LONGWALL SHIELD AND STANDING GATEROAD SUPPORT DESIGNS – IS BIGGER BETTER?

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ABSTRACT

Roof support systems, longwall shields in particular, have persistently grown in size and capacity for the past 25 years. Why is this? Is it a good thing or is it unnecessary? What are the consequences of this "bigger-the-better" design philosophy? Rarely do we see a "one size fits all" approach to roof support except when it comes to longwall shields, where the historical trend for new procurements is to simply purchase the highest capacity support you can buy. Does high capacity ensure failures will not occur? The answer is no! The highest capacity tailgate supports are typically the ones that fail the most often. What does this tell us? It tells us that there are fundamental aspects of support design and ground control that we still do not understand or recognize when designing a support system. This paper provides an interesting evaluation of these issues and proposes a different approach to support design that attempts to match the support performance characteristics to the ground behavior. Along the way, some of the old premises of support design will be discarded, and new "controversial" ideas developed. Thinking outside the box never hurt any industry. Mining has made it a common practice.

Introduction

The debate about whether bigger is better obviously refers to the support capacity not the size of the support, although in some cases the two are related. The debate is really about the degree of control that manmade supports have on ground behavior in underground mining. The key issue is whether the support system causes the ground to act in force or displacement control. The reason this is so important is that they have opposite effects in terms of support design requirements. In a force-controlled load environment, the goal is to provide enough support capacity to offset the rock load and provide equilibrium of the rock mass. Conversely, in a displacement-controlled load environment, the ground movement is not influenced or completely controlled by the support. The goal is to maintain support stability and roof support capability as convergence inevitably continues.

With this background, this paper will evaluate the "bigger-is-better" design philosophy for longwall shields and standing roof support systems. The conventional support design approach based on simplistic models of supporting the full dead weight of detached rock masses is replaced by a ground reaction design approach. Here, the goal is to match the support characteristics to the ground response, and not to try and overpower the ground forces with some massive support capability. The ground reaction concept embodies both the force and displacement controlled loading aspects, and therefore provides a more accurate representation of the support loading requirements.

Does anyone think that shield capacities can continue to increase forever? Obviously, they cannot. So at some point, more rationale design must prevail. Although standing supports have grown in capacities as well during the past 15 years, higher capacity standing supports can certainly still be designed. However, the highest capacity supports are typically the ones that fail prematurely. What can we learn from these failures?

There are also design issues that are often a derivative of the pursuit of higher capacity support systems. For example, the desire to provide higher setting pressures is one of the reasons given for wanting to have higher shield capacities. The impact of these issues will also be addressed and here too some surprises are revealed.

Key Points in Current Shield Design

The basic shield design has changed very little since its inception in the 1970's. The primary change has been a steady increase in shield capacity as shown in figure 1, resulting in larger hydraulic cylinders and support structures (U.S. Longwall Census, 2005). A few key points in shield design and behavior will facilitate the ensuing discussion on shield design issues.

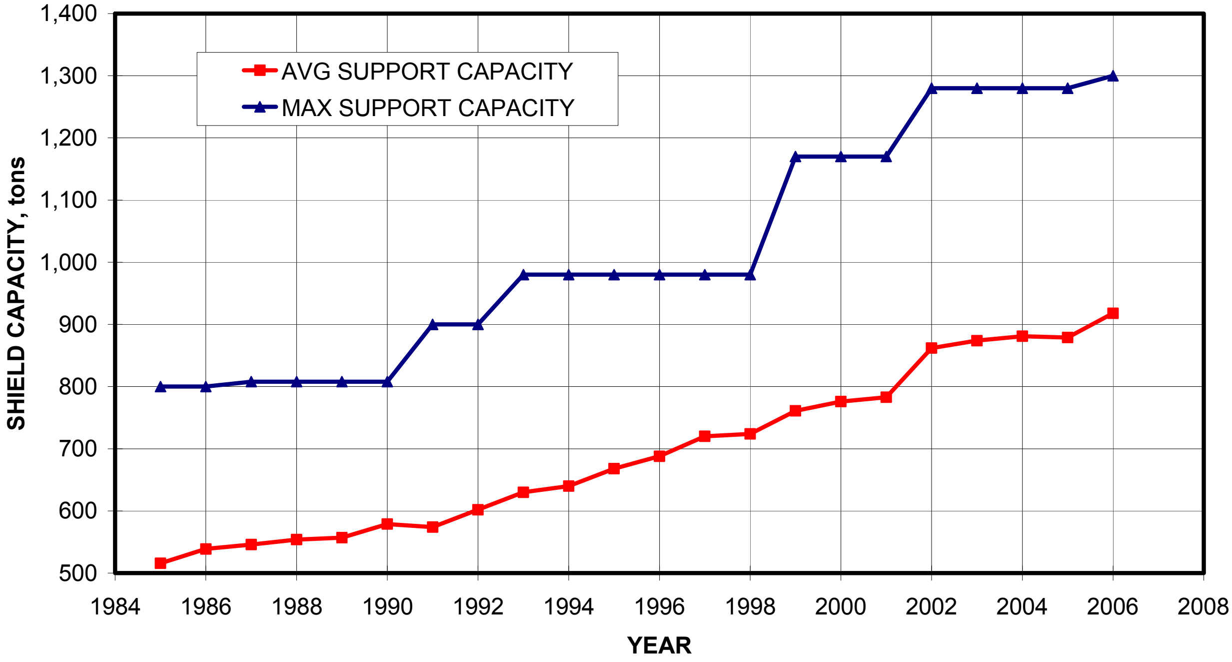

Figure 1 - Historical overview showing trend of increasing shield capacities during past 20 years.

- ***Capacity increased by increasing leg diameter*** – The approach used to increase shield capacity has always been to increase the diameter of the leg cylinder while maintaining the same yield pressure, which limits the load carrying capacity of the shield.

- ***Shield stiffness increases in direct proportion to the capacity*** – The approach used to increase shield capacity by increasing the leg diameter also results in a direct increase in shield (vertical) stiffness. This means that a higher capacity shield will develop more loading for the same roof-to-floor convergence than will a lower capacity shield. The caving shield-lemniscate assembly has no vertical stiffness and does not contribute significantly to the rated shield capacity. The stiffness of the shield is a function of the stage extensions (all current shields are two-stage designs). In general, the stiffness of the shield reduces as the mining height increases due to the cylinder extension.

- ***Setting pressure does not increase shield stiffness*** – The setting pressure provides an active force to the mine roof and floor, but does not change the stiffness of the shield.

Hence, regardless of what pressure the shield is set at, its reaction to convergence in terms of load development will always be the same at least for the same operating height and leg extensions.

- ***Canopy and base pressure distribution is not uniform*** – Although this assumption is often made in analyses of shield performance and used to justify higher capacity needs for larger supports, the pressure distribution is far from uniform. On the canopy, the pressure is focused near the leg connection, with very little and sometimes no significant pressure at the forward tip of the canopy. Conversely, the kinematics of two-leg shield designs tend to focus the pressure near the toe of the base.

- ***Yielding lets fluid out of the leg causing it to lower*** – Yielding is accomplished by releasing hydraulic fluid from the leg cylinder, which causes the leg to lower a slight amount during each yield event. The resetting pressure of the yield valve will determine how much fluid is lost and how much closure will occur. Most yield valves have a resetting pressure of 90 pct or higher, meaning the pressure will decrease by 10 pct before the yield valve closes.

The Ground Reaction Concept

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 in the tunneling industry (Brown et al., 1983). The problem with the ground reaction concept is not that it's not useful; the problem is how you develop 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. For longwall shields, the curve (at least part of it) can be determined by lowering the setting pressures in a controlled series of steps and calculating the convergence from the resultant shield loading assuming the stiffness of the shield is known.

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 (Itasca, 2005) can be used to develop meaningful ground response curves. The software can be used 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 face or tailgate entry, the ground response curve can be determined (Esterhuizen and Barczak, 2006). Once this is done, more appropriate design criteria for roof support can be developed.

The ground response curve plots the support pressure against the convergence, as shown conceptually in Figure 2. 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).

