of a *deterministic* approach to gate design. This is emphasized by the current lack of a methodology or set of guidelines for the design of the integrated pillar-entry-support yielding gate system.

Fortunately, as described by Mark, "deterministic methods are not the only ones for the solution of complex ground control problems" (3). In support of this, he describes the method of *back-analysis* as it was applied to the refinement of the empirically based abutment pillar gate road design methodology called Analysis of Longwall Pillar Stability (ALPS) (4). Essentially, back-analysis determines significant relationships between specific parameters describing a large database. In the case of Mark's most recent application, analysis of design data from a total of 69 longwall case histories found a significant correlation between mine roof quality and the ALPS stability factor (4). This correlation allows longwall planners to estimate the required pillar sizes at operations utilizing abutment pillar gate designs after making a quantitative evaluation of the roof quality.

The remainder of this paper describes preliminary back-analysis of yielding pillar designs, employing a database of 15 case histories representing 10 mines. The cases were evaluated to determine if any apparent relationships could be identified between readily available mining parameters that could be used to define the success or failure potential of specific designs. The database used in this evaluation was considered too small to attempt to draw mathematical relationships for a success/failure criterion, yet the results indicate the promise of back-analysis techniques in providing such a criterion once a sufficient database is collected.

## DESCRIPTION OF THE DATABASE

Of the 15 cases, 6 were considered satisfactory and 9 were considered unsatisfactory examples of yield pillar usage. Only three cases involved multientry (more than two) applications. All of the mines evaluated operate within the Utah, Colorado, and New Mexico coal regions, with depths ranging from roughly 200 to 900 m (650 to 3,000 ft). Generally, each satisfactory case history represents many applications of that particular design across the property, while each unsatisfactory case represents as few as a single application. The final analysis involves only a few mining parameters (listed in table 1), including pillar width-to-height ratio, mining depth, roof quality rating (CMRR), and floor quality rating. Although the ratings are fairly subjective, as described next, the correlation indicated by these parameters is notable.

### Case History Success/Failure
### Performance Determination

The case histories were objectively described as being either *satisfactory* or *unsatisfactory* based on a general performance criterion largely patterned after that employed by Mark (4). Some additional considerations have been added to Mark's criteria that are more specific to yield pillar gate designs.

To be considered *unsatisfactory*, a case history had to meet any one of the following criteria:

- Pillar design and/or entry support was significantly changed in response to poor ground conditions in either the headgate or tailgate entries.
- The panel was abandoned owing to intolerable gate road ground conditions.
- Unacceptable conditions were encountered in areas of poor roof and/or floor quality.
- Pillar bumps had been reported, regardless of severity, timing, location, or frequency.
- Significant face-end bumping occurred that could be attributed to the yielding gate system.

- There were significant longwall delays attributable to ground conditions in the headgate and tailgate entries, most commonly experienced as tailgate closures.

To be considered *satisfactory*, a case had to meet *all* of the following criteria:

- The design was used for at least three successive panels, *or* proven site-specific design guidelines had been established based on a substantial record of yield pillar performance.
- Tailgate blockages were rare or nonexistent and of minimal extent.
- Good ground conditions, with minimal delays attributable to ground control, were reported.

Discriminating between degrees of gate performance is relatively clear-cut where critical pillars are concerned, but becomes much more difficult for cases involving yield pillars in marginal ground conditions. The immediate, severe pillar and entry loading conditions imposed when critical pillars are mistakenly employed typically engender among the worst ground conditions found in U.S. longwalling. The failure to achieve complete, nonviolent pillar yielding in a timely manner is often readily apparent in the form of severe pillar bumping, roof punching and shearing, and/or floor heave. Conversely, when pillar yielding is achieved as planned in marginal-quality roof and/or floor settings, and particularly at lower cover depths, factors such as mining rate, and amount and type of roof support can complicate the distinction between satisfactory and unsatisfactory performance for a given case history. Owing to the limited database available, the influence of these factors may not be fairly represented in all cases where failed yield pillar applications are concerned.

