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Design Methodology for Standing Secondary Roof Support in Longwall Tailgates

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ABSTRACT

Maintaining ground stability in the gate roads, particularly the tailgate, has always been critical to the success of longwall mining, both in terms of safety and productivity. Several new support technologies have been developed in recent years to replace conventional wood and concrete cribbing for secondary roof support. Since their performance characteristics are unique, the best practices that have been developed with conventional wood cribbing may not be applicable for these alternative support technologies. Therefore, with so many options to consider and the importance of achieving adequate ground control at minimal cost, the trial and error approach to longwall gate road support is no longer prudent. This paper discusses a design methodology for standing secondary tailgate supports. This design technique requires in-mine measurements of tailgate support loading and convergence to establish a tailgate ground reaction behavior based on the support and strata interaction. The methodology uses the performance characteristics generated in the National Institute of Occupational Safety and Health (NIOSH) Mine Roof Simulator (MRS) to match the stiffness and load characteristics of various supports to the measured ground reaction behavior. It can be used to determine the appropriate application of alternative roof support systems or to design in-mine trials such that a fair and equitable comparison of different support systems can be made. A case study of the methodology at a western Pennsylvania mine site is presented in the paper, including a comparison of four alternative support technologies to conventional wood and concrete cribbing historically used at this particular mine.

INTRODUCTION

The longwall tailgate support system must flawlessly control the tailgate ground conditions. Safety considerations, especially the limited escape routes from a longwall face, demand that the tailgate entry be a negotiable travelway. The location of the face electrics, support equipment, and belt line in the head gate entries dictate that the tailgate may be the only option for mine workers to escape from the face in the event of an emergency. A recent example is the longwall gob fire which occurred at a mine in Utah this past year (1998) in which several miners evacuated through the tailgate entry to safety. In addition to the emergency travelway requirements, inadequate tailgate support that results in poor ground control and blocked tailgates due to roof falls can severely retard or halt production. The heavy reliance by mines on the longwall production for survival dictates that loss of production for protracted time periods cannot be tolerated. Ventilation is another issue that depends on proper tailgate support. As the panel lengths continue to increase, excessive closure or restriction of the tailgate entry by the deformation and/or density of the standing support can be problematic and potentially unacceptable. In gassy mines, it also may be required that the tailgate be kept open inby the longwall face in order to establish effective bleeder ventilation of the tailgate area. Another important issue to consider is the material handling aspects of tailgate supports. Therefore, the onus is on the mine engineers to design a support system that maintains adequate control of the tailgate ground conditions at all times and with minimal ventilation resistance and material handling considerations.

Historically, the importance of ground control has led to very conservative applications of tailgate support. Most mines use conventional wood crib structures. When properly designed, conventional wood cribs provide effective ground control in most longwall tailgate entries, and in the past have been cheap enough that mines could afford to use a high density of cribs at relatively little cost. However, increasing timber costs, inconsistent timber quality that led to poor crib performance, and inadequate supplies of timber for western mines have reduced the advantages of conventional wood cribbing, and have encouraged many mines to consider other options for tailgate support. All of these factors have prompted the support manufacturers to develop innovative support technologies as alternatives to conventional wood cribbing.

Today, there are several alternative support technologies that have been developed by various support manufacturers and safety tested at the NIOSH Safety structures Testing Laboratory, whereby their performance characteristics have been determined. With increasing pressures to reduce support costs while ensuring the safety of the mine workers, mine operators more than ever before are looking for ways to optimize longwall tailgate support. Since the performance characteristics of these supports are unique, the best practices that have been developed largely through trial and error with conventional wood cribbing may not be applicable for these alternative support technologies. In addition, these new supports have limitations, which if not properly recognized, can lead to poor support application and inadequate tailgate ground control.

Therefore, with so many options to consider and the importance of achieving proper ground control at minimal cost, the trial and error approach to longwall tailgate support can be costly and indecisive. This paper proposes a design philosophy for longwall tailgate secondary support whereby the ground reaction behavior, as a function of the support load density and stiffness of the support system, is determined by measurement of underground support loading and roof-to-floor convergence. The goal of support design is then to optimize the use of the support by designing to the ground reaction curve, and controlling the convergence to acceptable limits that will ensure stability of the mine roof. This approach will allow mine operators to maximize the use of alternative support systems while ensuring the safety of the mine workers by avoiding risky and time consuming trial-and-error assessments of support technologies. In addition, it will provide MSHA with a means to assess various support systems on an equivalent basis when approving roof control plans. A case study is included in the paper which relates the use of the proposed design methodology to a trial of alternative support technologies at a western Pennsylvania longwall mine operating in the Pittsburgh coal seam.

TERMINOLOGY

Secondary Support - Secondary support is that which is intentionally added to assist the primary support (roof bolts) in controlling the mine roof when it is known that additional roof loading will occur. In longwall mining, it is installed in advance of the abutment loading. Secondary support is not to be confused with supplemental support which is additional support, that is installed beyond the primary and secondary support either for insurance purposes or in response to unanticipated poor ground conditions.

Ground Reaction Curve - A concept of how the ground reacts to the presence of a newly created opening. Specifically, as the ground deforms and sheds load to other structures, there will be a proportional decrease in roof loading and required support capacity to maintain equilibrium of the mine roof and floor.

Critical Convergence - In relation to the ground reaction curve, the critical convergence is where failure of the ground is inevitable, and the full weight of the failed rock mass above the mine entry must be supported by the secondary roof system to prevent a roof fall from occurring. The goal of secondary support design is to prevent this convergence from occurring.

Support Load Density - The load carrying capacity of an installed support system per unit area of exposed ground (tons/sq ft.) at a particular ground deformation.

Minimal Acceptable Support Load Density - Lowest load density of support that should be provided since a lower support load density will allow convergence greater than the critical convergence and thereby allow failure of the roof rock to occur that may lead to a roof fall.

Support Density - Term typically used to refer to the number of supports per unit area. Should not be confused with support load density, which is the capacity of the support system per unit area as a function of convergence.

Support Stiffness - A measure of how quickly a support develops its load carrying capacity in relation to convergence. For an individual support, stiffness can be determined from the slope of the load-deformation performance curve. "Softer" supports have a flatter slope than "stiffer supports" when plotted to the same load-displacement scale. Softer supports require more convergence to develop an equivalent load carrying capacity than stiffer supports.

Support System Stiffness - The resistance to load of a group of supports. The system stiffness is the sum of the individual support stiffness. Hence, a double row of supports would have twice the system stiffness of a single row of the same supports.

KEY FACTORS TO CONSIDER IN GATE ROAD SUPPORT

A design philosophy for standing supports must be based on the interaction of the support with the surrounding rock mass. The question that needs to be addressed to formulate a design methodology is to determine to what extent the support system is controlling the ground. To do this it is necessary to understand both the ground behavior and the characteristics of the individual support and the support system.