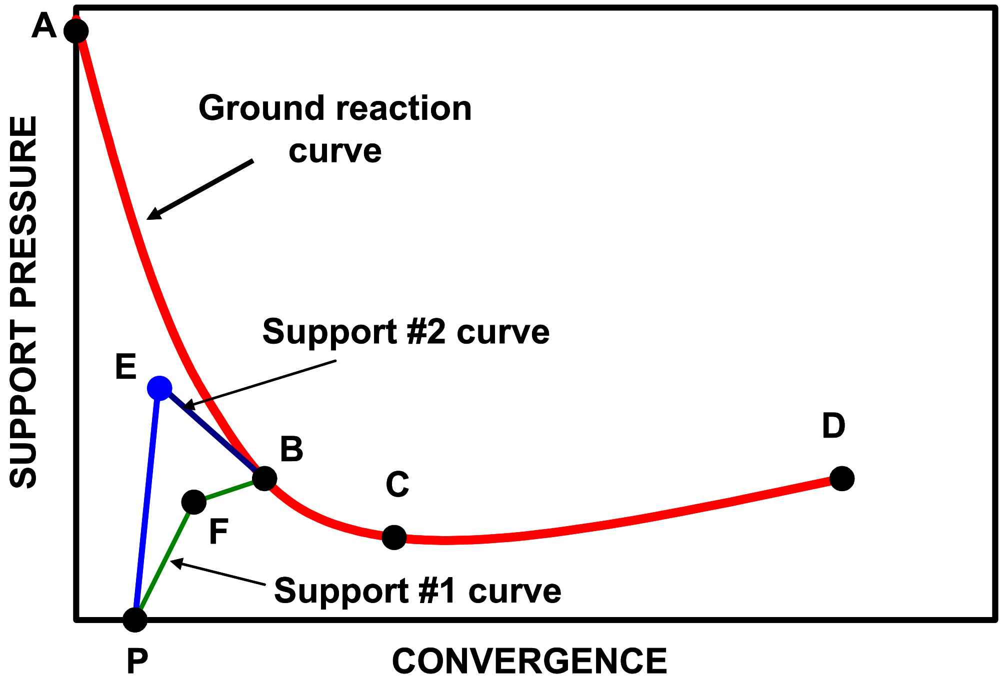

Figure 2 - Conceptual illustration of ground reaction curve and support response.

The effect of the support system can also be plotted on figure 2. Equilibrium is achieved when the support curve intersects the ground reaction curve (point B). Using two hypothetical support responses as shown in figure 2, two key points can be made regarding support design. The second support has a higher ultimate capacity (point E) than the first support (point F), but both reach the ground reaction curve at the same spot. This shows that higher capacity does not necessarily ensure better ground control. It also shows that from the perspective of the available support capacity, there is a component of ground response (convergence) that cannot be prevented by the support system. Hence, a degree of "uncontrollable convergence" exists, and this must be accounted for in the support design.

Applying the Ground Reaction Concept to Shield Design

Can the ground reaction concept be developed and applied to shield supports? Absolutely. It has been widely accepted that increased setting pressures provide improved ground control by reducing face convergence. Field measurements of setting pressures when plotted against convergence produce a trend curve similar to that shown in figure 3. This is a ground reaction curve. As seen from the curve, higher support pressure results in reduced convergence, but it also shows that an optimum setting pressure exists due to the rapidly diminishing impact of support pressure beyond the inflection point in the curve in figure 3. It is also evident from this graph that 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.

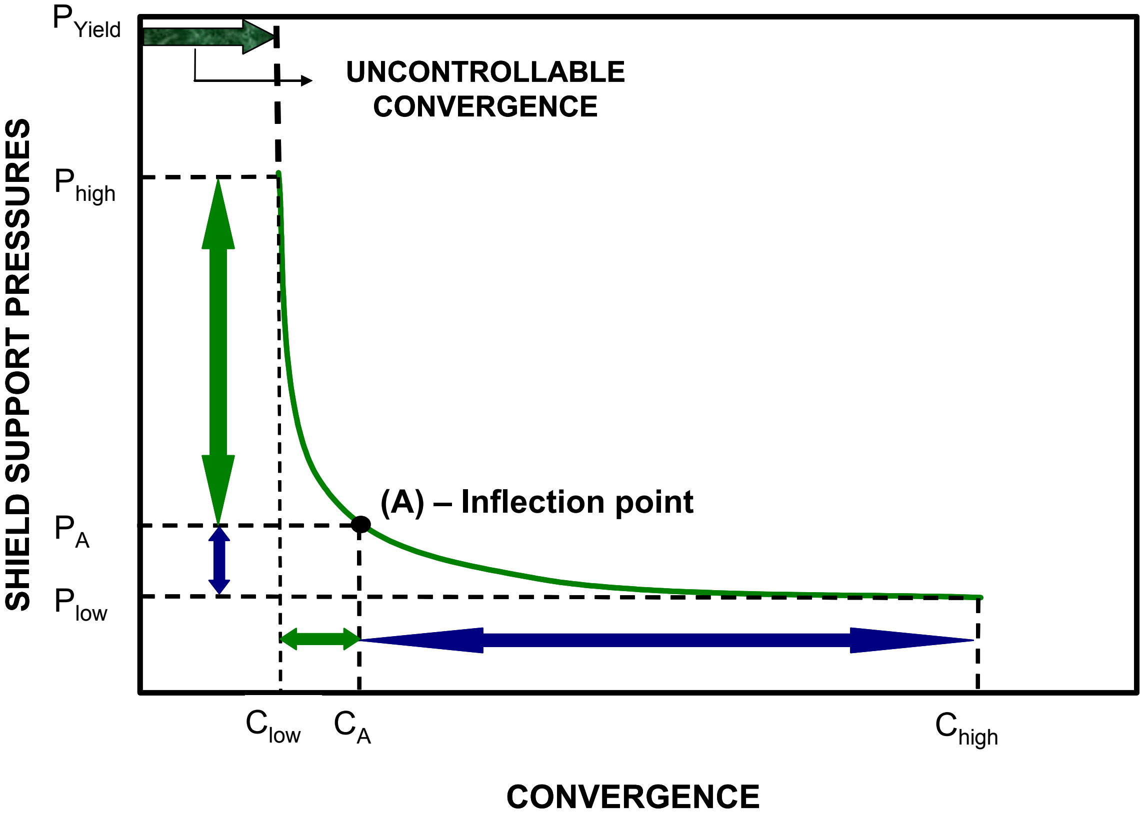

Figure 3 – Impact of shield capacities (setting pressures) on convergence.

Medhurst has incorporated the concept of the ground reaction curve into shield design analysis (Medhurst, 2005). As Medhurst correctly points out, the ground reaction curve is dynamic in the sense that it changes with changing conditions. For example, the curve moves to the right for increasing extraction heights as shown in figure 4, indicating the higher capacity shields will be needed to accommodate the increase in face convergence associated with the reduction in coal seam stiffness at the higher extraction height. Deeper cover will cause higher abutment loading, which increases the scale of the support resistance axis and essentially causes the ground reaction curve to shift to the right, again implying higher shield capacities are required. Periodic caving would do a similar thing; push the curve to the right and upward, causing higher shield loading. Therefore, it is important to realize that the ground reaction concept essentially consists of a family of curves, each representing a unique loading condition.

