A RETROSPECTIVE ASSESSMENT OF LONGWALL ROOF SUPPORT WITH A FOCUS ON CHALLENGING ACCEPTED ROOF SUPPORT CONCEPTS AND DESIGN PREMISES

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ABSTRACT

The era of the shield-supported longwall face began in the United States a little over 25 years ago. The most fundamental development of the shield in the past 25 years has been an increase in size and capacity and a progression toward two-legged designs in favor over four-legged shields. Is the “bigger-the-better” design philosophy justified? The advantage of the two-legged design is largely attributed to its active horizontal force caused by the forward orientation of the leg cylinders. How do we know this? You might be surprised to learn that shield loading data may suggest otherwise. In addition, what about setting pressures? Should they be set as high as possible? Some people have advocated that setting pressures should equal the yield pressure. Does this make any sense? Is yielding a good or bad thing? These are some questions still worthy of investigation that are addressed in this paper.

The first major change in gateroad support was the use of cable bolts to replace conventional wood cribbing particularly in Western mines. Standing support changed very little until the mid-1990s, when Strata Products [1] introduced the Hercules and Propsetter supports in Eastern mines and Burrell Mining Products introduced the Can support in Western mines. Since then, there has been a dramatic increase in new roof support technologies for longwall gateroad support. Historically, standing support, including shield supports, have been designed based on a simplistic model requiring the support to have sufficient capacity to support the gravity loading of a perceived detached rock mass. This approach ignores the stiffness of the support and the resulting ground deformation that is known to be critical to roof stability. Recently, a new approach based on the ground reaction concept has been promoted by the National Institute for Occupational Safety and Health (NIOSH) to account for the interaction of the support with the rock mass behavior in achieving ground stability. In addition to gateroad support design, this concept has ramifications for shield capacities, setting pressures, and recovery room support design that challenge current practices in these areas.

Although longwall mining has matured into the safest and most productive underground mining method used today, traditional concepts of roof support design and practice should still be evaluated and challenged. Ultimately, advancements in the science of ground control are made by recognizing deficiencies in current theories and thinking outside the box.

PRELUDE

Throughout the history of longwall mining, the design of the roof support system has been critical to the success of the mining operation. Early forms of longwall mining used wood props for face support and packwalls made from roof and floor rock to control caving of the immediate roof (1). These systems were replaced by powered roof supports that could be advanced easily while allowing the strata to cave behind them. The first powered roof supports were simple frame and chock structures. These designs were poor in their ability to resist horizontal displacements and the resulting moment loading caused by the strata dynamics during the caving process. They often experienced difficulty and failure (2). The shield greatly improved kinematic stability by providing a horizontal stiffness by structurally connecting the canopy to the base. The success of the shield support promoted the application of the longwall mining method in highly faulted and massive strata conditions where caving was difficult to control and where chock and frame supports were inadequate.

The basic shield design has changed little since its inception in the 1970's. The primary change has been a steady increase in shield capacity, resulting in larger hydraulic cylinders and support structures. The consequences of a “bigger-the-better” design philosophy are examined in the paper. However, more importantly, it is surprisingly interesting to see how the large capacities are still rationalized on the misconception that the shield loading provides full control of the ground, when in fact a large portion of the shield response is from ground behavior that is independent of the shield capacity or design. Misconceptions also exist about setting pressures, shield stiffness characteristics, and what happens during yielding that further challenge the “bigger-the-better” design philosophy and the rationale for the need for higher capacity to extend the service life of the shield.

There has also been a definite trend in the United States and world wide toward two-leg shield designs. With the leg cylinder inclined toward the coal face, this provides the opportunity for the shield to induce an active horizontal force toward the coal face that helps maintain stability of a disjointed immediate roof structure. In addition, the caving shield lemniscate assembly provides a passive

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[1] Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

restraint to face-to-waste strata movements. While these claims are true in theory when certain assumptions are made, is this what actually happens in practice? Here too, the evidence may be surprising.

What about standing supports? The transformation in passive gateroad support has been much more varied than in the powered face supports. Prior to 1980, timber was the dominant support material with wood cribs and timber posts used exclusively for tailgate and bleeder support. In the 1980's, various trials of concrete supports were conducted. These also revealed misconceptions about ground control regarding the "bigger-the-better" design philosophy. Concrete, with a compressive strength and material modulus an order of magnitude higher than wood, had to provide superior roof support was the thinking at that time. Wrong again! Fill a tailgate or a longwall recovery room full of concrete cribs and everything will be fine. I don't think so! Why, because fundamental rock mechanics issues were misunderstood or ignored.

Well, if all of this is true, then how can we have had so much success? Record longwall productions and downward trends in blocked tailgates cannot be denied. True, but I would propose that these successes are still largely a product of trial-and-error with a little science thrown in. Things have evolved because we have learned from our mistakes. However, I think the science still lags practice and to some extent, successes have been achieved in spite of the roof support design.

Sounds controversial, I know. However, I think it should make for an interesting discussion in this 25th anniversary of the International Conference on Ground Control in Mining.

POWERED ROOF SUPPORTS

Historical Overview of Shield Design

Two fundamental changes in shield design have been made since the introduction of the shield in 1975: (1) the caliper design was replaced with a lemniscate-guided caving shield that maintains a constant tip-to-face distance throughout its operating range; and (2) electrohydraulic control systems have replaced manual systems to permit remote and automated operation of the shield.

Material Specifications -- In order to accommodate ever-increasing capacities, while still maintaining component cross sectional dimensions small enough to provide adequate working space and manageable shield weights, the trend has been toward the use of high strength steels (100,000+ psi yield). One consequence of some high strength steel applications is that special welding practices are required (heat control, etc.), making underground repairs more difficult.

Capacity -- Support capacity has continued to increase throughout the history of longwall mining. This trend has continued during the past two decades as shown in figure 1 (3). Average support capacities in the United States have increased by 70 pct since 1985 and by 32 pct since 1995 to an average support capacity at yield of 879 tons for the 52 operating longwalls in the U.S. in 2005. Ten installations (19 pct) employ shields with capacities greater than 1,000 tons, and 37 installations (71 pct) have capacities equal to or greater than 800 tons. The highest capacity shield is 1,280 tons (3). As shown in figure 1, maximum shield capacities have evolved from 800-ton shields, which were common from 1985 to 1990 to 980-ton shields, which were frequently installed from 1993 to 1998, to the 1,170-ton designs from 1999 to 2001, and then the 1,280-ton shields first installed in 2002.

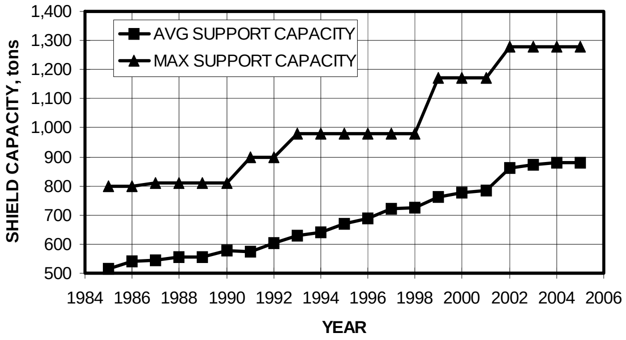

Figure 1 – Trend in shield capacities.

Type of Shield -- Beginning in 1985, there has been a steady increase in the use of two-leg shields. Today, all shields in the United States are two-leg designs. The application of high-capacity, two-leg shield designs was primarily controlled by the development of larger size hydraulic cylinders. A 1,280-ton shield requires a bore diameter of approximately 16.2 inches (412 mm).