Understanding the Function of the Support System

Obviously, the support system is employed to prevent roof falls. How this is accomplished is the important issue. While secondary supports provide the last means of support in the event there is roof failure above the bolted horizon, the primary function of the secondary support system is to assist the primary support system in maintaining the integrity of the immediate roof. As the ground deforms by the creation of an opening due to mining, it gradually sheds load to the surrounding mine structures, which in the case of longwall mining are the gate road pillars and longwall panel. Secondary support must be placed in sufficient time and develop sufficient capacity to bring deformation of the ground into equilibrium before a critical deformation is reached at which point failure of the ground is inevitable. Otherwise, the secondary support will be required to carry the entire dead weight of the detached rock mass to prevent a roof fall from occurring. This embodies a fundamental concept in rock mechanics known as the "ground reaction curve"(*1*).

In longwall mining, the tailgate entry is subjected to three phases of loading and equilibrium. Each will have a distinct ground reaction curve. The first phase occurs on development where the mine opening is created and the primary support (roof bolts) are installed. Relatively little ground movement occurs during this phase since the development loads are small and the primary support is sufficient to provide equilibrium. The next phase is adjacent panel mining. The future tailgate is subjected to side abutment loading, and while secondary support is typically installed to ensure that equilibrium of the rock mass is obtained, the convergence is typically minimized by the load density of the support. The final phase of tailgate behavior is where the active tailgate is subjected to front abutment loading from the panel extraction. It is this phase where the secondary supports play their most important role in preserving the stability of the entry. A hypothetical tailgate ground reaction curve is shown in figure 1. It should be noted that the ground reaction curve will be a function of the several factors in addition to the load density of the support system. These include the geology, roof spans, vertical as well as horizontal stress around the opening, and some time dependent factors such as creep. Hence, the ground reaction curve is generally unique to a specific mine and can change within the mine as these factors change. From the perspective of secondary support design, it is important that the ground reaction curve be examined under the worst case load conditions where ground control is required. Since the ground reaction is dependent upon roof span, a different ground reaction behavior will typically be observed in intersections compared to the non-intersection areas of the entry. Hence, the support design must be altered for the intersections to accommodate this difference in ground reaction.

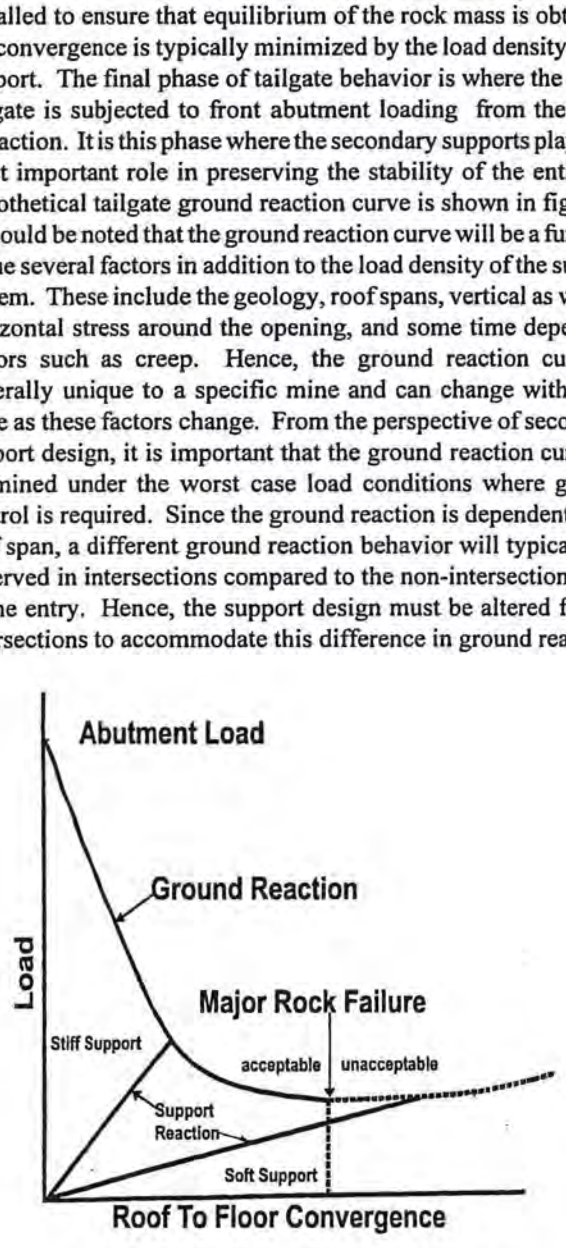


Figure1. Ground reaction curve concept.

It is seen from the hypothetical tailgate ground reaction curve (figure 1) that if the goal is to prevent convergence completely, then the full abutment load must be resisted by the support system. This resistance for all practical purposes cannot be obtained by the installation of secondary support since the required capacity would need to be equivalent to that of all the coal that was removed by the mining process. The support capacity required to achieve equilibrium is reduced as the deformation increases, since the roof is shedding load to other mine structures as it deforms. In other words, by allowing the roof to deform and shed some load to the coal pillars and longwall panel, less support capacity is required since the roof load is decreased. Hence, the lowest required support capacity would be one that is developed just before the critical roof deformation occurs where failure of the immediate roof is fast approaching. However, designing to this lower limit of support capacity leaves no margin of error in the event that load conditions worsen. Also, it can be seen that if a support system is too soft (develops load carrying capacity too slowly), equilibrium of the mine roof will never be achieved and failure of the roof will be inevitable.

In summary, since most standing supports are passive supports, convergence must take place before sufficient support loads are developed to provide equilibrium. While some supports have active loading capability, the magnitude of active loading is not sufficient to achieve equilibrium or the active loading cannot be maintained indefinitely. The supports must be loaded in compression to provide the required load resisting forces to achieve equilibrium of the rock mass. The amount of convergence required to produce equilibrium is then a function of the stiffness of the support system. Equilibrium will be achieved at less displacement for a stiffer support system since the support resistance to roof loading will develop quicker (at less displacement) compared to a softer support system. Hence, as the support load resistance (load density) of a support system increases, the convergence at which equilibrium is attained will decrease. If too much convergence is permitted to occur by utilizing too soft of a support system, failure of the rock mass (mine roof) will be inevitable. Hence, the goal of support design is to provide sufficient support stiffness to ensure that the required support capacity to achieve equilibrium of the rock mass occurs before the rock mass deforms to the point of failure. However, a prudent mine engineer would ensure that sufficient support capacity is developed long before the critical convergence is reached. Since minimizing convergence is achieved by increasing the support capacity (load density) and generally the cost of support, the goal of optimizing the support selection is not to install more support than is necessary to provide a reasonable margin of safety to prevent roof failure.