### Roof Quality Rating

Roof qualities were quantified using the CMRR recently developed by Molinda and Mark (5). This rock mass rating system for coal measure rocks provides a weighted evaluation of the overall quality of the roof strata within the bolted horizon, considering such parameters as discontinuity intensity and shear strength, unit rock strength, weatherability, number and sequencing of beds, and the presence of groundwater inflows. The individual roof quality ratings are expressed on a scale of 0 to 100 and fall within three broad classes described by the developers:

- *Weak* roof (CMRR < 45): Roof typically consisting entirely of low-strength 56 MPa ( < 8,000 psi), closely bedded, jointed, and/or slickensided rocks, usually shales and coals.

Table 1.—Data set for yield and critical pillar analyses

| Mine, entries,[1] pillar type,[2] performance[3] | Mining depth, m | Pillar width, m | Seam height, m | Pillar w/h ratio | Coal Mine Roof Rating[4] | Floor rating (FR)[5] | CMRR$^2$ × FR (×100) | CMRR$^2$ × FR × w/h (×1,000) |
|---|---|---|---|---|---|---|---|---|
| Mine A: | | | | | | | | |
| 2E, YP, S . . . . . . . | 550 | 9.1 | 2.4 | 3.8 | 75 | 4 | 225 | 86 |
| Mine B: | | | | | | | | |
| 2E, YP, S . . . . . . . | 550 | 9.1 | 2.4 | 3.8 | 80 | 4 | 255 | 97 |
| Mine C: | | | | | | | | |
| 2E, YP, S . . . . . . . | 455 | 9.1 | 2.4 | 3.8 | 60 | 2.5 | 90 | 34 |
| 3E, CP, U . . . . . . . | 455 | 16.8 | 2.4 | 6.9 | 60 | 2.5 | 90 | 62 |
| Mine D: | | | | | | | | |
| 3E, YP, S . . . . . . . | 245 | 9.1 | 3.0 | 3.0 | 55 | 3 | 90 | 27 |
| Mine E: | | | | | | | | |
| 2E, YP, S . . . . . . . | 855 | 9.1 | 2.1 | 4.3 | 80 | 3.5 | 225 | 96 |
| 2E, YP, U . . . . . . . | 730 | 9.1 | 2.1 | 4.3 | 50 | 3 | 75 | 32 |
| 2E, CP, U . . . . . . . | 855 | 16.8 | 2.1 | 7.9 | 80 | 3 | 190 | 152 |
| Mine F: | | | | | | | | |
| 2E, CP, U . . . . . . . | 355 | 9.1 | 2.1 | 4.3 | 75 | 6 | 340 | 145 |
| 2E, CP, U . . . . . . . | 490 | 15.2 | 2.1 | 7.1 | 75 | 6 | 340 | 240 |
| Mine G: | | | | | | | | |
| 2E, CP, U . . . . . . . | 150 | 9.1 | 2.4 | 3.8 | 33 | 2 | 20 | 8 |
| Mine H: | | | | | | | | |
| 3E, YP, U . . . . . . . | 245 | 12.5 | 2.1 | 5.9 | 38 | 1 | 15 | 9 |
| Mine I: | | | | | | | | |
| 3E, YP, S . . . . . . . | 550 | 7.6 | 2.1 | 3.6 | 70 | 3 | 145 | 53 |
| Mine J: | | | | | | | | |
| 2E, YP, U . . . . . . . | 490 | 9.1 | 2.1 | 4.3 | [6]33 | 5 | 55 | 23 |
| 2E, CP, U . . . . . . . | 490 | 24.4 | 2.4 | 10.0 | [6]75 | 5 | 280 | 281 |

[1]2E refers to 2-entry systems, 3E to 3-entry systems.
[2]YP refers to yield pillar, CP to critical pillar.
[3]Performance is either satisfactory (S) or unsatisfactory (U).
[4]On a scale of 0 to 100.
[5]On a scale of 0 to 6.
[6]Estimated from previous on-site investigation.