Size -- Longwall shields have increased in length to accommodate one-web-back operations and larger face conveyors and deeper shearer webs, making these units over 20 feet in length. The standard canopy width is now 1.75 m, replacing the 1.5 m designs that were prevalent 10 years ago. The first 2.0-meter wide shield was installed in Foundation Coal's Cumberland mine in 2003. This trend of increasing canopy width to 2.0 m is likely to continue. The 2.0-m width may represent an upper limit with current shield construction materials since wider shields weigh more, thereby requiring more effort to transport during face moves. The potential benefit of wider shields is less cost since much of the cost is due to the machining of the hydraulic leg cylinders, and fewer legs are required with wider supports. However, this cost advantage is being offset by higher capacity systems. The wider supports may also be more stable in thick-seam operations. A decrease in move time might also be realized, since 15 pct and 30 pct fewer supports are employed on a face with the 1.75-m wide and 2.0-m wide designs, respectively, compared to the 1.5-m designs of the initial generation of shield supports.

Setting Forces -- Setting forces have increased in proportion to the increase in yield capacity because the size (diameter) of the leg cylinders has increased to accommodate the higher yield capacities, while the hydraulic setting pressures have remained constant in the 4,200 to 4,400 psi range. Most hydraulic power supply systems and electrohydraulic control technologies still try to maintain a set-to-yield ratio in the 0.6 to 0.8 range. Optimum setting forces as a function of overall support loading and geological conditions are not pursued by current control technologies.

Component Constructions -- The component that has changed the most is the canopy. Extensible canopy designs were occasionally used in Europe, where friable roof geologies had to be maintained (4). The trend in the United States has been towards rigid canopies without any extension or flipper arrangements to control face sloughage, except in thick seam (> 10 ft) operations. Canopy tips have been curved upward to promote tip contact. However, the force generated at the tip is typically about 10 pct of the leg force and is mostly a function of the distance of the tip from the leg cylinders. The distribution of loading on the canopy and base is also dependent upon the stiffness of these components and the deformation characteristics of the immediate strata. There has been increased usage of solid base configurations to alleviate splaying that occurs with individual base pontoons and to improve load distribution on the mine floor.

Control Systems -- Improvements in the electrohydraulic control systems continue to be made. Positive-setting algorithms are more sophisticated with pressure monitoring at programmable thresholds to more intelligently achieve full setting, or deactivation if full setting is incapable of being achieved due to some sort of hydraulic failure on a particular leg cylinder. Improvements have been made in face-end control logic to allow for full automation of bi-directional cutting. The cycle times for shield advance continue to be minimized. Combinations of multiple functions pertaining to the powered lowering, base lift, and conveyor push of individual shields are now routinely performed at the same time to compress the support advance time requirements.

Hydraulic Components -- Solenoid-operated valving systems are now standard. Spool valves have been shown to be superior to ball and seat designs that are prone to contamination problems. In addition, these systems allow the solenoid to be activated upon demand, unlike previous systems that required the hydraulic feed to be interrupted by a control solenoid. This leads to both quicker and smoother control of support functions.

Is the "Bigger-the-Better" Design Philosophy Justified?

Perhaps, but not for the reasons you might think. First, the question itself is somewhat misleading. The shields were forced to get bigger to accommodate wider web extractions and wider face conveyors to convey the coal from the face at ever-increasing production rates. Therefore, the bigger part is understandable, although it is interesting to note the trend for higher capacities occurred before the increase in shield size. Why? The question can be analyzed from the perspective of rock mechanics models for longwall mining.

Wilson was the first to promote the detached block-loading concept back in the early 1970's (5). A caving zone occurs when a portion of the immediate roof is fractured by the overburden pressure, causing that portion to separate from the overlying rock mass and the full gravity weight of this block must be carried by the support (see figure 2). The size and therefore weight of the block that determined the required shield capacity was dependent upon the bulking factor of the immediate roof rock. Early on when longwall mining first began in the U.S. with powered supports, it was concluded that the more competent strata found in U.S. mines caved in more blocky fashion with less of a bulking factor than the weaker, more friable roof geologies found in most European mines. This immediately prompted a demand for higher shield capacities for the U.S. market. However, the requirement did not stop there, and shield capacities continued to grow beyond what bulking factors would justify. One reason was that the shields were also getting bigger (at first mostly longer and then wider as well). Hence, as the shields got bigger (longer and wider), they would need more capacity to carry the weight of the detached roof block. These factors started the ball rolling along the path of higher capacity, and I personally believe this model is an oversimplification of the rock behavior. I believe that elements of this thinking persist in roof support design even today, and they continue to promote the belief in the "bigger-the-better" design philosophy.

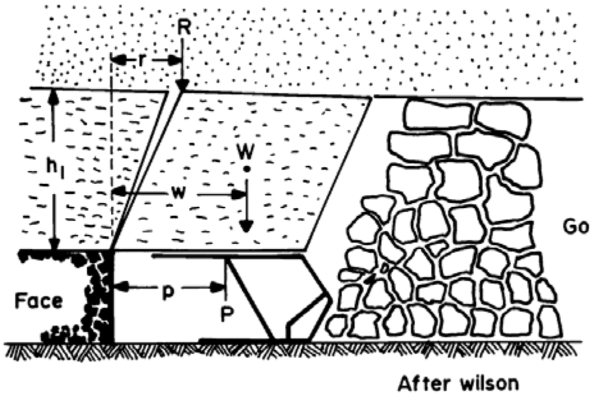

Figure 2 – Detached block model of longwall roof behavior.

Another motivating factor for the continued increase in support capacity was the desire to have higher and higher setting forces. Measurements taken during the early growth of the longwall shield capacities from the mid-1970's to the early 1980's indicated that increasing setting force resulted in less face convergence suggesting a force-controlled model of rock mechanics for longwall mining. This is conceptually illustrated in figure 3 which shows that some convergence cannot be controlled by the shields due to their limited capacity relative to the ground stress and that the benefit in reducing the convergence is diminished once a certain setting pressure is achieved (6). Further, these measurements were generally taken when shield capacities and thus setting forces were small compared to today's standards. Even these measurements show the benefit from increased setting forces diminished with relatively small increases in setting forces, suggesting that a practical optimum setting pressure exists, well below that of today's standards. For example, Gupta made the claim in his 1982 Ph.D. dissertation that in British coal mines increasing the setting load density from 1.15 to 4.39 tons/ft^2 completely converted the tensile stress zone above the shields into a compressive zone and all but eliminated ground control problems (7). Today's shields sustain setting load densities of over 8 tons/ft^2.

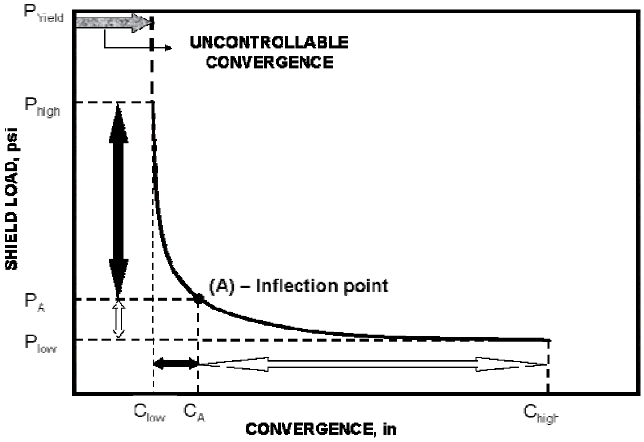

Figure 3 – Impact of shield capacities (setting forces) on convergence.

From a rock mechanics perspective, it is important to understand what the increased setting pressures are trying to accomplish. The benefit of the setting pressure, as in all active support loading, is to "precondition" the immediate roof in order to enhance its structural stability. Can this be done? The setting force will act to increase the bending stiffness of the immediate roof by developing increased shear resistance along laminations (8). In theory, the stiffer cantilevered roof beam will result in reduced deflections, thereby reducing stress development in the beam and lower shield loading beyond the setting load. Better ground control and less shield loading, just what we are looking for, right? However, that is not the whole story. In addition to increasing the bending stiffness of the roof beam, the setting force may also increase the stiffness of both the roof and floor structure. The consequence of this is higher shield loading since the equivalent stiffness of the roof-shield-floor structure increases. Therefore, the increase in setting pressure produces contradicting benefits from the perspective of shield loading and roof control.