Understanding the Performance Characteristics of the Support

The load-displacement characteristics of numerous roof support technologies have been determined at the NIOSH Safety Structures Testing Laboratory through full scale testing in the unique Mine Roof Simulator load frame (*2*). The load-displacement response of these various support systems are documented in figures 2 through 7, grouped by the following description of the support type: (a) conventional wood cribbing (figure 2), (b) engineered wood crib supports (figure 3), (c) conventional and engineered timber post supports (figure 4), (d) non-yielding concrete supports (figure 5), (d) deformable concrete supports (figure 6), and (e) yielding steel supports (figure 7).

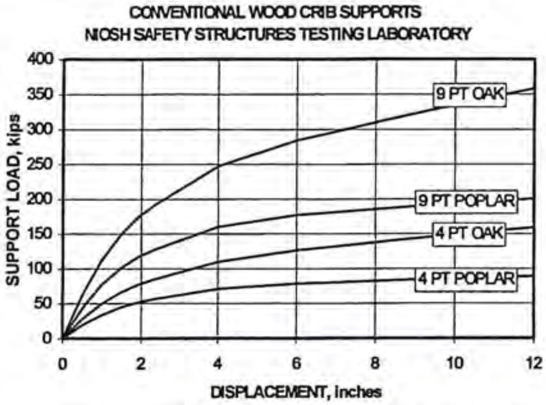


Figure 2. Load-displacement performance data for conventional wood crib supports.

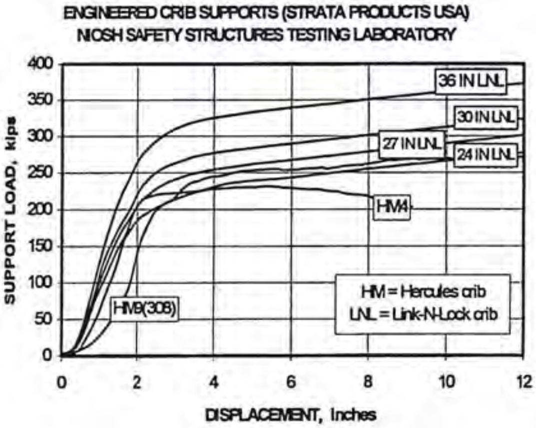


Figure 3. Load displacement performance data for engineered wood crib supports.

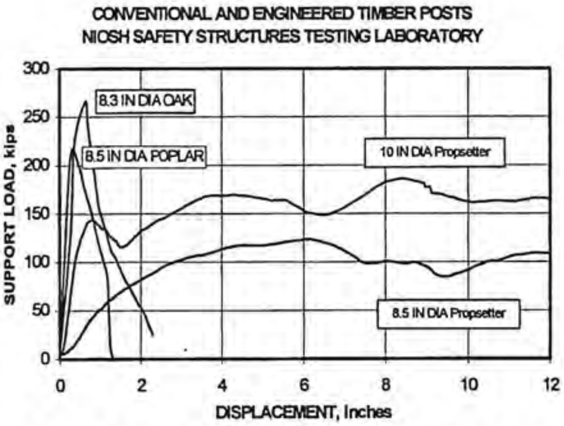


Figure 4. Load-displacement performance data for conventional and engineered timber props.

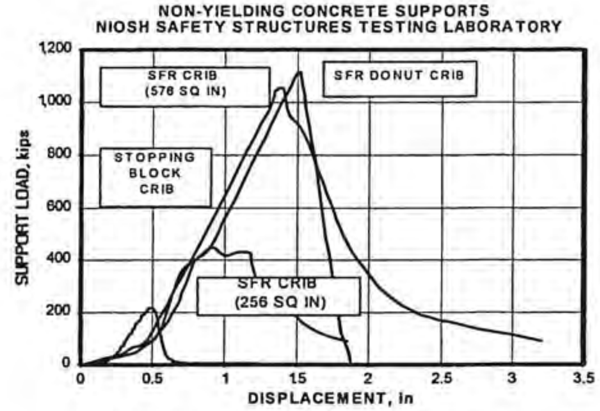


Figure 5. Load-displacement performance data for non-yielding concrete support.

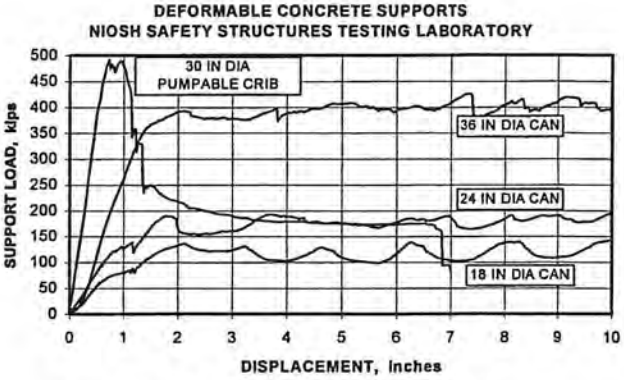


Figure 6. Load-displacement data for deformable concrete supports.

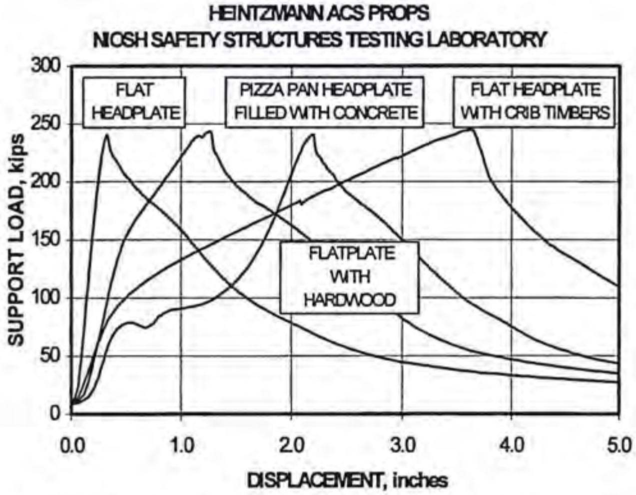


Figure 7. Load-displacement performance data for yielding steel supports.