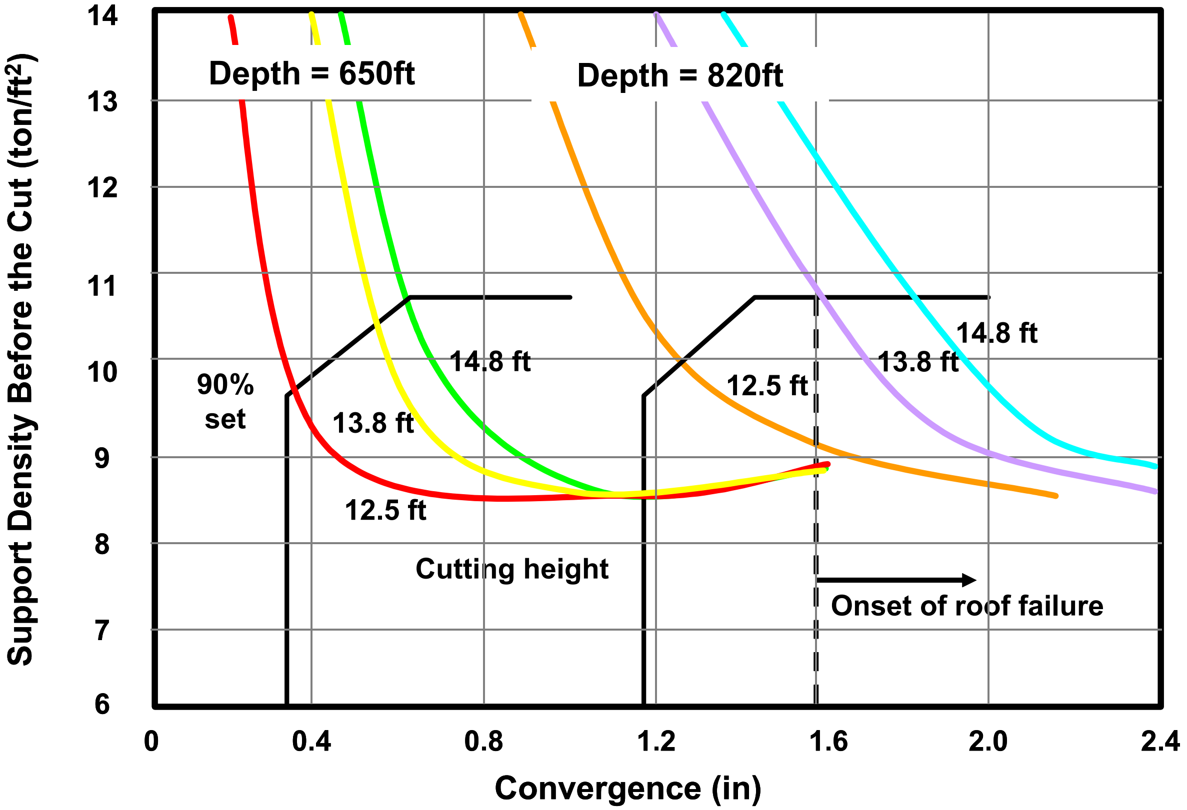

Figure 4 - Impact of depth of cover and extraction height on longwall ground reaction curve (from Medhurst, 2005).

Examining Individual Loading Cycles from a Ground Reaction Perspective

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 5a. 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 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 reapproaches 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).

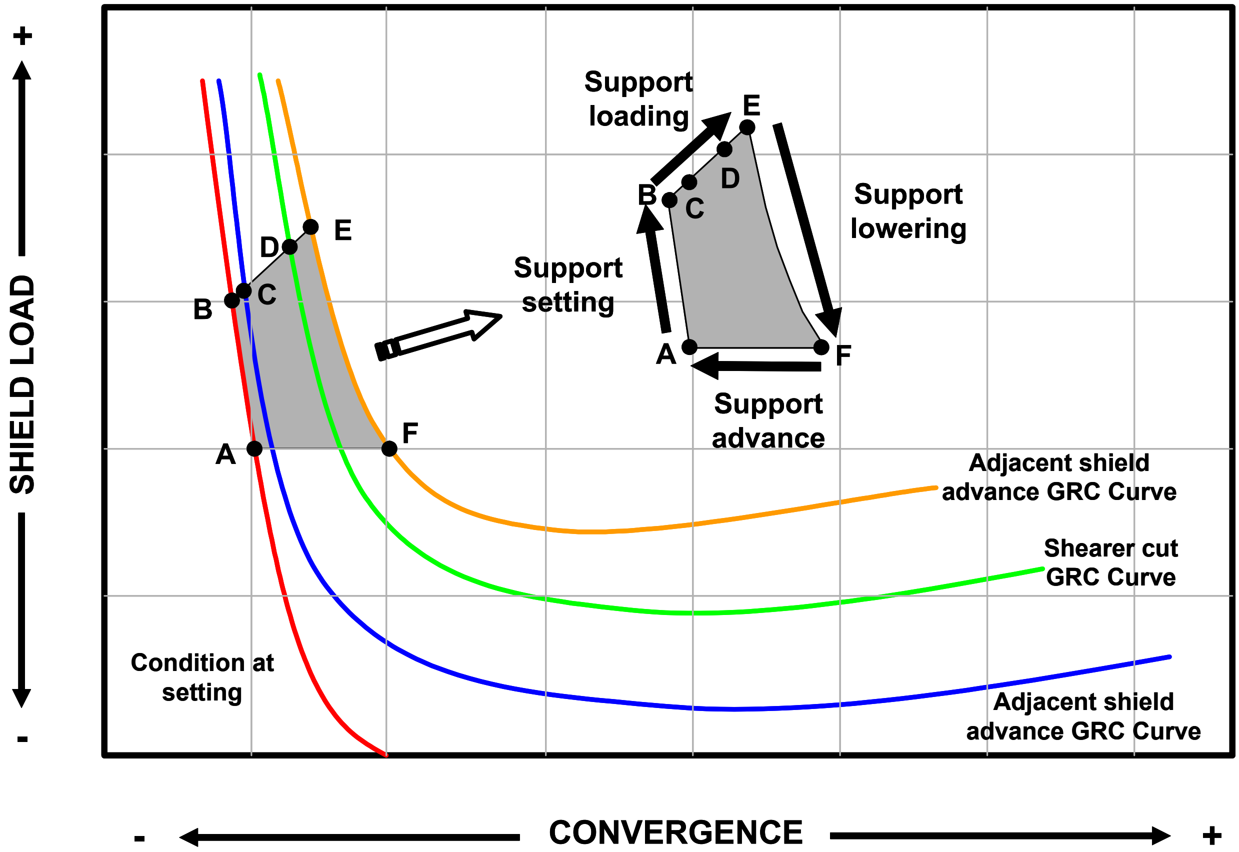

Figure 5a - Cycle loading pattern on ground reaction curve for individual or small group of shields.

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 5b, 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.

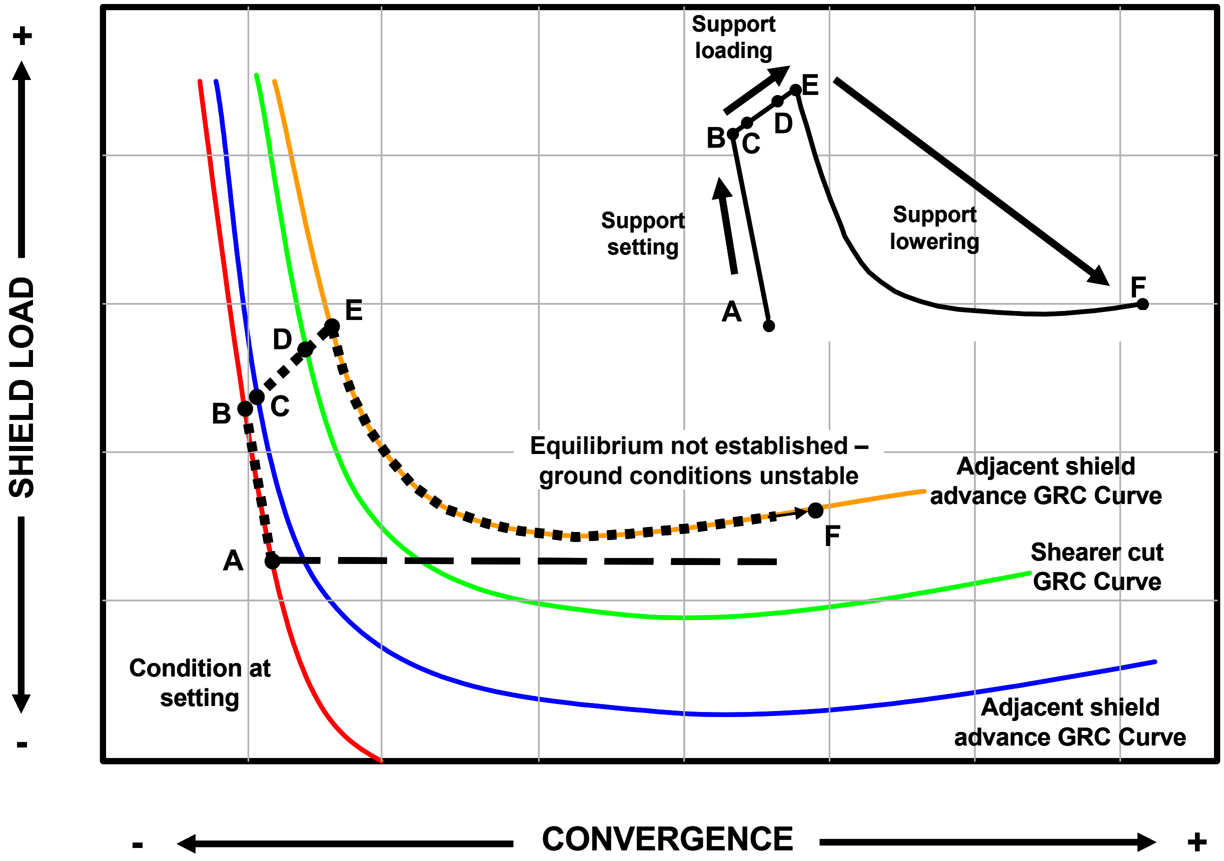

Figure 5b - Equilibrium is not established in this shield loading cycle due to inadequate shield setting force.