As more realistic models of longwall rock mechanics were developed, shield capacities continued to grow. Of these, I believe the cantilevered beam model integrating the stiffness of the coal seam and gob material into the deformation response of the roof beam was the most valid. Smart was one of the first to promote a stiffness model to determine longwall support requirements (9). As illustrated in figure 4, Smart suggested that the powered support was one of three yielding foundations which support the immediate roof and bridging beds. The other two elements being the coal ahead of the face and waste (gob) behind the face. The process, as Smart saw it, was that the powered support requirement is to control the subsidence (convergence) of the roof strata along the longwall face sufficiently to prevent fractures, which are generated ahead of the face line in the upper regions of the immediate roof, from migrating downward to the roof horizon at the longwall face. This is necessary to ensure that the immediate roof does not become unstable, resulting in excessive support loading leading to ground falls in front of the supports. The key to Smart's concept is that the stiffness of the coal and gob largely control the shield loading and design requirements. In particular, Smart hypothesized that the reason American supports were required to be higher capacity than their European counter parts was that the more competent immediate roof structures failed, in what he called controlled parting-plane-caving, as opposed to the bulking-factor-caving of the weaker European geologies. The result being that the gob material provided very little support and created an even larger cantilevered roof beam that must be supported by the longwall shields.

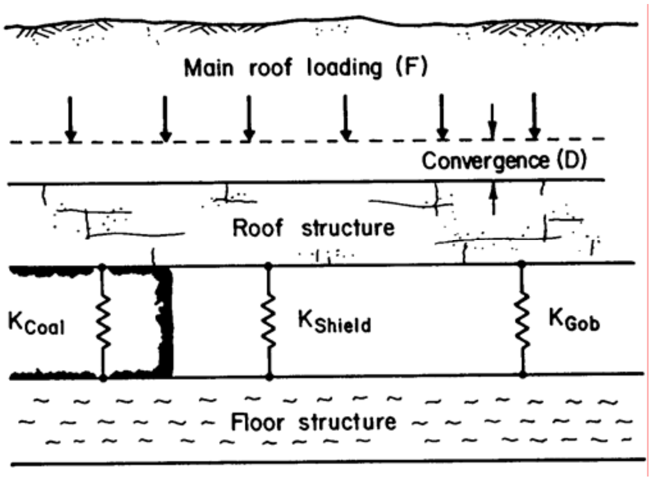

Figure 4 – Concept for evaluating roof shield response based on the stiffness of the shield, coal, and gob foundations.

I believe this to be a realistic model of longwall support and strata interaction with one missing component, that being that the subsidence factor that Smart was talking about, in particular the elastic response of the overburden is uncontrollable from the perspective of shield capacity. I do not give the shields as much credit as Smart implies in controlling the impact of the abutment pressures on the intermediate or immediate roof structure ahead of the face. I believe the shields are much more "reactive" as opposed to "controlling" in this phase of the rock mechanics. Most importantly, I believe that Smart's model was much more conducive to displacement or convergence-controlled rock mechanics behavior than the detached block concepts widely accepted before this. It is my belief that a significant portion of the shield loading is dictated by the reaction of the shield based on its stiffness to the uncontrollable convergence that occurs mostly from the main roof behavior and subsidence loading that Smart is addressing.

Therefore, is a bigger-the-better design philosophy justified? The field data from the 1970's and early 1980's clearly shows that there is a benefit, to increased capacity to a point. However, it also shows that the benefit at least from a convergence control perspective diminishes with increasing capacity. I do not think there is sufficient data from modern shields to quantify the optimum, and it is likely to be different for various loading conditions including depth of cover, extraction height, and roof geology. However, based on the data from the 1970's and 1980's, today's shields are well beyond the 2-3 tons per sq ft that produced inflections in the load density vs. convergence curves of that era. Another argument I do not believe holds merit is that the higher capacities are needed to maintain constant load densities over the supported roof area. The whole concept of analysis based on normalized pressure is misleading. The load distribution acting on the canopy is not even close to being uniform. Normalizing to the canopy or support area tends to diminish the true increase in load density of today's shields because the capacities have grown at a larger rate than the size of the shields. The one element that does lend some credibility to the "bigger-the-better" design philosophy has been the fact that the shield stiffness has increased in direct proportion to the increase in capacity. Why? Historically, the design practice has been to increase shield capacity by increasing the diameter of the leg, while keeping the yield pressure constant at about 6,200 psi. Because of the increase in leg area, the stiffness of the shield also increased in direct proportion to the increase in shield capacity (10). It may well be that the increased stiffness may be more responsible for improved ground control than the increased capacity. In other words, if the capacities we have today would have been achieved by reducing the stiffness of the shield, would we have the same improvements in ground control that are reported now. Personally, I do not think so. However, it is double-edge sword so to speak. The consequence of the increased stiffness is also greater shield loading from the uncontrollable convergence component of the rock mass behavior. In other words, as the shields grew in capacity and the demand for increased setting forces persisted as part of this growth, they had to have higher capacity just to accommodate the higher stiffness and resultant loading in a largely convergence-controlled load environment. That is the strongest justification I can give for a "bigger-the-better" design philosophy, and yes, it too has diminishing returns suggesting that an optimum capacity exists.

A Discussion of Active Horizontal Loading in Two-Legged Shield Design

Active horizontal roof loading is claimed to be one of major advantages of the two-leg shield design. In theory, the forward inclination of the leg cylinders provides a component of the leg force that acts to transfer compressive force into the immediate roof structure, which can help to maintain stability of a disjointed roof beam. The question is "Does this really happen or to what extent does it happen in the mine?" The mechanics of the shield relative to the development of an active horizontal force is illustrated in figure 5. The key issue is how much horizontal displacement of the canopy occurs, which can be ascertained from the reaction of the lemniscate links.

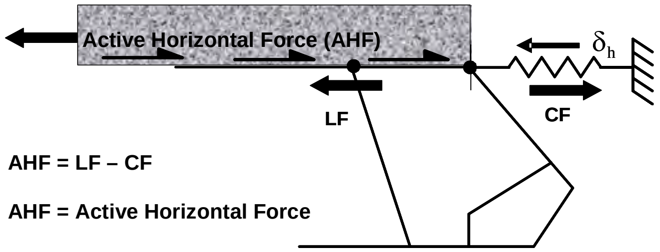

Figure 5 – Shield mechanics showing that caving shield/ lemniscate assembly reaction to forward canopy displacement reduces active horizontal roof loading caused by horizontal component of the leg force.

The lemniscate links develop stress in response to horizontal displacement of the canopy relative to the base. Without the horizontal displacement, there is very little stress developed in the caving shield-lemniscate assembly since it has no vertical stiffness (11). Using the canopy-caving shield hinge pin as a frame of reference, a horizontal displacement of this joint toward the face will produce compression in the top links and tension in the bottom links. When the shield is set against the mine roof, if the canopy does not slide forward (i.e., the friction prevents slippage of the canopy along the roof line), then there is very little stress developed in the lemniscates links and the horizontal component of the leg force is transferred to the mine roof as a compressive acting stress. Roof-to-floor closure produces no significant change in the stress in the lemniscate links since the caving shield-lemniscate assembly has no vertical stiffness. Conversely, the leg pressures increase in direct proportion to the roof-to-floor closure. Therefore, if the link stresses increase proportionally with increasing leg pressures, then the canopy is moving forward causing displacement of the canopy-caving shield hinge pin toward the coal face. If the canopy is not moving and instead the horizontal force is transferred to the mine roof through the friction between the canopy and the roof, then the link stress would ***not*** increase in proportion to the leg pressure. Likewise, if the canopy were displaced toward the gob, then the previously developed link stresses would decrease. In a similar manner, if at any time the canopy lost frictional contact with the roof, then the canopy would slide forward and the horizontal force from the leg component would be transferred to the caving shield-lemnicsate assembly. This force is then not recoverable in terms of active roof loading. It is lost forever. Any additional leg pressure development and active horizontal roof loading during a face cutting cycle will be relatively small.