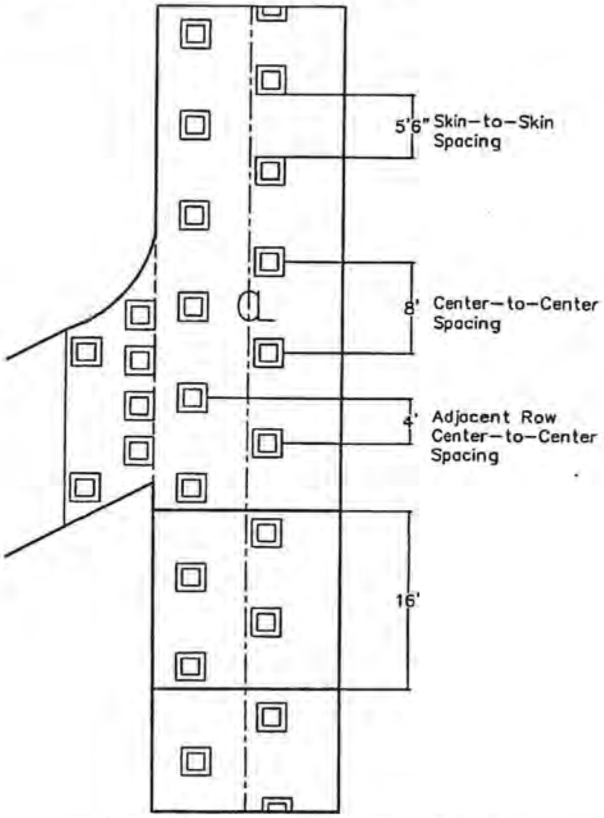
As previously indicated, all secondary supports must be loaded in compression to produce the required capacity to achieve equilibrium of the mine roof. In other words, the roof has to move down before the standing support develops sufficient load carrying capacity to achieve equilibrium of the mine roof and floor. Since it is this very downward movement of the roof that we are trying to control, the most important design parameter for standing supports is the stiffness of the support system. Stiffness is simply a measure of how quickly a support develops its load carrying capability in response to convergence of the mine roof and floor. Stiffer supports develop equivalent load carrying capacity with less displacement than softer support systems.

While the stiffness of the support is the primary design parameter, it is not the only issue to consider in the support application. Another important design parameter is the load carrying stability of the support. More specifically, it is important to know how well the support can sustain its load carrying capability as a function of convergence. Stiff supports, such as the non-yielding concrete supports (figure 5), which develop load carrying capacity quickly but fail at little convergence are not practical in many longwall tailgate applications. In order to keep such supports from failing prematurely, a large number of supports must be installed, such that the roof loading is sufficiently shared among several supports, while achieving a high enough load density to keep the convergence below the failure point for any one support.

The ideal support is one that the support stiffness can be controlled through the support design so that the support capacity at a given displacement can be engineered to match the ground reaction behavior. Furthermore, the ideal support would be able to maintain this capacity through a wide range of displacements without shedding load or failing prematurely, and therefore provide a margin of safety in the event that ground conditions worsen unexpectedly.

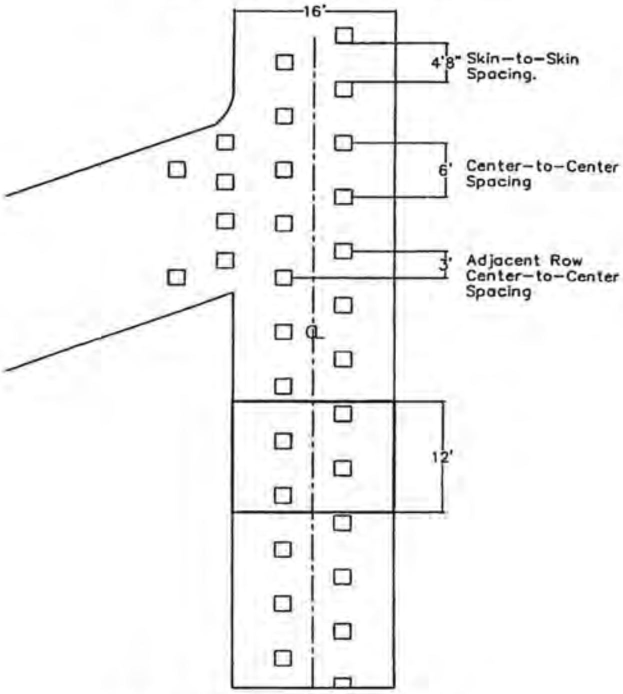
MEASUREMENT OF THE GROUND REACTION CURVE AT A WESTERN PENNSYLVANIA MINE

Studies were made at a longwall mine operating in the Pittsburgh coal seam in western Pennsylvania. The mine has historically used a staggered double row of 4-point wood cribs on a 4 ft spacing between supports in adjacent rows (figure 8) for longwall tailgate support. Due to uncertainties and inconsistent timber qualities, the mine also employed concrete cribs constructed from normal mine ventilation stopping blocks which were also employed in staggered double row arrangement as shown in figure 9. Since the stiffness of these two supports are significantly different (figures 2 and 5), and the supports were employed in a similar arrangement, a ground reaction curve was determined for this particular mine by measurement of the load on individual supports and the associated roof-to-floor convergence in the vicinity of the supports. The results are shown in figure 10.



Average Load on Wooden Cribs = 40 Tons
Support Load Density = $\frac{4X40}{16X16}$ = .0625 Tons/Sq. Ft.

Figure 8. Arrangement of 4-point wood cribs in a western Pennsylvania mine.



Average Load on Concrete Cribs = 65 Tons
Support Load Density = $\frac{4X65}{16X12}$ = 1.35 Tons. Ft

Figure 9. Arrangement of stopping block concrete crib support in a western Pennsylvania mine.

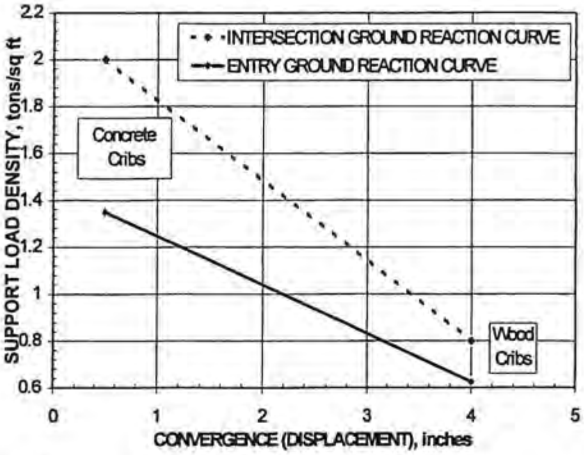


Figure 10. Measured ground reaction curve for western Pennsylvania coal mine.

First, it is important to note where these measurements were obtained. Since, the abutment loading changes dramatically in longwall mining as the face approaches, the ground reaction curve should always be established at the most severe load condition, which generally will be just behind the tailgate shield. In this case, the mine wanted to maintain sufficient control of the tailgate entry to maintain a ventilation air way back to the next open cross cut. Hence, measurements of support loading were obtained to distances of 50 to 100 ft inby the face. For reasons previously explained, a different ground reaction was measured through the intersections compared to the entries (figure 10). These measurements were also made under the deepest cover, again to establish the worst load condition.