Comparison of the Ground Reaction Concept to Other Models Used for Shield Design

Wilson was the first to promote the detached block-loading concept back in the early 1970's (Wilson, 1975). 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 6). 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. This is a strictly force-controlled loading concept and as such does not fit well within the confines of the ground reaction concept. 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 a 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.

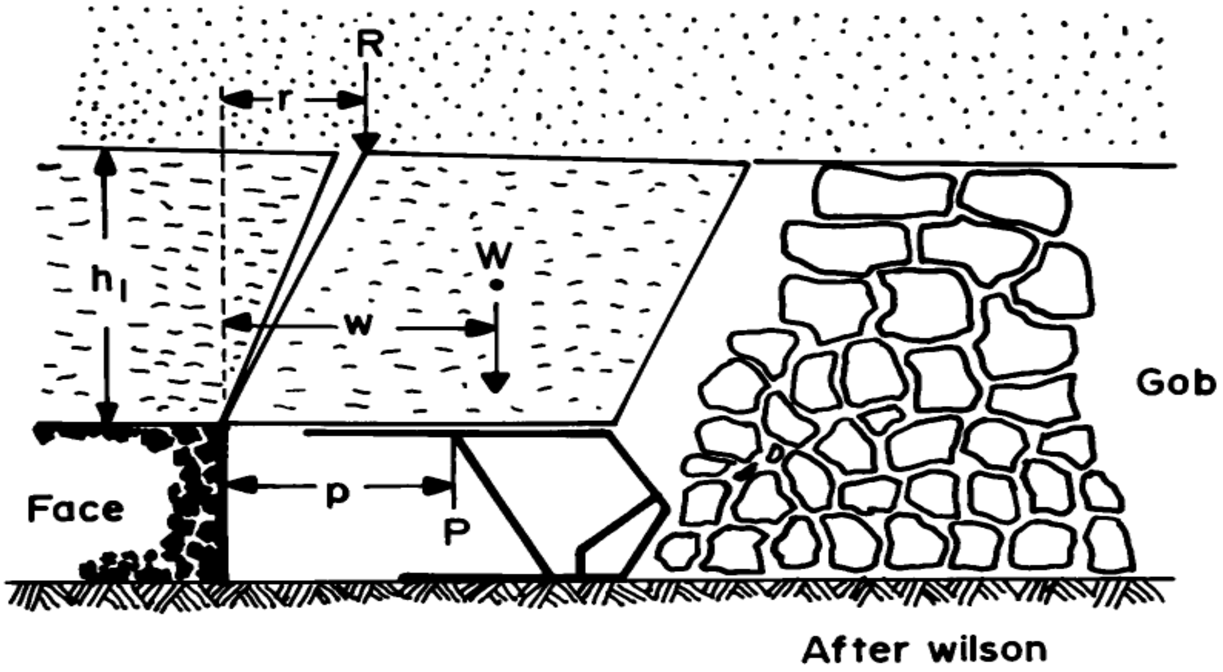

Figure 6 - Detached block model of longwall roof behavior.

A more realistic model of longwall rock mechanics is the stiffness model promoted by Smart (Smart, 1986). Smart suggested that the powered support was one of three yielding foundations, which support the immediate cantilevered roof and bridging main roof strata. The other two elements being the coal ahead of the face and waste (gob) behind the face (figure 7). 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 prevent the formation of the detached block condition promoted by Wilson. The key to Smart's concept is that the stiffness of the coal largely controls the shield loading and design requirements. In particular, Smart hypothesized that the reason U.S. 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. This model fits nicely with the ground reaction concept for shield design. First, it uses convergence as an outcome measure of the ground response based on the stiffness of the various supporting elements. Moreover, it allows for a component of uncontrollable convergence from the main roof loading relative to practical shield capacities.

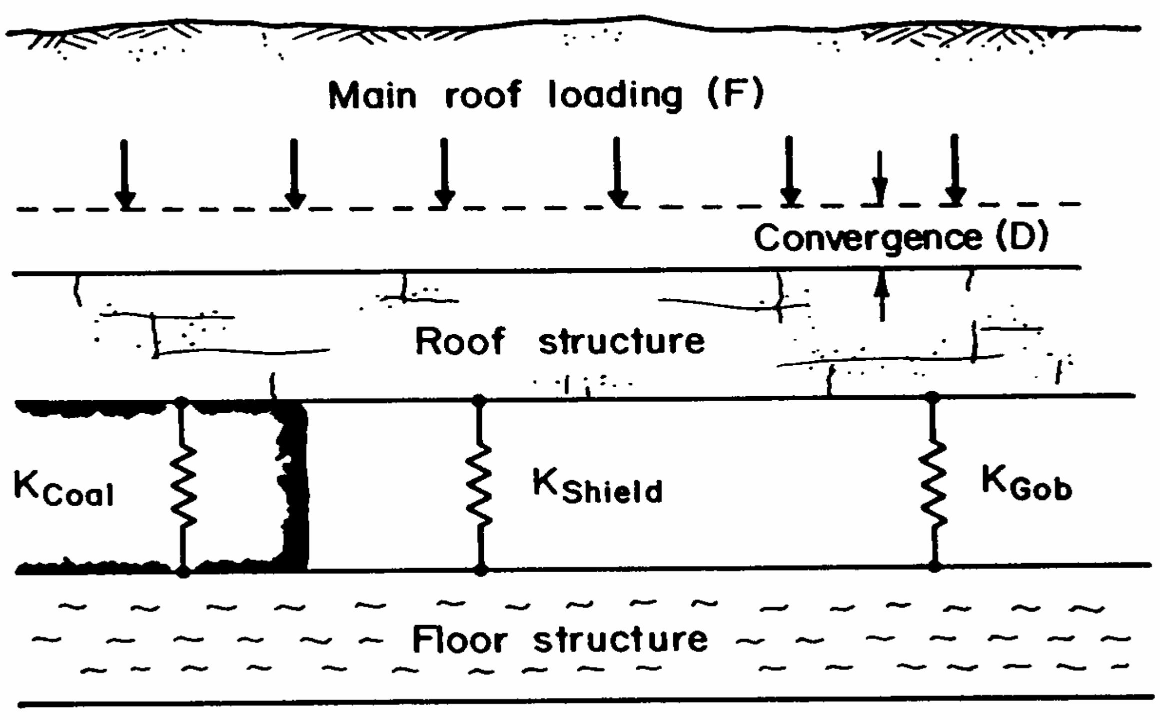

Figure 7 - Concept for evaluating roof shield response based on the stiffness of the shield, coal, and gob foundation.

Implications Toward Shield Design Requirements

Stiffness Considerations

The ideal situation would be one in which the mine roof does not know that the coal has been mined out from beneath it. In the global scale of the full panel, this is obviously quite impossible since the single row of shield supports would have to completely offset the full panel load of the overburden to prevent caving. On the more local scale of the supported advancing longwall face, the goal would be that the roof does not know the coal is mined out from beneath it at least to the point of the cave behind the shield line. To achieve this goal, the support design requirement should be to match the shield stiffness to that of the coal seam stiffness to provide a balanced stress distribution in the face area. Some researchers suggest that the reason why modern high capacity shields provide better ground control is that the increased stiffness of the higher capacity shields more closely matches that of the coalface structural stiffness. This would be one justification for increasing shield capacity under the premise that lower capacity shields were considerably less stiff than the coal structure, such that there was a large imbalance in stress acting on the immediate roof due to the degraded shield capacity compared to that provided by coal structure.