Unfortunately, very little link stress data has been obtained, particularly from active longwall mining shields. The U.S. Bureau of Mines collected some link strain data in the 1980's. This data shows that the link strains or link forces were generally correlated to the leg pressures (see figures 6 and 7); again suggesting that the horizontal component of the leg force was being transferred into the caving shield-lemniscate assembly and not into the mine roof (12). Further, the magnitude of the link forces provide a caving shield reaction force that is close to the horizontal component of the leg force. On occasion, data would show that the link strains decreased during the shield cycle indicating that the roof may have been moving toward the gob and pushing the canopy back toward the gob in the process (12), but these events were far less frequent than the trend of increasing link strains in proportion to the leg pressures. It is also clear from the data that the link strains were occurring immediately upon setting the shield, indicating the horizontal leg force was being absorbed by the caving shield/ lemniscate assembly and not going into the roof.

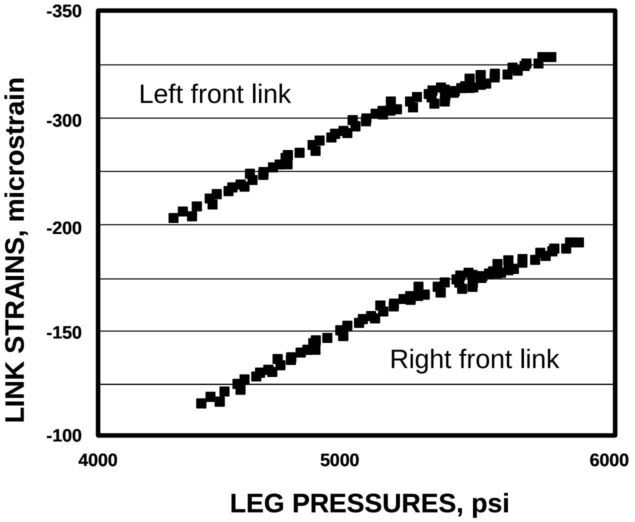

Figure 6 – Direct correlation found between link strain and leg pressures suggesting leg force is being absorbed by caving shield-lemniscate assembly and not induced into the mine roof.

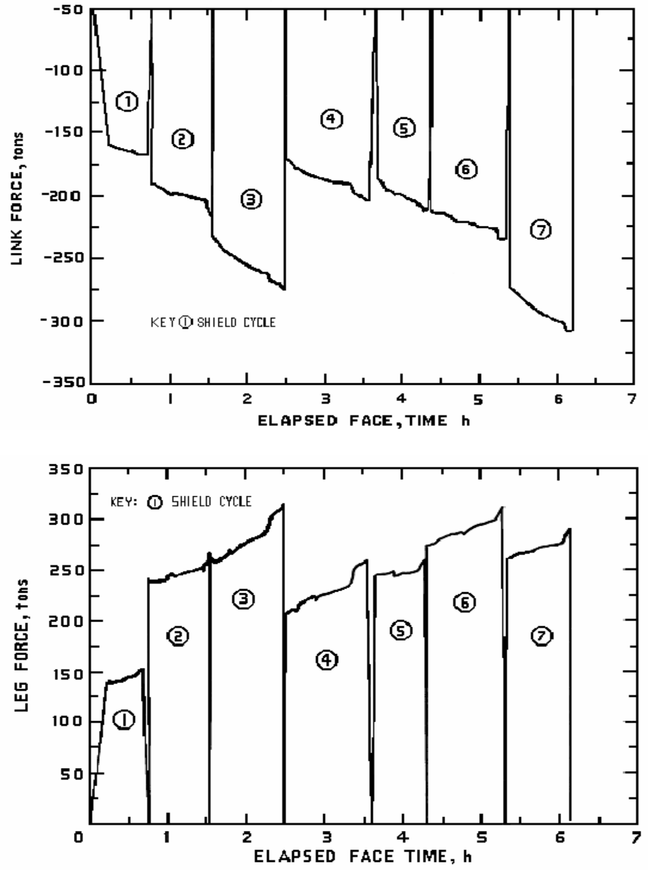

Figure 7 – Link strain and leg force data for selected shield loading cycles.

Peng directly measured the horizontal displacement of the canopy during the setting operation in one underground study of shield supports (13). He found that about 0.4 inches of horizontal movement of the canopy was occurring from the time the canopy first contacted the roof to the time when full set pressure was reached (see figure 8). The horizontal component of the leg force was computed as 150 tons. A caving shield/lemnsicate assembly stiffness of 192 tons/in would completely eliminate the active horizontal loading in this situation. Measurements of caving shield/lemnsicate assembly stiffness measured through full scale tests in the Mine Roof Simulator on a 360-ton support ranged from 162 to 340 tons/in (14). Hence, it is likely that most of the force was consumed in link force loading, although Professor Peng estimated that 100 tons of active load could have occurred. Peng also showed that when a steel plate was place above the canopy with rollers sandwiched between the plate and top surface of the canopy to create a "zero friction" condition, the measured displacement increased to 0.5 inches. In theory, a true "zero friction" condition would produce zero active horizontal force. Using a stiffness of 192 tons/in, this difference in displacement would indicate an active horizontal force of about 20 tons. Peng also found examples where the difference in the "zero-friction" and "normal" canopy contact produced larger variations in measured horizontal displacement, suggesting that higher active horizontal forces were developed.

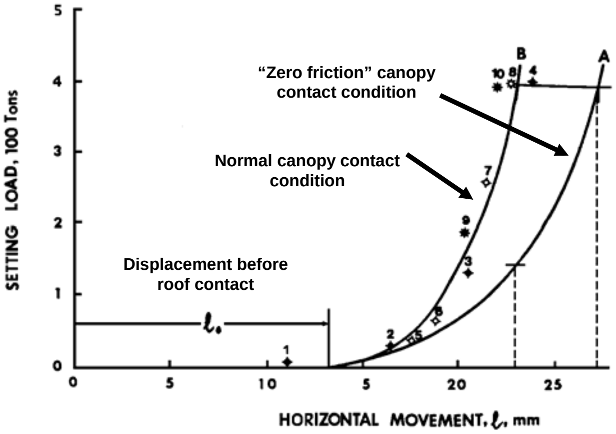

Figure 8 – Measurements of horizontal canopy displacement during setting operation of longwall shield (from Peng).

Is Yielding a Good or Bad Thing?

I think this one is easy. Yielding is good from the perspective of the shield and bad from the perspective of the roof. Let me explain. Yielding protects the shield from developing excessive pressures in the leg cylinder that can damage the leg or overstress the structural components of the shield. Yielding is accomplished by letting fluid out of the leg, which invariably results in lowering of the support canopy. Simply translated, whenever the shield is yielding the roof is moving down. Downward displacement of the roof is generally not a good thing.

Now, how much the roof moves down or how much the support lowers is also relevant to this discussion. Yield valves will typically have a 10 pct pressure resetting rating, meaning after a 10 pct reduction in leg pressure caused by the loss of fluid, the valve will close and allow pressure to increase in response to convergence once again (15). It would take several hundred to over a 1,000 yield cycles to fully eliminate the hydraulic stroke of the cylinder. That is hardly the issue. Lowering of the roof by one inch can be significant from a ground control viewpoint. It would take only 8 yielding events to cause one inch of downward roof movement or 44 yield events to produce 6 inches of downward roof movement on a typical modern shield.

Another controversial issue needs to be raised in this discussion. Why does the yielding stop? Since the lowering of the shield increases the leg inclination, the capacity of the shield also decreases slightly after each yielding event. If the roof is acting in force control and the worst case scenario is the shield is supporting the weight of a detached block of roof that remains isolated (detached), then the yielding would not cease to occur until the shield went solid since the load acting on the shield would not decrease with convergence. Since this rarely happens, it suggests that this simplistic model of roof behavior as promoted by Wilson is not accurate. This means that, for some reason, the support resistance required to produce equilibrium decreases as a result of the yielding or with increasing convergence, which is consistent with a ground reaction approach to shield design. It does not necessarily imply that the shield is responsible for this condition, it may well be that the shield had nothing to do with it and the load conditions changed because of stress relief in the ground due to deformation or macro movements of rock masses in the more global sense. However, from a ground reaction curve perspective, yielding is moving down the ground reaction curve toward a condition of decreased stability, hence, it must be concluded that ultimately it is not a good thing.