The following analysis applies to the entries at positions where there was no influence of the crosscuts. The load on the 4-point wood cribs was estimated at 40 tons with a roof-to-floor convergence of 4 inches. Qualitatively, it was noted that the integrity of the immediate roof was showing signs of deterioration at this convergence, which suggests that 4 inches is approaching the critical convergence where failure of the roof is inevitable. Some of the wood cribs in the area were also showing signs of premature failure, probably due to poor timber quality. Conversely, the convergence in the concrete crib supported area was only 0.5 inches and the measured load on the cribs was 62 pct greater at 65 tons per crib. These support loads are converted into a support system load density of 0.625 tons per square foot for the wood cribs (equation 1) and 1.35 tons per square foot for the concrete stopping block cribs (equation 2).

$$\text{LOAD DENSITY (Wood Cribs)} = \frac{4 \text{ Cribs} \times 40 \text{ tons/Crib}}{16 \text{ ft} \times 16 \text{ ft}} = 0.625 \text{ tons/sq.ft.} \qquad (1)$$

$$\text{LOAD DENSITY (Concrete Cribs)} = \frac{4 \text{ Cribs} \times 65 \text{ tons/Crib}}{16 \text{ ft} \times 12 \text{ ft}} = 1.35 \text{ tons/sq.ft.} \qquad (2)$$

These two data points are then used to establish the ground reaction curve for the tailgate entry inby the longwall face as depicted in figure 10. Since measurements were made on only these two support systems, a linear approximation to the ground reaction curve is made using these data as end points with a straight line connecting between them. This curve can then be used to determine the support load density required to control the convergence inby the longwall face from 0.5 to 4.0 inches. For example, if the goal is to limit the convergence to 2 inches, then drawing a line from 2 inches vertically upward until it intersects the ground reaction curve, and then drawing a line horizontally to the y axis, reveals that a support load density of 1.04 tons per sq ft must be provided. An algebraic solution to the problem can also be found by determining the slope and y-intercept for the ground reaction curve. Once the algebraic equation for the line is determined, the support load density at any displacement can be calculated.

$$\text{Load Density (2 in convergence)} = -0.20171 \times 2.0 + 1.45 = 1.04 \text{ tons / sq ft} \qquad (3)$$

The next requirement is to transform the required support load density into a support system design. Support load density is determined primarily by two factors: (1) the stiffness of each support and (2) the spacing of the supports. Continuing with our example, if we want to increase the support load density of the 4-point wood crib support system from its current 0.625 tons per sq. ft. to 1.04 tons per sq. ft. in order to reduce the convergence in the entry from 4 inches to 2 inches, then we would need to decrease the spacing of the wood cribs from the current 4 ft spacing, but the question is by how much? The required center-to-center spacing to provide a support load density of 1.04 tons/ sq. ft. can be determined by first identifying the load capacity of a wood crib at 2 inches of convergence, which is found from the performance data developed from the laboratory tests conducted in the Mine Roof Simulator (figure 2). As shown in figure 2, the capacity of a 4-point wood crib is 27 tons at 2 inches of displacement. The spacing of a single row of cribs is then determined by dividing this capacity by the product of the required support load density and the entry width. As the following analysis shows, the required spacing of 4 point wood cribs to achieve a 1.04 tons per sq. ft. support load density is 1.6 ft. Such a tight spacing can only be achieved through a staggered double row arrangement, where the center-to-center spacing in each row is 3.2 ft.

$$\text{Spacing (2 inches convergence)} = \frac{\text{Capacity (2 inches)}}{\text{Load Density} \times \text{Entry width}} = \frac{27}{1.04 \times 16} = 1.6 \text{ ft} \qquad (4)$$

DESIGN METHODOLOGY FOR LONGWALL TAILGATES

The concept examined for the western Pennsylvania mine can be generalized and employed at any mine to optimize secondary support design and application. The first step in the design process is to determine the ground reaction behavior. This can be done by installing at least two, and preferably three, support systems of ***varying*** support system stiffness, and measuring their loading and corresponding convergence of the mine roof and floor. It is important that these supports cover a wide range of stiffness to provide a ***full picture*** of the ground reaction behavior. As part of this process, an effort should also be made to determine the critical roof-to-floor convergence where roof failure occurs, since this will be a critical design value for the support design. However, in order to do this, a low density support system must be installed that will allow considerable convergence to occur. Since this poses a risk of inadequate ground control, precautions should be taken. One possibility is to set additional wood cribs through this trial zone with the top layer removed such that they could be reinstalled to provide additional support if necessary, or in the worst case provide ground support after the roof deforms (5-6 inches) to the cribs if they cannot be topped off.

Altering the support system stiffness can be done several ways. One way is to utilize the same support and same spacing down the entry, but increase the number of rows of support across the mine entry from one to two to three, which would proportionally increase the system stiffness by the same factors. Another way is to keep the spacing and number of rows of support constant, but use supports of varying stiffness. This will eliminate the impact of both span and roof coverage issues, which can be limiting factors in the support placement (load deformation) strategies. For example, using conventional wood cribs, the support construction could be varied from a 4-point to a 9-point to a 16-point crib. The support load density would increase in direct proportion to the increase in support stiffness. Adjusting the support spacing down the entry can also be considered. The support load density is proportionally increased as the spacing is decreased. Care should be taken to avoid excessive spacing that will cause span related problems. A good rule of thumb is that the support spacing should not exceed half the entry width. The load bearing area (quality and extent of the contact area) of the support also an important factor to consider. The pressure exerted by any support should not exceed the strength of the mine roof or floor.

Ideally, the loads should be measured underground on the various support systems. Support load measurements are typically made through a hydraulic flat jack. This will be more difficult to do on some support designs than others. Supports with a single contact area, such as concrete cribs are easier to work with than something like a conventional wood crib which has multiple load paths. Theoretically, if loads cannot be measured, they can be estimated directly from laboratory load-displacement data provided convergence (support displacement) measurements are made. However, this estimate may not be accurate for materials such as wood where creep can occur and distort the approximation of load that produced the measured displacement. Measurements of convergence are essential to this design methodology. Roof-to-floor convergence measurements can be made in several ways, but it is important that these measurements correlate to displacements induced in the support structure.

Readings of load vs displacement (convergence) should be made under the most severe load conditions that occur. For most longwall mines, this will be at the back of the tailgate shield. If it is critical that the tailgate be kept open inby the face for ventilation reasons, then ideally the load - displacement readings should be made inby the face. Of course, this may not be as easy to do, but it is important to realize that the design methodology assumes worst case load conditions, and safety factors will need to be employed if measurements are taken under less severe load conditions. Another good rule of thumb to follow is that the face should be retreated a distance approximating the width of the face before the full ground reaction behavior is established. In other words, if the face width is 1,000 feet, then the face should be retreated at least 1,000 feet before the ground reaction behavior is measured. Of course, the first requirement for any tailgate design is proper pillar design. While in theory a ground reaction behavior can be determined for any pillar design and roof geology, the methodology proposed here assumes that the pillar design falls above the ALPS design line for a given CMRR (*3*).