Evidence to support this claim is provided by Medhurst (2005). 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. This indicates 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 and setting practices where the set pressure is about 70 pct of the yield pressure.

This reasoning would also imply that the shield stiffness, by design, should be adjusted as a function the extraction thickness (lower stiffness required at higher seam extractions). Here too, the shield response is favorable in that the shield stiffness is reduced with operating height. Therefore, assuming the shield stiffness is correctly matched, one shield design should function reasonably well through the full range of operating heights.

Is Yielding a Good or Bad Thing?

Generally, yielding is good from the perspective of the shield and bad from the perspective of the roof. 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 the lowering of the support canopy. Simply translated, whenever the shield is yielding the roof is moving down. Downward displacement of the roof is generally an indication of reduced stability of the rock mass.

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 (Barczak and Gearhart, 1998). It would take several hundred to over a 1,000 yield cycles to fully eliminate the hydraulic stroke of the cylinder. However, 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 as much as 6 inches of downward roof movement in a typical shield design, or you can become iron bound if there is not enough stroke left in the cylinders.

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 or load condition is strictly acting in force control and the worst case scenario is that 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, support yielding is moving down the ground reaction curve toward a condition of decreased stability, hence, it must be concluded that ultimately yielding is not a good thing.

This ground reaction analysis is also 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 through 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 will be shifting to the right, and thereby cause a dramatic increase in the convergence required to reestablish equilibrium and substantially reduce the number of yielding events that will create poor ground conditions (Barczak, 2006).

Set Pressures

The desire to increase set pressure is another justification given for increasing shield capacity. The primary function of set pressure is to strengthen the immediate roof beam by creating a more laminated structure. The immediate roof beam does provide some control over the behavior of the intermediate roof. Perhaps, more correctly, failure of the immediate roof beam can lead to the stress fractures of the intermediate roof. In the face area, this failure can lead to a detached block that cannot be controlled by the support, almost regardless of the shield capacity. The deflection of the immediate roof beam from the loading of the intermediate roof is the mechanism that produces the reduction in convergence associated with increased set pressures. However, as previously discussed in reference to figure 3, the inflection point of the ground reaction curve indicates that beyond a certain level of set pressure or shield resistance, relatively little benefit is gained in terms of reduced face convergence. Essentially, if the convergence is produced by mechanisms beyond the control of the shield, such as deformation and yielding of the coal face, then increased setting pressures beyond the inflection point could cause premature yielding of the support. In other words, if the goal is to prevent yielding of the support, lowering the set pressure to accommodate the convergence (that cannot be controlled by the shield) can, at times, improve ground control.

The Impact of Leaking Cylinders

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. You get to the trough of the ground reaction curve or miss the curve, and poor ground conditions are likely to occur.

Reading Too Much into Leg Pressure Data

The ground reaction concept suggests that much of shield loading is due to ground responses that are beyond the control of the shield. For example, the shield cannot change the stiffness of the coal face or the gob structure. The overburden and abutment pressures will produce deformations of these structures that cannot be prevented or significantly altered by the shield.

Likewise, the increase in span, as a result of the shearer cut, is going to cause the majority of shield loading in most cases; and here too the shield has limited control. High setting forces and stiff shields will help to maintain better control of the immediate roof beam. This can influence both the intermediate roof response and the span problem associated with the shearer cut, but no matter what the shield capacity, this change in state (movement of the ground reaction curve), will produce shield loading in proportion to the shield stiffness. Ultimately, the shield force is there to control the immediate roof response, build a good roof beam and keep its response coupled to the main roof response. Beyond this, the shield is simply reacting to the main roof activity, which is not controlled at all by the shield.

Since the load environment is largely displacement or convergence-controlled (i.e., not directly influenced by the shield capacity), then shield load (i.e. maximum leg pressure) is not a good indicator of required shield capacity. Just because the shield is heavily loaded or even if it is yielding, does not necessarily mean that the support has inadequate capacity. If the immediate roof stays coupled to the main roof, then the shield response can be dominated by the main roof response and the coal face behavior. In this case, a higher capacity shield will exhibit the same behavior, i.e. heavy loading. In fact, since the higher capacity shield is also stiffer, it may show even higher levels of loading. Without a full understanding of the ground response, it is easy to see how one could jump to the wrong conclusion by focusing only on the shield loading as a measure of the required shield capacity.

Unsupported Roof Span Issues for Shield Design

A study by Langosch showed the relevance of the canopy tip to face distance to the probability of roof falls or cavity formation in front of shields (Langosch et al., 2003). A critical unsupported span was determined based on the thickness and strength of the immediate roof layer or composite roof beam. When the unsupported span stays less than this critical distance, cavity formation is highly unlikely. Underground assessments were made on 14 German longwall faces and an empirical formulation was developed that relates the probability of cavity formation to the following parameters when the unsupported span is exceeded: (1) the shield resistance, (2) abutment stress, (3) directional orientation of stress induced roof fractures, which are likely to be influenced by the disparity in rock strength of the immediate roof and the coal in the longwall panel, and (4) the distance by which the critical roof span was exceeded. Figure 8 shows the relationship for support (load density) capacity for favorable and unfavorable fraction orientation; where favorable fraction orientation is such that the coalface helps to prevent movement along fracture planes leading to the dislodgment of the rock segments. Here too, the trend is the same as that observed with shield resistance and face convergence. The figure indicates a diminishing return in terms of reduction in cavity formation as the shield capacities are increased. For the favorable fracture orientation, shield load densities as low as 3.5 tons/ft^2 reduce the probability of roof falls to less than 10 pct and doubling of the load density to 7.0 tons/ft^2 lowers the probability of roof fall to only a 3 pct.

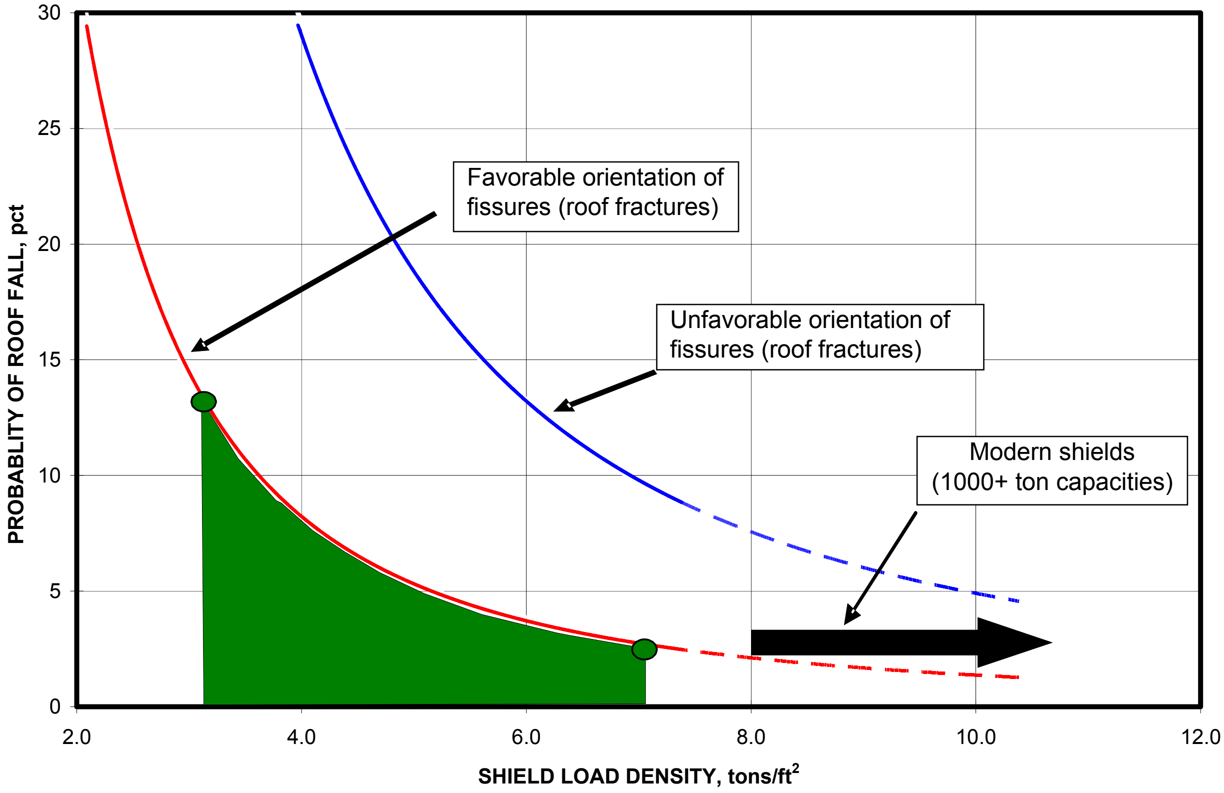

Figure 8 - Impact of shield load density on the probability of roof falls in front of the shields when the critical unsupported span is exceeded (after Langosch, et al., 2003).