Why do the higher capacity, modern, shields last longer?

Many people believe the modern high capacity shields last longer than their lower capacity predecessors ***because of*** their higher capacity. I do not believe this to be true. As previously indicated, the higher capacity shields are also stiffer than their lower capacity predecessors. Therefore, from the convergence-controlled roof behavior and the uncontrollable convergence produced by the main roof loading, they are just as likely to be as fully loaded relative to their yield capacity, if not more fully loaded, than their predecessors. I believe the manufacturers achieve the longer life from better management of the stress in the shield components through improved design. I think the advancement of numerical modeling has matured to the point where prototype shields for new procurements are designed to better manage the stress and avoid stress concentrations that have been problems in the past. I would suspect that fabrication methods have also improved quality control as well.

In summary, shields have proven to be effective roof supports providing adequate face control in a variety of mining conditions. However, fundamental issues regarding design requirements and their intervention in ground behavior are still not well understood. The "bigger-the-better" design philosophy has worked, but does not address persistent controversial issues that need to be considered to pursue optimization of the support system with the realization that capacities cannot continue to increase forever.

GATEROAD SUPPORT

Historical Perspective of Gateroad Support Technologies

There has been a dramatic change in standing roof support products for longwall gateroad support. Timber supports in the form of wood cribs and posts were all that was used prior to mid-1980, when trials of concrete supports were common. Then, the

1990's saw a revolution in new support technologies, providing a wide range of support capabilities. Figure 9 shows a distribution of several types of tailgate supports over the past 14 years. Many lessons were learned during the past 25 years, both in terms of support design and design requirements for longwall mining.

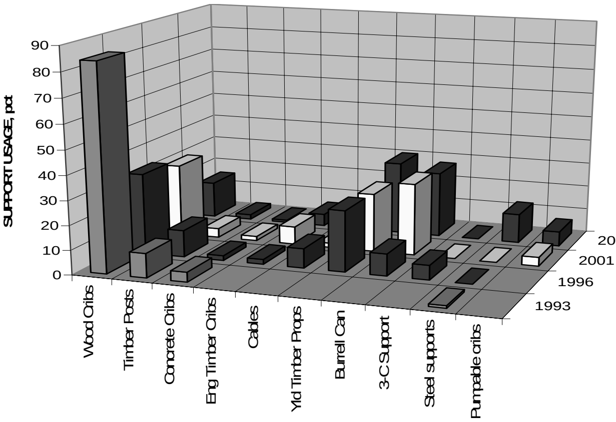

Figure 9 – Distribution of tailgate support since 1993 showing change in support practices from conventional wood cribs and posts into a variety of alternative support technologies.

What Concrete Supports Taught Us about Ground Control

As indicated in the introductory comments, the thinking at the time when concrete supports were introduced to longwall mining was that with a compressive strength and material modulus an order of magnitude higher than wood, concrete had to provide superior roof supports. This hypothesis was completely wrong. Why, because fundamental rock mechanics issues were ignored or misunderstood. Plain and simple, you cannot prevent all of the closure of a mine opening with any practical and economical support system, and if the support cannot survive this uncontrollable convergence, it will fail prematurely and not provide adequate roof support. Any standing support or a longwall shield for that matter cannot control the behavior of the overburden. These super high capacity concrete cribs were crushed in several longwall tailgates (see figure 10).

Figure 10 – Failure of high capacity concrete crib in longwall tailgate.

A similar argument can be made in longwall recovery operations. One study, based on empirical data and qualitative assessments of predriven recovery rooms, suggested that the design requirement for successful roof support was 150 psi of support pressure (16). This too is misguided in that the stiffness and yield characteristics of the support are ignored. Concrete cribs fail at less than 1 inch of convergence. The uncontrollable component of convergence in these recovery room operations can exceed one inch causing premature failure of concrete cribs since they are not able to sustain any useable load capacity after reaching their peak load capacity. Here too, failures of high capacity concrete cribs were observed in practice (figure 11).

Figure 11 – Failure of high capacity concrete crib in longwall recovery room.

Clearly, concrete supports taught us that not all convergence can be stopped by practical standing support systems, and that this uncontrollable convergence must be considered as part of the design process. As such, the simplistic model of detached block loading was no longer completely valid for support design.

Improvements in Material Handling and Support Installation

Part of the revolution in standing support design has been the development of support systems that can be installed more easily with less manual effort and in less time. The Can support, which actually began the revolution out of a need to find an alternative to conventional wood cribbing in western mines, was the first system to be installed with a machine. The installation of this system overcomes the bulkiness and heavy weight of the support by using an articulated claw attached to a scoop or load-haul dump vehicle to pick the support up and place it in the desired spot in the mine entry. Recently, pumpable support technologies have taken a different approach by pumping the support materials from the surface into an empty, lightweight, containment bag hung from the mine roof. While it can be argued that the material handling function was simply transferred from underground to the mine surface, the work environment above ground is far less restrictive and more conducive to safe working practices than is the underground environment. Material handling advantages are also included in crib type supports such as the Link-N-Lock or Hercules crib, where the components have been reduced in size and weight while providing several times the support capacity with less support material. One of the first alternative products was the Propsetter support. This support provided capability equivalent to that of the wood crib, but was fashioned as a timber post that could be much more easily installed than the piece-meal construction required by wood cribbing. Installation rates improved by as much as 200 pct with the Propsetter support. Other than the Propsetter, most prop-type supports were non-yielding, and therefore would not function well in many longwall applications. Within the past 5 years, there has been a dramatic increase in prop-type support development, primarily because of their ease of installation. These include: (1) Little and Big John Extreme Plus Props, (2) Rocprop, (3) Pencil Prop, (4) Spider Prop, (5) Ball Buster, and the (6) MX Prop. Overall, their performance has been satisfactory, with most premature failures attributed to eccentric load conditions in systems where the yield load is too close to the buckling capacity of the props.

NIOSH Full-Scale Support Testing and the STOP Software

All of the support products now on the market have been full-scale tested in the NIOSH Mine Roof Simulator active load frame using a rigorous protocol that subjects the supports to a variety of loading conditions that are the most realistic simulation of the in-service loading. The design requirements, performance characteristics, material handling specifications, and cost information for 144 designs of 56 different support systems are currently implemented into the Support Technology Optimization Program (STOP) (17). New support systems are added annually, as they are evaluated and commercialized. The implementation of this information into the STOP design software has helped to eliminate the trial-and-error approach to new support technologies that was common in the past. This provides insurance toward successful support applications without exposing miners to uncertain, potentially hazardous support performance. STOP can provide an engineering foundation to ensure that inadequate support designs, as well as ultraconservative support applications, are avoided. Safety will be improved by matching support performance to mine conditions. This reduces the likelihood of roof falls and blocked travel and escapeways. Figure 12 shows that tailgate blockages during the past 15 years have decreased by 64 pct based on MHSA reported data on roof falls.

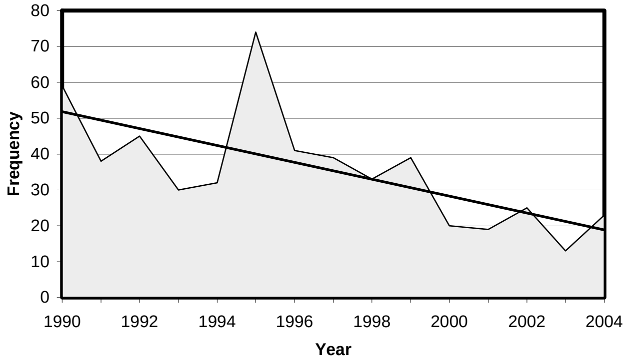

Figure 12 – Graph illustrating decreasing trend in longwall tailgate blockages.