The load-displacement data is then used to generate a plot of support load density as a function of convergence (ground reaction curve). Each support type with different stiffness represents one data point on the ground reaction curve. The support load density is determined as the measured load in the support at the observed convergence times the number of supports per unit area of mine entry (equation 5). For a single row of supports employed on a constant center-to-center spacing, the support load density can be determined by equation 6.

$$\text{Support Load Density} = \frac{\text{Number Supports} \times \text{Support Load}}{\text{Area Of Support Coverage}} \quad (5)$$

$$\text{Support Load Density} = \frac{\text{Support Load}}{\text{Center - To - Center Spacing} \times \text{Entry Width}} \quad (6)$$

Once the ground reaction curve is developed, the center-to-center spacing (down the mine entry) of alternative support systems employed in a single row arrangement required to achieve ground control (equilibrium) at a desired convergence can be determined from equation 7. The center-to-center spacing of a double row of supports is simply twice that of a single row arrangement.

$$\text{Spacing (displacement)} = \frac{\text{Capacity (displacement)}}{\text{Load Density} \times \text{Entry Width}} \quad (7)$$

where Spacing(displacement) = Center-to-center spacing in feet of a single row of supports;

Capacity (displacement) = Individual support capacity in tons at a specified displacement (obtained from laboratory performance data) equal to the desired convergence control;

Support load density = Support load density in tons per sq. ft. at the required convergence (obtained from ground reaction curve);

Entry Width = Width of the entry in feet.

This design methodology is a valuable tool in optimizing the utilization of standing secondary roof support technology. However, as previously described it is still up to the mining engineer to decide how close to the critical convergence he/she wants to operate based on their knowledge of the particular ground conditions. A margin of safety is provided by designing for a convergence that is less than the critical convergence (minimal acceptable support load density). In order to make equivalent comparisons of alternative support systems, a safety factor can be quantified by comparing the design support load density to the minimal acceptable support load density which will be representative of the maximum allowable (critical) convergence. This is referred to as the ground reaction curve (GRC) safety factor (equation 8).

$$\text{GRC Safety Factor} = \frac{\text{Design Load Density}}{\text{Minimal Acceptable Load Density}} \quad (8)$$

Another factor to consider is whether the support is being fully loaded and how much reserve capacity is left in the support at the design load. In the event that load conditions worsen beyond expectations, this reserve support capacity may be needed to support the mine roof. If the support characteristic is such that the support sheds load quickly after reaching its peak load, such as the non-yielding concrete supports (figure 5), then consideration must be given to avoid designing near the peak loading capability of the support. A safety factor for the support can be defined based on the support loading at the required support load density in relation to the peak loading capability of the support (equation 9). Hence a safety factor of 1 indicates that there is no reserve capacity available and a safety factor of 2 indicates that the support is loaded to only 50 pct of its maximum support capacity.

$$\text{Safety Factor (Support)} = \frac{\text{Peak Load Capability}}{\text{Load at Installed Load Density}} \quad (9)$$

ALTERNATIVE SUPPORT STUDIES AT THE WESTERN PENNSYLVANIA MINE

Four different standing support systems and one cribless system in addition to conventional 4-point wood crib supports and concrete stopping block supports were installed in the longwall tailgate entry of this mine. The alternative standing supports were: (1) Heintzmann Corporation's Alternative Crib Supports (ACS's); (2) HeiTech Corporation's Pumpable Crib Supports; (3) Strata Product's Propsetters; and (4) Burrell Mining Products "The Can". Cable trusses were used in the cribless area. The alternative supports were assigned sections of the tailgate in between the standard wood cribbing. This was done to ensure that there was no interaction between support installations, thereby allowing a fair and equal evaluation to be made (i.e., normal cover, no excessive roof or floor damage, normal geology).

Table 1 shows the installed spacing of the alternative support systems and the typical 4-point wood crib system and concrete stopping block crib system. The support load density of the alternative supports is calculated by matching system performance to the ground reaction curve. Essentially, this requires working backwards through the design methodology. The following steps can be used.

1. Pick an arbitrary convergence within the bounds of the ground reaction curve.
2. Determine the required support load density that matches the ground reaction curve for this convergence.
3. Identify the individual support capacity at this displacement from the laboratory performance data at this convergence.
4. Determine the support load density from equation 6.
5. If the support load density is greater (falls above the curve) than the required support load density - pick a lower convergence, or if the support load density is less (falls below the curve) than the required support load density - pick a higher convergence, and repeat steps 1 through 4 until the support load density matches the ground reaction curve.

An analysis of table 1 reveals that all four alternative support systems were installed with sufficient support load density to control the convergence well below the critical level of 4.0 inches that the 4-point wood cribs provided. The high safety factor utilized in these alternative support applications was to provide a margin of safety in anticipation of a tailgate horizontal stress concentration on the next panel.

Table 1. Assessment of standing alternative support technologies utilized in study at a western Pennsylvania. mine.

Support System	Installed Spacing, ft	Installed Load Density, tons/ft^2	Conv. control inches	Safety Factors		Observed Roof Condition	
				GRC[1]	Support[2]	Outby face	Inby face
4-Point Wood Crib	8 ft (DR[3])	0.625	4.0	1.00	1.8	Good	Marginal
Concrete Stopping Block Crib	3 ft (DR)	1.35	0.5	2.16 (0[4])	1.0	Good	Marginal
Heintzmann ACS	5.0 (DR)	1.20	1.24	1.92	2.5	Excellent	Good
HeiTech Pumpable Concrete Crib	9.2 (SR)	1.35	0.5	2.16	1.3	Excellent	Excellent
Strata Products Propsetter	4.0 (DR)	1.12	1.6	1.79	1.7	Excellent	Good
Burrell Mining Products Can Support	7.0 (DR)	1.19	1.25	1.90	1.8	Excellent	Excellent

[1] Ground Reaction Curve safety factor is determined from equation 8 as the ratio of the installed support load density to the minimum allowable support load density.

[2] Support safety factor is determine from equation 9 as the ratio of the peak loading capability of the support to the load developed at the installed spacing.

[3] DR stands for double row of cribs. All double rows of supports were installed in a staggered fashion. The spacing here refers to the spacing of one row of supports. With the staggered arrangement, the spacing between adjacent supports of both rows is half of that of the individual row (see figure 8 or 9). SR refers to a single row arrangement.

[4] The roof condition was good prior to the failure of the support. Hence, the installed support load density actually dropped to zero once the support failed and accounted for the deterioration in the integrity of the roof.

The HeiTech pumpable support had the highest load density at 1.35 tons per square foot which limited convergence to approximately 0.5 inches. Conditions both inby and outby the face as shown in figure 11 were excellent with the Heitech pumpable support system. However, it should be noted that the Heitech support also had the lowest support safety factor (1.3) of the four alternative support systems utilized, meaning that load development approached the peak loading capability of the support. If the maximum loading capability of the support was exceeded due to unexpected additional roof loading or variability in the peak strength of the support, the convergence would increase to approximately 4 inches at the installed spacing based on the residual support capacity of approximately 90 tons. Since this is the critical convergence for this mine at which point roof conditions deteriorate significantly, it is critical that the peak pumpable support capacity not be exceeded through the zone where it is desired to maintain full roof control, which means that the spacing must be properly maintained during installation so as not to overload the support past failure.