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

Active horizontal roof loading is claimed to be one of the 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 acting in the horizontal plane parallel to bedding, 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 9. The key issue is how much horizontal displacement of the canopy occurs, which can be ascertained from the reaction or loading of the lemniscate links.

The lemniscate links develop stress in response to the 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 (Barczak and Schwemmer, 1988). 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.

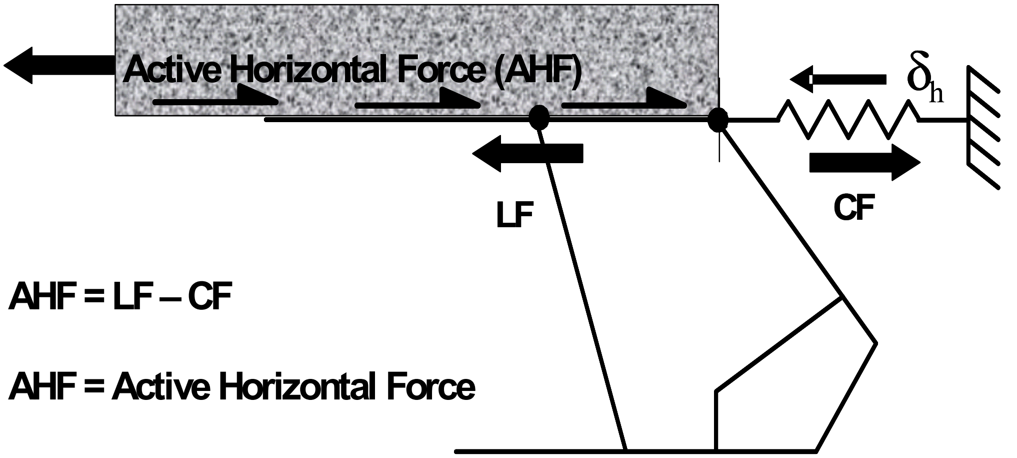

Figure 9 - Shield mechanics showing that caving shield/ lemniscate assembly reaction to forward canopy displacement reduces active horizontal roof loading caused by the horizontal component of the leg force.

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; 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 (Barczak and Garson, 1986). Further, the magnitude of the link forces provide a caving shield reaction force that is close to the horizontal component of the leg force. 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 and not going into the roof. A recent study of link loading on a modern (1,000 ton capacity) longwall shield confirms this conclusion, as shown in figure 10, by showing the strong correlation between the shield leg pressures and lemniscate link strains.

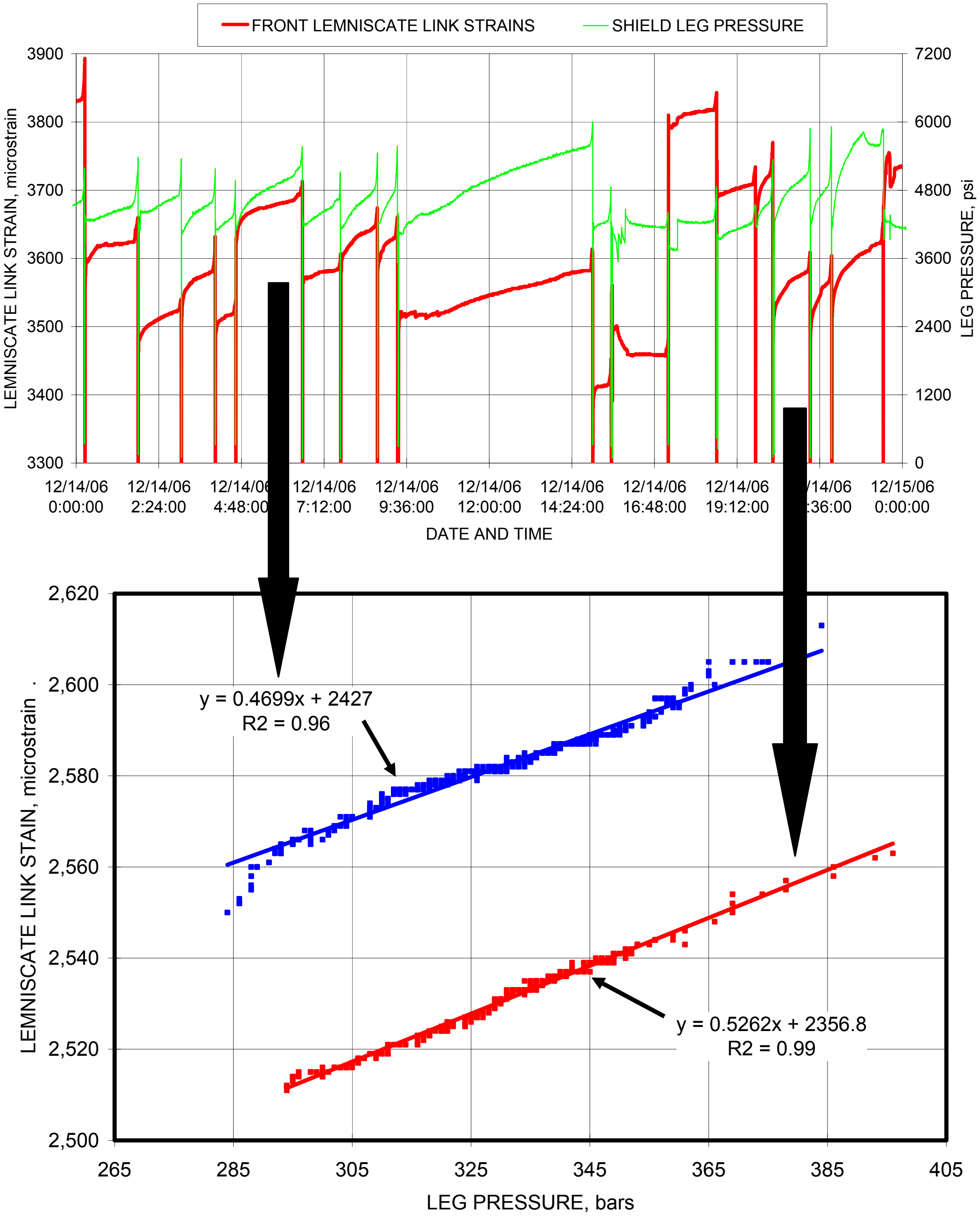

Figure 10 - Comparison of shield leg pressures and lemnsicate link strain.

Dr. Syd Peng directly measured the horizontal displacement of the canopy during the setting operation in one underground study of shield supports (Peng, 1990). He found that as about 0.4 inches of horizontal movement of the canopy was occurring from the time the canopy first contacted the roof to the time full set pressure was reached. The horizontal component of the leg force was computed as 150 tons. A caving shield/lemnsicate assembly stiffness of 384 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 (Barczak and Schwemmer, 1988). Hence, it is likely that most of the force was consumed in link force loading. Dr. Peng also showed that when a steel plate was placed 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 384 tons/in, this difference in displacement would indicate an active horizontal force of about 20 tons, an 80 pct reduction in the full active horizontal load potential had no slippage occurred (Barczak, 2006).

Why do the Higher Capacity, Modern, Shields Last Longer?

Many people believe modern high capacity shields last longer than their lower capacity predecessors ***because of*** their higher capacity. 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. The manufacturers achieve the longer life from better management of the stress in the shield components through improved design. 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. Fabrication methods have improved quality control as well.