The Australian Experience

An Australian Coal Association Research Program (ACARP) project was commissioned in 2005 to evaluate longwall tailgate standing support design (18). The major outcome of this research was the promotion of a "skewed roof deformation mechanism". "Skewed roof" refers to the propensity of the gateroad roof to skew towards the adjacent or approaching gob. This activity creates shear stress damage to the immediate roof and can often destroy intrinsic support, including cable bolts. The major finding of the project was that existing standing support products are often too soft and of insufficient capacity to effectively interact with the strata deformation mechanisms, particularly the "skewed roof" condition where 3D numerical modeling indicated that capacities of at least 400 metric tons would be required to limit the lateral roof movement.

The "skewed roof" roof movement concept obviously has serious implications for standing support design. Equivalent measurements of lateral movement have not been obtained for U.S. longwall conditions and while lateral movements and associated support loading have been observed, my initial thought is that it is not as prevalent in the U.S. This may be related to fact that U.S. mines typically employ a three-entry gateroad design in lower seam heights, which if wider would reduce the effect of the skewed roof loading in U.S. gateroads. Some western longwall mines in the U.S., which have used two entry designs in deep cover conditions, have experienced lateral movements of the roof relative to the floor.

Preloading of Standing Supports

Until recently, with the introduction of hydraulic pressure cells, preloading of standing supports were limited to a few products, primarily the Propsetter support system, which utilized a pressurized grout bag on top of a yielding timber post (19). Mettiki was one of the first U.S. mines to routinely employ the prestressed Propsetter support and reported improved ground control in difficult tailgate conditions. The hydraulic prestressing devices are two thin sheets of metal that are welded along the perimeter to form a capsule that can be filled through an inlet port with plain water and pressurized to create a preload on a passive standing roof support product. The units can be sized to accommodate various support geometries. Yield valves can also be incorporated to allow the units to act as load limiting devices and provide some controlled yielding to otherwise non-yielding support structures.

I don't think any rock mechanics engineer can effectively argue that preloading is not beneficial to ground control. The argument is really about how much benefit is actually achieved, given the zone of influence of the prestress and the practical limitations of sustaining it on a standing roof support system. I will reserve the right to debate that subject in another paper, but I think an important point that needs to be recognized is that the secondary benefit of preloading standing support products is that it helps to offset many of the installation practices that routinely degrade the support response. The examples are too numerous to discuss in detail here, but suffice it to say that most mistakes are made in "topping off" a support to establish roof contact. If this is not done properly, a support such as the Can, which on its own has an outstanding performance response in terms of stiffness and stability, can be made to act like a poorly built wood crib.

The Missing Piece of Support Design

The performance characteristics of standing roof support systems have been well defined through rigorous full-scale testing and documentation in the NIOSH Support Technology Optimization Program (STOP). The ground response and the interaction with the support, however, have been poorly understood. How much control do the standing supports have on roof behavior? Do they influence the stress changes and ground movement around the opening? Until this understanding is developed, proper support design cannot be accomplished, and premature failures of supports or excessively conservative applications of support will continue. The goal is to match the support to the load imposed by the surrounding rock mass. The lack of knowledge in this area is responsible for the misconceptions and poor premises that still plague proper support design. Recently, the concept of support design based on ground reaction has been gaining strength here and abroad (20, 21, 22).

UNDERSTANDING THE GROUND REACTION CURVE – THE KEY TO ALL SUPPORT DESIGN

The ground reaction concept is a method that relates the support pressure to the convergence of the mine opening. The goal of any support design is to achieve equilibrium of the rock mass. The question is always the same, how much support is needed to accomplish this objective? The ground reaction concept can answer this question. The ground reaction concept is not a new idea. It has been around for several decades and was used in the tunnel industry (23). So why the big deal about it now? The problem with the ground reaction concept is not so much that is not useful, the problem is how do you get the curve. While in theory it can be done by taking measurements of support load and convergence in the mine, in practice it is difficult to do because the support pressure must be varied to get the curve. The problem is that the support system is not varied (most mines will find a support that works and stick with it or make small changes in support capability not large ones), and the mine loading conditions are not controlled enough to develop a curve. The result is that only bits and pieces of the ground reaction curve is ever developed from empirical data.

However, the advancements made in numerical modeling are providing new opportunities to develop ground reaction information. The key issue is that the modeling is no longer constrained by elastic analysis and homogenous materials. Finite difference software such as FLAC (24) can be used to develop meaningful ground response curves. The software is able to realistically model rock behavior from the initial elastic response to the large displacements and deformations that are associated with rock failure. It has the capability to model strength anisotropy found in the bedded coal measures and can simulate strain related weakening of failed rock. The software also has a built-in programming language which allows the user to control loads and displacements in the model. By applying internal pressure to the entry excavation, such as a longwall tailgate, the ground response curve can be determined (25). Once this is done, more appropriate design criteria for roof support can be developed.

The concept has been described in detail in other papers and will only be briefly summarized here to facilitate a further discussion of its significance in developing support design criteria (25). The ground response curve plots the support pressure against the convergence, as shown conceptually in figure 13. Prior to excavation, the excavation boundaries are subject to pressure equal to the field stresses (point A). After the excavation is created the boundaries converge and the pressure required to prevent further convergence reduces as arching and the self-supporting capacity of the ground develops (point B). A point is reached (point C) where loosening and failure of the rock occurs and the required support resistance begins to increase as self-supporting capacity is lost and support of the dead weight of the failed ground is required (point D). The effect of the support system can also be plotted on the chart. Equilibrium is achieved when the support curve intersects the ground reaction curve (point B).

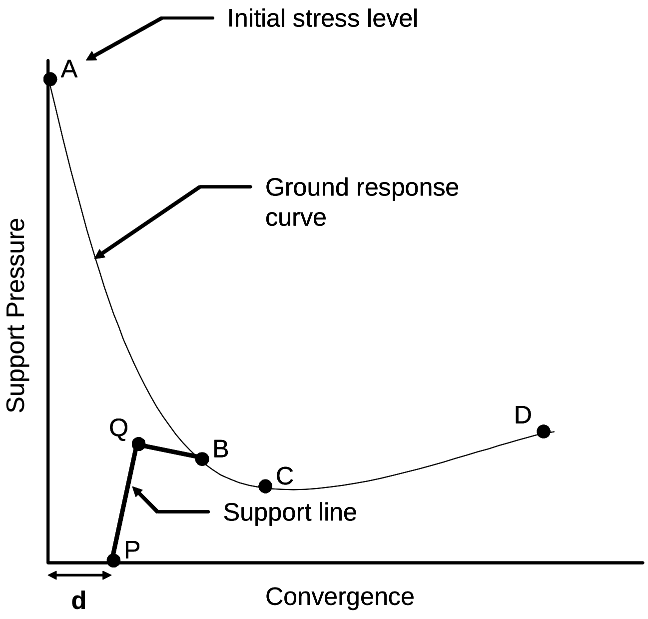

Figure 13 – Conceptual illustration of ground reaction curve.