- *Moderate* roof (45<CMRR<65): Bolted interval usually contains at least one competent unit, typically a siltstone or strong shale, i.e., at least 0.6 m (2 ft) thick containing few bedding planes or other discontinuities.
- *Strong* roof (CMRR>65): Bolted interval typically contains at least one very competent, massive bed, at least 1 m (3 ft) thick that exceeds 56 MPa (8,000 psi) in strength, usually a sandstone or limestone.

CMRR ratings for most western U.S. operations are generally found to be high, over 70 in most cases. Yet, the database used in this analysis includes several examples of roof qualities appraised much lower, including three estimated in the 30's range. With the exception of two values that were estimated by the author, based on proximity to known CMRR data points, all of the roof quality data were acquired from the developers of the CMRR (4).

## Floor Quality Roofing

In the absence of a method to rate floor qualities similar to that of the CMRR, a very subjective rating was applied to available floor data for each mine in the database. Based on the general categories of weak, moderate, and strong, a scale of 0 to 6 was applied that allowed some discrimination as to how weak or strong the floor was from site to site. While future evaluations will attempt to more accurately describe this parameter, it is worth noting that the floor largely does not influence the outcome of the relationship between satisfactory and unsatisfactory designs *as long as the pillars yield*. The floor does play a significant role, however, when the pillars do not yield—the critical pillar failure modes discussed earlier.

## QUALITATIVE DATA ANALYSIS

It was determined that a relationship between mining depth and the multiplied product of w/h, CMRR$^2$, and the floor rating provided a very descriptive discrimination between the performance attributes of each case history within the database. Two perspectives on this relationship relative to the database shed considerable light on the potential for back-calculation to provide a very useful design tool for yielding gate systems in much the same way it has been used for abutment pillar systems. The first considers just those cases where pillar yielding was actually achieved, while the second considers the distinctions between those cases where the application failed.

Considering just those cases where pillar yielding was achieved, shown in figure 18, a clear distinction between satisfactory and unsatisfactory performance can be seen, with an apparent trend also indicating the need for a higher CMRR with increased mining depth to ensure success. While this plot suffers the already admitted failings of limited data, the implied trends coincide with

the basic ideas presented in figure 3. It should be noted that the presented relationship is largely independent of the floor rating since pillar yielding largely minimizes the occurrence of floor instabilities.

Considering just those cases that were determined to be unsatisfactory, shown in figure 19, a distinction begins to
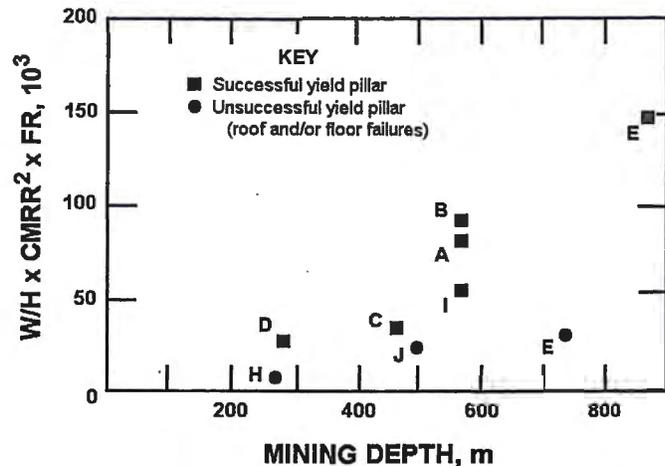