Figure 11a. Outby area supported with pumpable crib.

Figure 11b. Inby area supported by pumpable crib.

The Propsetter support had the lowest margin of GRC safety at 1.79, but even this system is conservatively applied in that the convergence was limited to 1.6 inches. Conditions outby the face were excellent as shown in figure 12a and relatively good inby the face (figure 12b). Some of the Propsetter supports well inby the face mostly in the intersection areas (figure 12c), appeared to be in a state of post-yield deformation where "brushing" (yielding) caused the props to tilt from a vertical orientation, which is normal for this load condition. It does not mean that the prop is shedding load. Another possibility is that the props were being dislodged or moved laterally by flushing of the gob material, floor heave, and/or lateral displacements of the roof relative to the floor by the cantilevered roof beam. Despite these occasional abnormalities in the support condition, the Propsetter was able to maintain an effective air way beyond the first open cross cut inby the face. It was also reported by the mine that 5 or 6 Propsetters were dislodged from the mine roof and floor outby the face. Since convergence was minimal outby the face, the cause of these props "falling over" was never definitively determined. The same props were reinstalled and performed well throughout the duration of the test area.

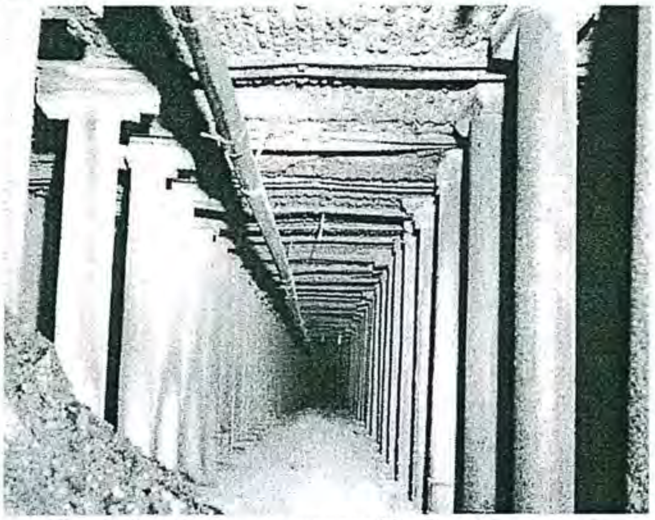


Figure 12a. Outby area supported by Propsetter support.


Figure 12b. Inby area supported by Propsetter support.


Figure 12c. First open cross cut intersection inby the face supported with Propsetter supports.

The Heintzmann ACS support had the most limited yield capability of the four alternative support technologies used at this mine. The ACS also sheds load rather quickly after reaching its peak loading capability at about 2.2 inches (figure 7). However, the installed spacing provided the highest support safety factor (2.5), meaning the loads were kept well below the peak capacity of the support. Likewise the installed load density limited the convergence to 1.2 inches, which is considerably less than the yield point of 2.2 inches. Hence, this is a good example of how a stiff support with limited yield capability can provide effective ground control in a longwall tailgate, provided that a sufficient number of supports are installed per unit area to establish a high enough load density to minimize the ground movement. Figure 13 shows the condition of the entry both outby and inby the face in the area supported by ACS's. Similar to the Propsetter support, a few of the ACS props were tilted inby the face, but continued to provide support capability in this condition without becoming unstable.

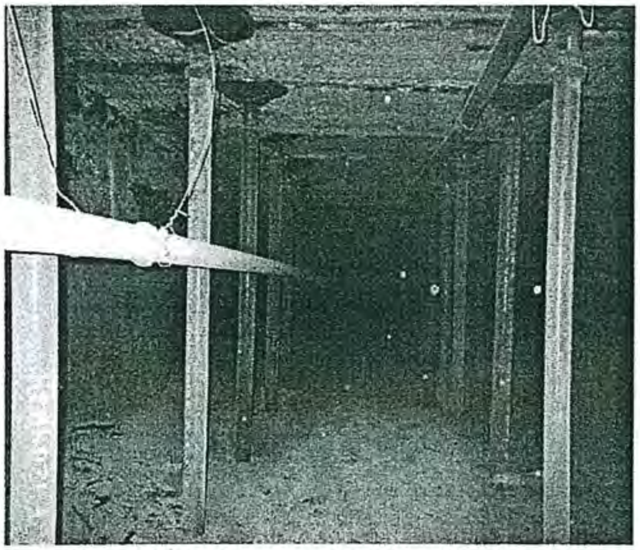


Figure 13a. Outby area supported by ACS supports.

Figure 13b. Inby area supported by ACS supports.

The Burrell Can support installation had a GRC safety factor (1.92) almost identical to that of the Heitzmann ACS supported area. The 1.92 GRC safety factor means that the installed load density is almost twice that needed to prevent roof failures from occurring. The entry conditions, both inby and outby the face were excellent with the Can support as shown in figure 14. Inby, the conditions were slightly better than in the ACS area. This improvement is attributed to the larger surface coverage and improved stability of the Can support compared to the ACS.

Figure 14a. Outby area supported by the Can Support.

Figure 14b. Inby area supported by the Can Support.

Once the ground reaction curve is determined, applications of any other support technology can be defined by strategic employment strategies relative to the ground reaction curve. Table 2 shows alternative placement strategies for these and other alternative support systems for this particular mine site based on the measured ground reaction behavior with conventional wood and concrete support systems.

Examining table 2 reveals that other support technologies could be favorably used in this application. One example is the Link-N-Lock crib support developed by Strata Products. A 24-inch Link-N-Lock crib could be installed in a staggered double row with a center-to-center spacing of 11 feet per row (5.5 feet between cribs in opposite rows) and limit the convergence to 2 inches. Another alternative would be a single row of 36-inch Link-N-Lock cribs on an 8-foot center-to-center spacing, which also would limit the convergence to 2 inches. In contrast, a single row of 9-point cribs would have to be installed on a 5.2 ft center-to-center spacing to provide equivalent ground control capability.