One example for a longwall tailgate condition is shown in figure 14. Here, a typical three-entry tailgate representative of a Pittsburgh seam mine geology is modeled (25). The ground response curve was developed by simulating a uniform support pressure on the roof and floor of the tailgate entry, while sequentially modeling the four external loading stages. Internal pressures of 0.01 tons/ft^2 up to 26 tons/ft^2 were applied to provide a range of results that would bracket the typical range of standing support capacities. Ground response curves were developed by plotting the support pressure against the convergence for each loading stage. The model therefore produced four ground response curves, one for each loading stage. The results show that, up to the face abutment loading stage, the ground response curves are steep and convergence is limited to less than about 3 inches. The curves also show that the convergence is not dramatically affected by the amount of support. This indicates that this convergence is largely uncontrollable from the perspective of the standing support. The inby situation results in larger convergence values, more than 4 inches for 26 tons/ft^2 support resistance and apparent collapse is indicated when the support resistance is less than 0.26 tons/ft^2. Also plotted on this curve are the support responses for two rows of conventional 4-pt wood cribs and a single row of 30-in-dia pumpable supports on an 8-ft spacing. As seen from the intersections of the support response with the various ground reactions curves, it is concluded that the there is little impact of the stiffer, higher capacity pumpable crib outby the longwall face since most of this convergence is uncontrollable. Inby the face, the pumpable crib yields and provides about the same degree of control 98 ft inby the face as the wood crib in this particular model. From this perspective, there is no clear advantage of the pumpable crib over the wood crib. It should be noted that this model is still considered a research effort. There are issues pertaining to the two-dimensional aspects of the stress conditions and localized failures around the support itself that are fully addressed in this example. Additional research is planned in this area as part of the NIOSH ground control program.

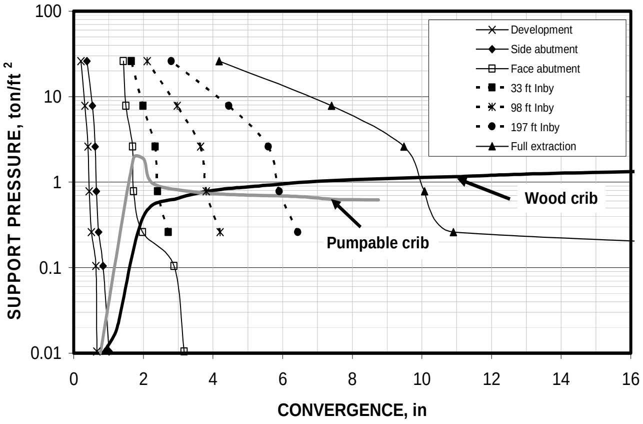

Figure 14 – Example of a ground reaction curve for longwall tailgate developed using 2D Flac numerical model.

Can the ground reaction concept be applied to shield supports? The information shown in figure 3 that was previously presented to discuss the impact of setting pressures is actually a ground reaction curve. The curve not only shows that an optimum setting load exists due to the rapidly diminishing impact of setting loads as they increase beyond the inflection point in the curve in figure 3; but the response to the left of the inflection point is a clear indication that one is approaching uncontrollable convergence produced by the main roof activity, which is well beyond the capability of even modern day shield supports. The loading produced by this activity must be considered in defining the yield load capacity of the shield.

Terry Medhurst has used the ground reaction concept to evaluate design issues for shield support in Australian longwall mines (22). Medhurst used the ground reaction concept to evaluate the impact of support settting pressure, hydraulic leakage of leg pressures, support capacity, extraction height, and extraction depth. Conclusions and comments drawn from his work are summarized as follows:

- ***Longwall mining and the resulting support response is largely dictated by convergence - controlled loading.*** – I completely agree and would take this one step further. As discussed before, what this is saying is that the roof behavior (particularly the overburden response) is governed by the stiffness of the supporting elements that include the coal seam, and the gob. Since the shield does not control the stiffness or properties of these elements, the shield, regardless of its capacity, is being loaded in proportion to its stiffness. In other words, this convergence is uncontrollable from the perspective of the shield design.

- ***The successful application of longwall support technology in recent years might be partly due to close matching of the support stiffness with the coal seam stiffness.*** – While I would like to believe that this was by design, both Medhurst and I believe it is far more coincidental than it is by design. His point is that assuming that the coal seam yields at about 0.5% strain (based on laboratory testing of coal samples), the required shield stiffness can be determined. With similar stiffness, this will help ensure a uniform vertical compression profile and minimize mining-induced shear stresses in the immediate roof. For example, a 10-ft seam would produce about 0.5 inches of convergence from the abutment loading before it fails, indicating that a shield should accommodate about 0.5 inches of convergence beyond the setting load to reach the yield load and this is consistent with modern shield stiffness measures. This reasoning would also imply that the shield stiffness by design should be adjusted as a function the extraction thickness and abutment loading (i.e. depth of cover), neither of which are done.

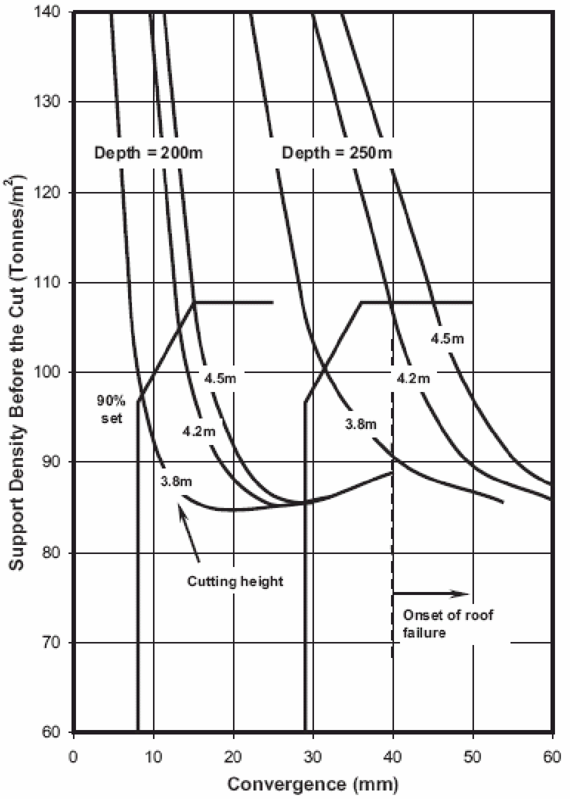

Figure 15 – Impact of depth of cover and extraction height on longwall face ground reaction curve (from Medurst).

- ***Higher extraction heights require higher capacity shields.*** – As shown in figure 15, the ground reaction curve shifts to the right and slightly upward as the extraction height increases. At higher extraction heights, the coal seam stiffness is reduced; additional face spalling is likely which increases the roof beam deflection and the roof span supported by the shield. One other point, which is not shown in Medhurst's curves, is that the shield stiffness is also reduced with increasing extraction height.

- ***Setting pressures are critical in weak roof conditions to preserve confinement of the roof beam.*** – It is here where we hope that the shield can provide meaningful control. The goal is that the shield pressure will reduce the convergence of the immediate roof beam, thereby helping avoid loss of confinement that may result in the formation of roof cavities. As Medhurst correctly points out, the impact of the support pressure decreases fairly rapidly as the distance from the canopy into the roof increases (he claims the effective zone is about 3 ft). Hereafter, the stability is dependent on the self-confining effects of the roof strata. From a ground reaction perspective, lower shield capacity and/or stiffness, can allow increased convergence, thereby increasing the likelihood of failure of the immediate roof beam.

- ***Leaking cylinders result in more convergence and poorer roof conditions.*** – This one is obvious to anyone who has ever looked at a ground reaction curve. Leaking cylinders essentially means you are moving down the curve, allowing more convergence. Get to the bottom of the ground reaction curve or miss the curve, and guess what --- trouble.