Figure 18.—Rock quality/pillar size ratio relationship versus mining depth with respect to successful and unsuccessful yielding gate road system case histories. Mines A through E and H through J are listed in table 1 and represent those cases where the pillar actually yielded. W/H = pillar width-to-height ratio; CMRR = Coal Mine Roof Rating; FR = floor rating.
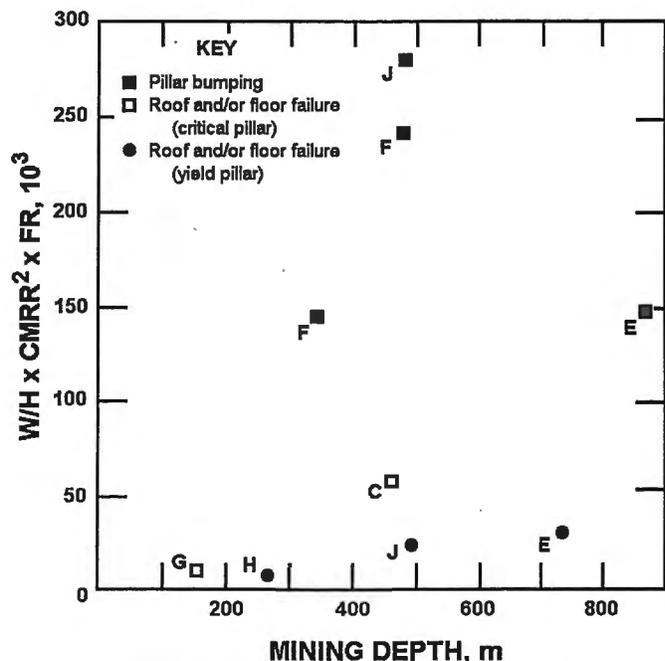


Figure 19.—Rock quality/pillar size ratio relationship versus mining depth with respect to three forms of unsuccessful designs: yielded pillar in weak ground, critical pillar in moderate-weak ground, and critical pillar in strong, bump-prone ground. W/H = pillar width-to-height ratio; CMRR = Coal Mine Roof Rating; FR = floor rating.

emerge between the types of failures to be experienced by inappropriate applications. For weak roof and floor conditions where the pillars actually yielded, the observed failure mode was generally massive roof instabilities (mines E, H, and J). Where the pillars did not yield adequately in both weak to moderate strata conditions, the observed failure modes were dominated by both massive roof and floor instabilities (mines C and G). The worst conditions were experienced at mine C, which also happens to be the deepest of the two experiences given in this database. Although not shown (since it was not evaluated as a separate case history), mine D reported floor problems at cover depths less than 180 m (600 ft), where adequate pillar yielding was not occurring as planned. Finally, where the pillars did not yield under strong strata conditions, entry failure was solely due to explosively severe pillar bumping (mines E, F, and J). In several cases, numerous tailgate stoppings were blown out, and the travelway along the tailgate was closed for varying lengths of time. Mine F was forced to abandon longwalling in two panels largely because of pillar bumping and eventually closed owing to both severe gate road and face bumps. Mine E experienced bumping in the headgate pillars shortly after first face passage.

## SUMMARY

Yielding pillar gate road systems have been shown through historical practice to be viable considerations when deep, bump-prone and/or multiseam mining conditions are present. It can also be shown, however, that this gate design option is not solely limited to difficult mining settings, but may be used very effectively in moderately shallow mining conditions as well. The greatest hurdles facing the routine, successful application of these gate road systems appear to be (1) the lack of a proven design methodology that quantifies the performance potential of the entire yielding gate road system, coupled with (2) the frequent occurrence and severity of failed applications within the limited experience base attained thus far.

USBM research is currently attempting to address these deficits in design capabilities and the database of experience through both on-site evaluations and reviews of the historical performance record. Utilizing the proven techniques of back-analysis, particularly in light of the promise that the preliminary analysis presented herein has engendered in this evaluation approach, it is conceivable that very specific methodologies for the application of full-yielding gate road designs may be developed for a broad spectrum of applications in the not-too-distant future.

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Special Publication 01-94

# New Technology for Longwall Ground Control

Proceedings: U.S. Bureau of Mines Technology Transfer Seminar

Compiled by Christopher Mark, Robert J. Tuchman,
Richard C. Repsher, and Catherine L. Simon

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

Cover Photograph: The U.S. Bureau of Mines has developed highly practical technologies for maintaining effective ground control in the hazardous tailgate entries of longwall mining systems, which will significantly improve the safety of the Nation's underground mineworkers. *(Photo: Alan A. Campoli, Pittsburgh Research Center, U.S. Bureau of Mines)*