Three other points can be made by examining the data in table 2. First, the spacing of stiff, high capacity support systems can become excessive at large displacements. It is important to remember that the ground reaction behavior was measured in the immediate vicinity of secondary support. It is assumed that the support loading is sufficiently transferred to control the roof and floor between the supports. Obviously, there are some limitations to this capability, which largely depend on the strength of the immediate roof. Generally, stronger roofs can span greater distances between supports than weaker roof. Currently, this capability is best obtained from empirical data within the mine, but a good rule of thumb to follow in the absence of this information is that the span between supports should not exceed half the entry width, particularly in weak roof conditions such as those observed in the Pittsburgh coal seam. Using this criteria, it is seen from table 2 that 9-point cribs and Link-N-Lock cribs must be employed at a load density greater than 0.63 tons per sq ft to avoid an excessive spacing where failure might occur between the cribs. Surface control of the immediate roof is another issue. Surface control refers to failure of the immediate skin of the roof. This is different from the excessive spacing issue discussed above in that there is no major failure of the roof rock. If surface control is necessary to prevent flaking of the roof skin between cribs, then methods such as wire meshing can be effectively employed as a control measure.

Second, it is seen from table 2 that stiff concrete supports must be installed at a high enough support load density to limit the convergence to less than 2 inches, otherwise the supports will fail prematurely, resulting in no support capability and unstable ground conditions after failure of the support. Thirdly, it is seen that required load density to limit convergence below 1 inch is not practical with the passive wood crib supports including the stiffer Link-N-Lock cribs. Wood is just too soft to generate meaningful loads at such small displacements.

Table 2. Recommended placement and safety factors for alternative support technologies.

	Center to center support spacing & individual support capacities at convergences of 0.5,1, 2, and 4 inches.							
SUPPORT SYSTEM	**0.5 INCH (LD =1.35) (SF =2.16)**		**1 INCH (LD = 1.24) (SF = 2.0)**		**2 INCHES (LD = 1.04) (SF = 1.7)**		**4 INCHES (LD = 0.63) (SF = 1.0)**	
	Load (tons)	Space (ft)	Load (tons)	Space (ft)	Load (tons)	Space (ft)	Load (tons)	Space (ft)
4-Point cribs	8	0.7	17	0.9	27	1.6	39	3.9
9-Point cribs	14	0.6	55	2.8	86	5.2	115	11.4
24-inch Link-N-Lock	10	0.5	45	2.3	92	5.5	115	11.4
27-inch Link-N-Lock	11	0.5	49	2.5	102	6.1	127	12.6
36-inch Link-N-Lock	13	0.6	63.5	3.2	132	8.0	162	16.1
Propsetter (8.5 in dia)	12	0.6	25	1.3	42	2.5	57	5.7
Stopping block cribs	65	3.0	0	N/A	0	N/A	0	N/A
SFR Donut Cribs	86	4.0	280	14.1	0	N/A	0	N/A
SFR Block (2 per layer) crib	85	4.0	210	10.6	0	N/A	0	N/A
HeiTech Pumpable Crib	190	8.8	240	12	112	6.7	90	8.9
Burrell Can (24 in dia)	40	1.9	65	3.3	90	5.4	90	8.9
Heintzmann ACS (100 ton)	39	1.8	46	2.3	102	6.1	36	3.6

Note: N/A indicates that the support fails prior to the designated convergence and does not have sufficient post failure (residual) capacity to be considered for application in this condition. LD designates the support load density of a single row of cribs on the designated center-to-center spacing. Likewise, SF refers to the GRC Safety Factor as computed by equation 8 for a single row of cribs. If two rows of supports are utilized, the designated spacing at a specific displacement would be reduced by a factor of 2 and the safety factor would be increased by a factor of 2.

OTHER CONSIDERATIONS IN TAILGATE SUPPORT SELECTION AND APPLICATION OF THE PROPOSED DESIGN METHODOLOGY

While the primary consideration in support design is obviously the prevention of roof falls through proper ground control, there are other factors to consider. These include: (1) the cost of the support, (2) material handling requirements and ease of installation, and (3) the impact of the support structure on ventilation. These issues are beyond the scope of this paper, but will be addressed in a paper at the upcoming Longwall USA conference in Pittsburgh this September (1999).

While this paper is focused on standing roof support applications, several mines have explored the application of intrinsic secondary support such as trusses to replace conventional standing support in longwall tailgates (*4*). Two points need to be made in reference to the truss support consideration. First, it should be noted that the design methodology proposed in this paper applies only to standing roof support. While some of the basic rock mechanics principles used here may apply to intrinsic support, the support mechanisms are different and these have not been examined in this study.

Another caveat of the design methodology pertains to the application in yield pillar gate roads. While in theory a ground reaction behavior can be established for yield pillar systems, the mechanisms of ground behavior and support interaction are different. In particular, the yield pillar system is a high deformation environment by design. Secondary support should ideally allow the ground to yield in accordance with the pillar deformations and not interfere to the point where the secondary support develops sufficient capacity to damage the roof while it is yielding. Hence, a stiff, high density support may ***not*** be desirable in this environment, and the important secondary support design consideration may well be the ***stability and yield capability*** of the support.

CONCLUSIONS

Several alternative technologies to conventional wood and concrete cribbing have been developed in recent years. These new support technologies provide improvements in supporting capability as well as material handling advantages. However, since their supporting characteristics are all different, a design methodology must be developed in order for mines to safely employ these technologies and to maximize their benefits without increasing the overall cost of support. Conservative applications or ***trial and error assessments are no longer practical nor prudent for state-of-the-art longwall mines.***

The design methodology proposed in this paper and examined through a field trial at a western Pennsylvania coal mine embodies a fundamental concept of rock mechanics, that being the "ground reaction curve". Measurement of the ground reaction curve at the western Pennsylvania coal mine indicated that at this mine operating in the Pittsburgh coal seam, the support capacity had a significant impact on the ground behavior in the longwall tailgate. Increasing the support load density by a factor of 2 from 0.625 tons per square foot to 1.25 tons per square foot decreased the convergence in the entry from 4 inches to 1 inch. Conventional 4 point wood cribs installed in a double row with an 8 ft center-to-center spacing in a staggered arrangement (4 ft center-to-center spacing among adjacent rows) resulted in marginal ground control. Concrete cribs constructed from concrete stopping blocks reduced convergence to 0.5 inches, but some failed at this deformation resulting in localized poor ground control due to the support failure.

Four alternative standing support technologies were installed at the western Pennsylvania mine: (1) The Can Support (Burrell Mining Products), (2) the Alternative Crib Support (Heintzmann Corporation), (3) Pumpable concrete support (HeiTech Corporation), and (4) the Propsetter (Strata Products USA). These alternative support technologies were installed at a support load density ranging from 1.12 tons per square foot to 1.35 tons per square foot, providing ground control safety factors of 1.79 to 2.16. Ground conditions for all these support applications were generally very good, which is consistent with the measured ground reaction behavior and installed support density.

The NIOSH Wood Crib Performance Model is currently being upgraded to a windows format. Included in this new version will be the addition of the performance characteristics of alternative support technologies such as those discussed in this paper. In addition, a subroutine will be provided that incorporates the longwall tailgate design methodology proposed in this paper. This program will facilitate the use of this design methodology and will allow mines to optimize the use of any support technology once a ground reaction curve for that particular mine is identified.

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