Shield Design – Thinking Outside The Box

The modern, two-legged, lemniscate shield design has performed very well and some would argue why change it. Although its performance record supports its effective design, there are design issues which still should be evaluated if further improvements are to be realized. These include:

- **High toe pressure** – Two-leg shields inherently have high toe pressure due to the kinematics of the design. The forward inclination of the leg cylinder, coupled with the reactions of the lemniscate links, produces a resultant force acting on the canopy and base that induce a moment causing high toe pressures.

- **High link forces** – As described in the analysis of horizontal shield loading, the forward inclination of the leg cylinder and potential loss of frictional control on the canopy or base makes the two-leg shield design prone to high link loading.

- **Low tip loading** – Solid canopy designs have prevailed and the canopy ratios have grown to the point where tip loading is getting less and less. Canopy ratios have exceeded the 2:1 limit which is required to provide some roof pressure over the full length of the canopy. Attempts to generate additional tip loading by having the canopy tip project upward structurally leads to additional toe loading.

- **Reduced setting forces at full bottom stage leg extension** – The setting forces can be reduced by as much as 50 pct when the bottom stage is fully extended during the setting operation. The condition is created primarily by having the bottom stage extend and retract first. A design where the bottom stage extend and retract last would solve the problem.

These deficiencies in support performance suggest that alternative designs might offer some additional improvements in shield performance. For example, a more vertical leg orientation would reduce the toe loading and caving-shield lemniscate assembly stress, but would require a longer canopy to preserve full canopy contact pressure. This would be detrimental if the canopy is carrying the full weight of the immediate roof, but would be less of a factor if the roof is acting only as a cantilevered beam. Four-leg shield designs provide more uniform base and canopy loading, but provide multiple load paths that can cause significant reductions in shield capacity if one set of legs act in tension. Another approach might be to include vertical stiffness in the lemniscate design. This could be including a hydraulic cylinder between the canopy connection and the front lemniscate connection. The caving shield lemniscate assembly could also be inverted or reversed. The benefit of this configuration is that it either reverses or repositions the state of stress in the links and loading to the canopy and base to a pattern which reduces the moment that promotes toe loading.

Standing Supports – Clearly Bigger is Not Always Better

Perhaps the misconception that bigger is not always better is best exemplified in standing supports for longwall tailgates. Several examples support this claim. The transformation from wood to concrete crib structures in the 1980's provided the first indication that high capacity is not always the answer. Concrete, with a compressive strength and material modulus an order of magnitude higher than wood provided a unit support capacity of 500 tons compared to only 50 tons for wood cribbing. "This had to provide superior roof support" was the thinking at that time. This hypothesis was completely wrong. These super high capacity concrete cribs were crushed in several longwall tailgates (see figure 11). Again, the ground reaction curve explains why. Much of the loading outby (before the approach of) the longwall face is uncontrollable. The supports simply do not have enough capacity to offset or control the global forces of the overburden in creating the abutment pressure on the longwall tailgate. Unless the supports can survive the ***convergence*** associated with the abutment pressures during advancement of the longwall face, the supports will fail prematurely within the realm of practical standing support capacities. This example also clearly indicates that the stiffness of the support must be considered in determining the required capacity. The reason is that the convergence in not controlled by the capacity. A stiffer support will require higher capacity than a less stiff support design.

Figure 11 - Failure of concrete cribs in longwall tailgate due to convergence beyond the control of the support system.

Premature failures of concrete cribs in pre-driven longwall recovery rooms also support the need to match the support stiffness to the ground response to achieve an acceptable support design. The yielding of the panel fender, which is carrying a tremendous amount of load, causes uncontrollable convergence in the longwall recovery room. Here too, concrete cribs as shown in figure 12 with capacities of over 1 million pounds, will fail unless the support can be sufficiently softened to absorb the ground deformations without inducing loading beyond the peak capacity of the support.

Another example of this was a trial of two different pumpable support systems on a longwall tailgate. The two support systems had similar loading stiffness and residual load capacity, but the maximum capacity of the one support was lower than the other due to a weaker grout material. During trials of the two support systems on the same longwall panel, the lower capacity support yielded outby the longwall face while the higher capacity one did not. Again, the stiffness of the support is the relevant design issue. The convergence is largely driven by the ground behavior, not the support capacity. With similar loading stiffness, the lower capacity support failed first, since the capacity of the support did not stop the tailgate convergence. The higher capacity support was able to continue loading as the tailgate convergence continued to increase as the face advanced toward the supports. This support also yielded just inby the longwall face, as its capacity too was exceeded by the face convergence beyond the shield line.

Figure 12 - Failure of pre-driven longwall recovery room support due to convergence beyond the control of the support during panel fender yielding.

Numerical modeling can be used to develop ground reaction responses for various mining conditions. The FLAC 2D finite difference software was used in a recent investigation of standing support in a three-entry longwall tailgate in the Pittsburgh coal seam. FLAC is well suited to modeling the layered coal measure rocks, since the bedding layers can be described as strain softening ubiquitous joints, while failure of the rock matrix can be simulated as a strain softening Coulomb material. The Pittsburgh coal seam is overlain by a weak stack rock followed by interlayered black shale and thin coal rider beds providing a weak immediate roof structure. A thick limestone structure provides a strong structure that can deform and bridge to the rear abutment. Figure 13 shows a ground reaction curve developed from the model for tailgate conditions just outby the longwall face due to front abutment pressures. Also shown on the curve are support responses for a 4-point wood crib, pumpable support crib, and a concrete donut crib. As seen by the intersection points of the support loading with the ground reaction curve which indicates a condition of ground equilibrium in the model, none of the supports have much impact on the resulting convergence in the longwall tailgate despite large differences in support capacities, although the wood crib is on a section of the curve, near where convergence does increase quickly when capacities are reduced below that of wood cribbing. Figure 14 shows the impact of these support systems when abutment loading increases, causing damage and strain softening of the rock mass. The roof structure remains intact with the pumpable supports, while separations occur with both the concrete cribs and wood crib. The results show that extensive yield capability, coupled with adequate support capacity, is required to maintain control over the roof deformation. The wood cribs, while having a large yield capacity, do not have sufficient resistance to prevent separation in the roof. The donut cribs, while having a significant initial capacity, do not have sufficient residual yield capacity to maintain control during extended closure. It was concluded from these studies that the stiffness of the support will have a positive impact on controlling the ground and minimizing the convergence of the tailgate, provided they can sustain their load carrying capacity. The benefit is small until the near seam rock has strain softened and is depending on its residual load capacity for stability. After this stage of behavior, a support that is too soft or sheds load after yielding can allow too much deformation to occur increasing the risk of roof instability and falls.

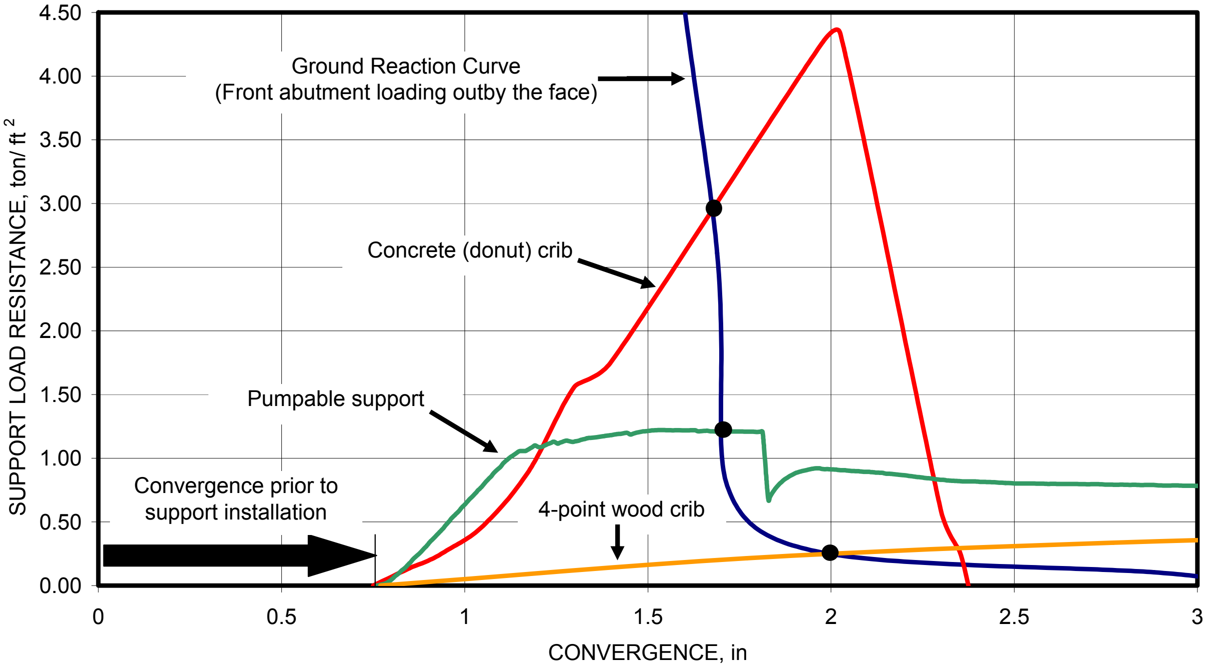

Figure 13 - Ground reaction for longwall tailgate just outby the face developed from FLAC model with comparisons of wood crib, concrete donut crib, and pumpable roof support systems.