While Medhurst has done well to incorporate the concept of the ground reaction curve into shield design analysis, I think the concept can be still be improved by separating the global conditions from the more localized conditions that occur on a shield by shield basis. As Medhurst correctly points out, the ground reaction curve moves to the right for increasing depth of cover and increasing extraction heights, two global factors that influences ground response and shield loading. Locally, the ground response is also affected by the shearer cut and adjacent shield moves. If you consider a three-shield environment, the ground reaction curve might look like something shown in figure 16. When a shield is lowered, the support pressure in that particular shield drops to zero. While this hardly affects the support resistance across the entire face, it does lower the support resistance locally, i.e. over a three-shield area. As this particular shield is reset against the mine roof (point A on the first curve), the setting pressure increases from zero at roof contact to the full setting pressure, normally the pump pressure less frictional losses in the delivery system. As the setting pressure is increasing from the initial roof contact, the load path is the up the first curve, indicating that the convergence is actually decreasing during the setting operation. Since the ground reaction curve is steep, the decrease in convergence is relatively small, but measurable nonetheless (point B on the curve). Physically, the support pressure is compacting debris on top of the canopy or under the shield base or compacting loose rock debris along bedding planes that have been damaged from shear stress along these laminations resulting in some bulking or dilation of rock material, or simply closing openings within the roof structure. At this point, the ground reaction curve will remain static until there is a change in load conditions. Since the adjacent shield is also being reset in short order, the ground reaction curve shifts to the right from this activity and the loading on the first shield increases in proportion to the shield stiffness (point C). The conditions remain nearly static once the shearer leaves the vicinity of the local area. Then, as the shearer approaches the local area and takes a cut from the face, the ground reaction curve again shifts to the right and the first shield again sees an increase in loading in proportion to its stiffness (point D). Release of the other adjacent shield again causes a slight shift in the ground reaction curve, again increasing pressure on the monitored shield (point E). The support is now at peak loading for the cycle, and as it is lowered, it follows down the ground reaction curve that it is currently located on until it loses contact with the mine roof. At this point (F), the shield is advanced and reset and the conditions are restored to the initial ground reaction curve (point A).

The individual shield will then follow this cyclic load path from cycle to cycle (A, B, C, D, E, F). The ground will be stable as long as the shield has a load path (ground reaction curve) to follow that can complete the load cycle. If the shield fails to provide adequate support resistance to stay on a ground reaction curve that can complete the cycle as illustrated in figure 17, equilibrium of the ground is not achieved and unstable conditions are likely to prevail. This could be caused by inadequate set pressures, leaking leg cylinders, or dramatic shifts in the ground reaction curve by such things as periodic weighting induced by the intermediate roof structure.

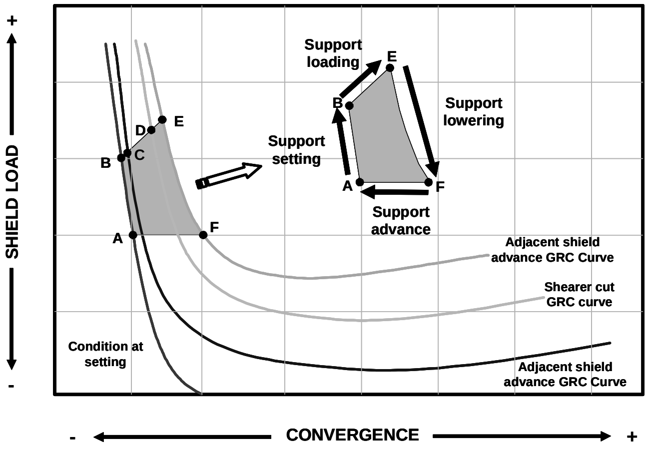

Figure 16 – Cycle loading pattern on ground reaction curve for individual or small group of shields.

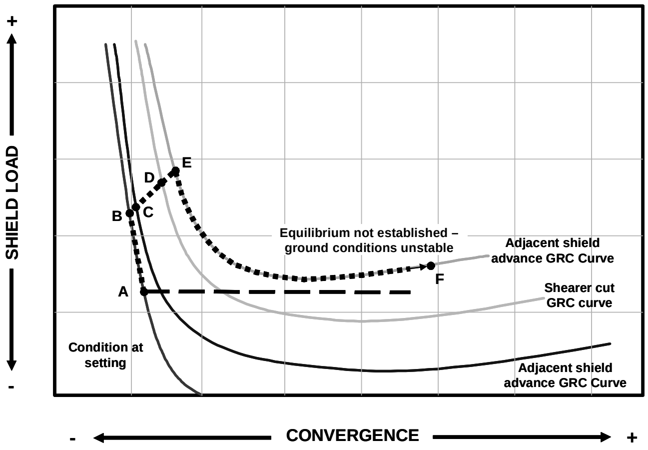

Figure 17 – Equilibrium is not established in this shield loading cycle due to inadequate shield setting force.

This type of analysis may also be useful to reexamine the impact of yielding. Each yield event drops the support pressure, and equilibrium is reestablished through additional convergence, i.e., moving down the ground reaction curve to a condition of less stability. As you move down the ground reaction curve though successive yielding events, the convergence required to reestablish equilibrium grows. In addition, the premise thus far has been that you remain on the same ground reaction curve. If the yielding degrades the immediate roof structure, then the ground reaction curve may will be shifting to the right, and thereby cause a dramatic increase in convergence required to reestablish equilibrium and substantially reduce the number of yielding events that will create poor ground conditions.

SUMMARY AND CONCLUSIONS

The full potential of longwall mining was not realized until powered roof supports, particularly shield support systems, were developed. The stability of the shield permitted the application of longwall mining in conditions where caving was difficult to control and where chock and frame supports were inadequate.

Shield capacities continue to increase as a "bigger-the-better" philosophy prevails in longwall mining throughout the world. Several 1,280-ton shield systems are now in operation in U.S. coal mines. Several models have been developed based on theoretical and empirical support and strata interactions to determine shield capacity requirements. However, it is difficult to justify the current capacities strictly in terms of ground control requirements. Increasing the life expectancy of the shield has become a driving factor in current shield design and capacity considerations.

The increase in shield capacity has resulted in higher setting forces. Historically, mine operators have welcomed the higher setting force capability under the premise that it will help to strengthen the immediate roof beam by increasing the frictional restraint between bedded layers, and provide additional active horizontal loading to provide further confinement to the face-to-waste strata movements that lead to roof falls in front of the shields. However, rock mechanics theory and limited underground shield loading data suggest that there is an optimum setting pressure that state-of-the-art high capacity shields may have exceeded. More research needs to be conducted to determine optimum setting pressures in order to provide the most effective ground control in various mine geologies while maximizing the life of the shield.

An often overlooked consequence of the increase in shield capacity is an increase in shield stiffness. If there is a strata control benefit in using higher capacity shields, it may well be due to their increased stiffness more so than their increased capacity. By developing the supporting forces more quickly in relation to the face convergence, the stiffer shields may reduce separation of immediate strata layers and minimize movement of the rock along fracture planes that lead to premature roof failures. Conversely, when the face convergence is irresistible, as is the case with main roof and overburden loading, the increased shield stiffness will result in higher shield loading. Since the stiffer shields will use up their available capacity as a passive support in irresistible strata movements more quickly, they will be fully loaded to their yield capacity as frequently as the less stiff, lower capacity shields they have replaced. In this scenario, one should not expect an improvement in the life expectancy of the high capacity shield over that of the previous generation of supports. This provides further justification for optimizing the setting forces, since the final support load will largely be dependent on the setting loading.

Significant advancements have been made in standing roof support technology for longwall mining. Over 50 new support concepts are now available for longwall tailgate support. These new support products have shown to provide superior roof control as well as material handling advantages that ease installation requirements. Full-scale testing in the NIOSH Mine Roof Simulator has provided accurate information on the performance characteristics and limitations of these support products. The NIOSH STOP software has helped to eliminate trial and error approaches to application of these support products by providing performance and design information in an easy to use design tool for standing support.

Yet, with all these improvements in roof support technology, there is still a poor understanding of exactly how the support interacts with the strata to provide ground control and how much control it actually provides in this process. The ground reaction curve is a means to help answer these questions and provide a better engineering design approach to ground control than can lead to optimization of support designs and application strategies. Numerical modeling has matured to the point where it can provide the means to more easily evaluate ground reaction implications than are possible through empirical in mine studies, but the models need to be calibrated with field data and more of these studies need to be done. The procedure can be applied to all support, including longwall shields to help answer the question about how much support is really needed. The “bigger-the-better” design philosophy cannot last forever and is already based on false pretenses. Actually, obtaining a ground reaction curve for longwall faces is as easy as it gets, simply lower the setting pressures in a controlled manner and monitor the change in loading which can be back calculated to convergence through the shield stiffness and you have a ground reaction curve. Hey, lets go try it!

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