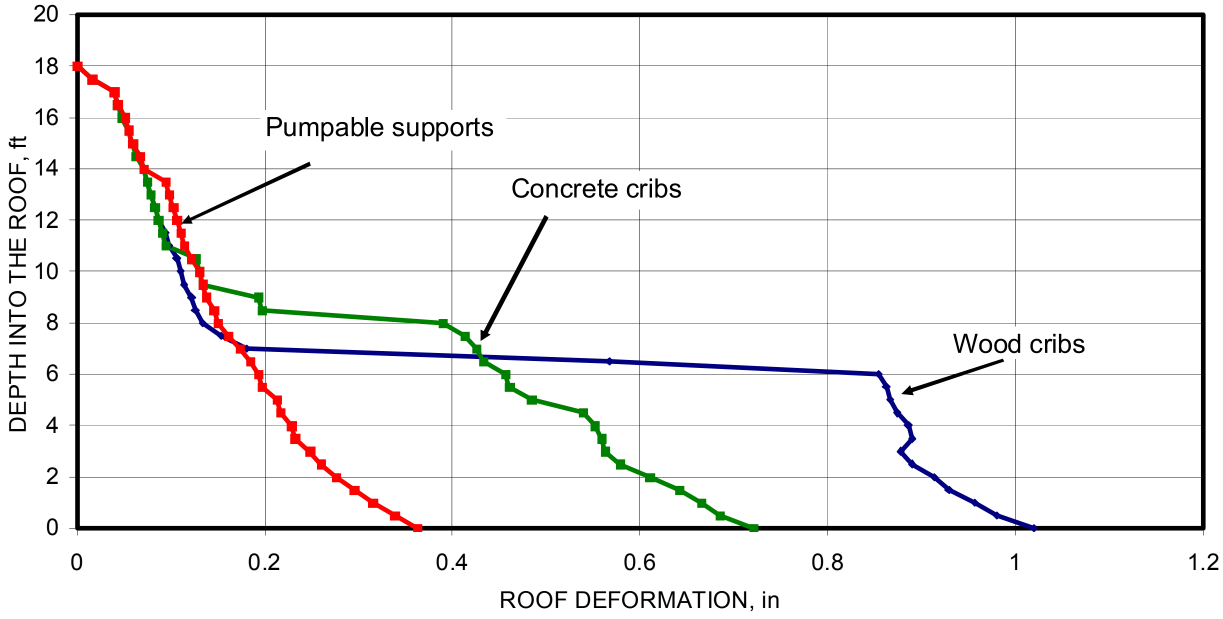

Figure 14 - Roof deformation in longwall tailgate from FLAC model for wood crib, concrete crib and pumpable roof support systems.

CONCLUSIONS

The goal of any support design is to match the support performance to the ground response. From a ground reaction perspective, "bigger is always better" in the sense that higher support resistance results in reduced convergence, which ultimately is a good thing. The question can also be addressed in another manner. Is "bigger-the-better" justified? If operating on the steep part of the ground reaction curve, then the reductions in convergence may be so small, that they produce negligible benefits in ground control and at what cost are these convergence reductions obtained?

The bigger-the-better design philosophy is most contentious when it is applied to longwall shields. The ground reaction concept is essentially addressing the entire support system, which in longwall mining includes the coal face and gob along with the shield support. The shield does not control the other two; so in fact, there is an upper limit to shield capability. This was the premise behind the design philosophy of matching the shield stiffness to the coal structure stiffness. Essentially, there is no need to have the shield do more work than the coal in the longwall panel ahead of the shields. Therefore, from that perspective, there is a logical upper limit to shield capacity.

As the discussion on active horizontal loading indicated, it is likely that much of the horizontal component of the leg force is consumed internally in the caving shield-lemniscate assembly, particularly in weak roof geologies. The larger the shield capacity, the more load that is being transferred to these components, with essentially no direct benefit in ground control. Moreover, since the joints in the caving shield-lemniscate assembly are the first structural components to wear out on modern longwall shields, is the "bigger the better" design philosophy improving this problem or actually making it worse? Higher capacity also means that canopy and base structures must be able to transfer higher stress through the structure. Toe loading on two-legged shield designs becomes more of a problem as the capacities increase in greater proportion than the size of the support, resulting in higher toe pressures.

The fact that the shield stiffness increases with capacity results in a self propagating rational for increasing support capacity. If the load environment is largely convergence or displacement controlled and the shield is simply reacting to the rock mechanics, then the shields will have to have higher capacity because they are stiffer and will develop more loading from the "uncontrollable convergence" component. Simply stated, a stiffer support will develop more loading than a softer support under the same load conditions. This phenomenon is observed throughout mining. For example, higher modulus or stiffer rock structures develop more stress than lower modulus materials due to strain-induced loading of the rock mass. The higher modulus rock must have sufficient strength to handle the high stress or it will fail prematurely, while a lower modulus rock can have lower strength and survive.

The shield's primary job is to control the immediate roof. It can do this by strengthening the roof beam in the same manner that roof bolts help to facilitate beam building, except of course the loading capacity and active loading far exceeds that of roof bolts. None-the-less, the theory is essentially the same; the moment of inertia of the beam is increased by increasing the frictional resistance along laminations. The increased moment of inertia enhances the bending stiffness of the beam and reduces beam deflections under loading. There is a limit to beam building capability, which occurs when there is no slippage. Beyond this, the rock structure is loaded in compression and the immediate roof beam is essentially pressed against the intermediate roof structure. As long as the immediate roof beam stays coupled to the intermediate roof structure as face convergence occurs, there is no significant benefit developed from additional compressive loading of the immediate roof by the shield.

This logic also indicates that yielding does not indicate inadequate shield capacity. If the immediate roof stays coupled with the intermediate roof behavior, and the yielding is produced from the coal panel and main roof activity, then the shield is simply reacting to a load condition it cannot change. In fact, in this situation, a lower capacity shield may be less likely to yield since it is less stiff.

Obviously, a "bigger-the-better" design philosophy provides insurance against conditions that are abnormal. However, history clearly shows us that ***all*** of the capacity is not needed ***all of the time***, as many longwall panels have been successfully mined with no significant problems at far less capacity than is currently provided by modern longwall shields. The argument against using all of the capacity all the time is that it unnecessarily causes loading of the shield components, particularly the caving shield-lemniscate assembly and high toe loading in two-leg shields. An alternative approach would be to develop a "smart loading technology" design that uses the capacity only when it is needed. This could be done by lowering the set pressure to some acceptable threshold that provides good ground control under nominal conditions, and increases the setting pressure when the convergence rate increases due to worsening conditions. The convergence could be assessed from the shield loading profile through the leg pressure measurements, or convergence instrumentation could be included in the next generation shield design. This type of control logic is not beyond the capability of today's control system technology.

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. Here too, the stiffness of the support is an essential element of the support design. Stiffer supports will require higher capacity because there is always a component of convergence that cannot be prevented. As such, yielding supports will always provide the best ground control capability. The goal of standing support design is again to match the support response to the ground conditions, and prevent failure caused by inadequate yielding of the support.

In conclusion, is bigger better? No, bigger is not always better, but is often required because of the support design. The ground reaction curve holds the key to optimizing support design. NIOSH is continuing to explore the application of ground reaction design for roof support. Do you really think shield capacities can continue to increase forever?

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