Evaluation of Tailgate Ground and Support Interaction in the Illinois Basin for the Development of a Ground Reaction Curve Based Standing Support Design

Dennis Dolinar, Lead Research Engineer
Thomas M. Barczak, Branch Chief
NIOSH Pittsburgh Research Laboratory
Pittsburgh, PA

Harrold Gurley, Researcher
Dept. of Mining and Minerals Resources Eng.
Southern Illinois University
Carbondale, IL

ABSTRACT

Improperly designed support systems have led to unplanned roof falls in longwall tailgates. To prevent such falls requires appropriate support and adequately designed support systems. The National Institute for Occupational Safety and Health (NIOSH) is currently developing a standing support design methodology based on the ground reaction curve. To design the support system with this methodology requires a quantitative assessment of the ground and support interaction, which is developed from instrumented test sites installed in longwall tailgates. To compliment and expand the field data results and to optimize the support design, numerical modeling is also conducted. The models are calibrated from the test site data. In the present study, data was obtained from a longwall tailgate in the Illinois basin.

The test site was located in the Herrin No. 6 coal seam at a depth of 500 ft. At the site, the immediate roof was a weak shale overlain by a competent limestone. Above the limestone, sandstone formed the intermediate roof. The floor consisted of a weak underclay. In the study, the performance and interaction with the surrounding rock mass of two different standing supports, an engineered crib and a conventional 4-point wood crib were monitored. The two cribs have similar load-displacement characteristics at least through 6 in of displacement. Beyond 6 in, the engineered crib becomes unstable and begins to strain soften and shed load.

The measurements and developed ground reaction curves indicated that the tailgate at the mine was a low convergence environment until well inby the face. Because the convergence was well below their capacity, both supports provide more than adequate levels of support to the tailgate. Significant convergence and support loading did not occur until 90 to 100 ft inby the face. The results of this study were also compared with results from similar studies conducted in the Pittsburgh seam to further advance the development of the "ground reaction curve" based support system design.

INTRODUCTION

Standing support is used extensively in US longwall mines to provide secondary support to the tailgates. The tailgate entries can be subjected to high loads and large deformations and the standing support is required to prevent ground falls that could block the tailgate. There are a number of different supports that can be used to provide support in the tailgates. These supports have various load-displacement characteristics, including pre and post yield behavior that are important in the design and selection of an appropriate and adequate support system (Barczak 2003). Ideally, to maintain the tailgate entry requires the selection of a standing support with performance characteristics that will match the ground response or the roof-to-floor convergence (Mucho, et al., 1999). Therefore, a design methodology based on the ground reaction or response concept is being developed for longwall tailgate standing support. The key to this design methodology is to quantify the ground reaction curves for several different coal seams, mining and ground conditions and support types.

The laboratory load-displacement characteristics of the standing supports are well known (Barczak 2003). However, the ground response, the developed support loads and the support and ground interaction in the tailgate must be determined for each individual site. This in part can be remedied though in situ measurements. However, in a given tailgate situation, field measurements will only develop one or two points on the ground reaction curve because of the limited variation in the type or level of support under the same ground conditions. This is not sufficient to develop the entire curve. However, numerical modeling can be used to extend the field results to develop the full ground reaction curve. Therefore, the approach for developing the ground reaction curves that can be used in standing support design in tailgates is to use a combination of field measurements with numerical modeling.

Several field studies related to tailgate standing support have been conducted in the Pittsburgh seam with numerical modeling being used to complete the development of the ground reaction curves (Barczak, et al., 2008). As part of an effort to obtain more field data on the tailgate and support interaction, a study was conducted at a longwall mine in the Herrin No. 6 coal seam in southern Illinois. Convergence measurements related to the tailgate standing support and ground interaction from the test site at the mine and subsequent numerical modeling were used to develop the full set of ground reaction curves.

BACKGROUND

The ground reaction concept was developed originally for the design of support systems used in the civil tunneling industry (Brown et al., 1983). To establish the ground reaction curves for tunneling, the impact of the timing and degree of support are developed by measuring the support pressure and opening convergence. The concept has also been applied to support and ground interaction in the hard rock and coal mines (Hoek and Brown, 1980; Brady and Brown, 1985; Mucho, et al., 1999; Barczak, 2003; Medhurst and Reed, 2005; Barczak, et al., 2005). The ground reaction will depend on the rock mass characteristics, loading conditions and the support resistance. The support resistance will depend on the support load-displacement characteristics.

Figure 1 shows a conceptual ground reaction curve. The ground reaction curve is the support pressure plotted against the opening convergence. At the initial stress state, the support resistance is equal to the forces in the surrounding rock mass and there is no convergence (point A). This is equivalent to the force on the rock mass before the opening was created. As the level of support is reduced, there is increased convergence. Initially the curve is steep and nearly linear. This represents the elastic response of the rock mass. In this portion of the curve it takes a substantial change in the amount of support to limit or change the amount of convergence. Even standing support can do little to affect the amount of convergence in this region of the curve. As the support level is reduced, the ground reaction curve becomes nonlinear and begins to flatten indicating the rock is yielding or fracturing (point B). In this region of the curve much less support pressure is required to reduce or change the amount of convergence. It is in this region that the support can limit the convergence. After the nadir (point C) the amount of support pressure required begins to increase with continued convergence. The downward deflection of the roof allows for more rock to loosen and the weight of this additional material must then be controlled by the support (point D).

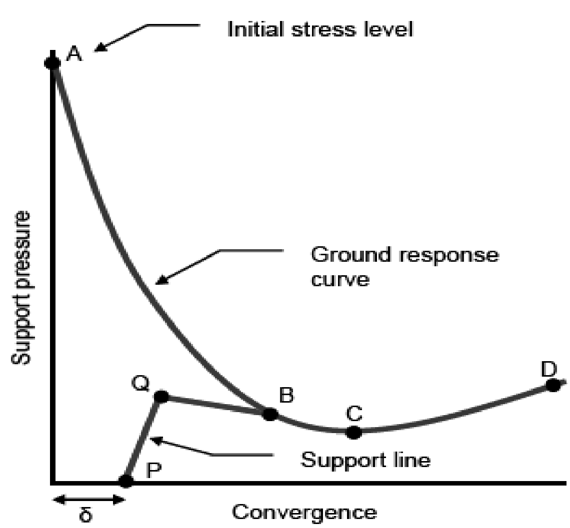

Figure 1. Conceptual ground reaction curve.

The interaction of the support and the rock can be seen in Figure 1. The load-displacement curve for a yielding support is represented by the points PQB. The support was installed after some initial convergence, delta. The support yields prior to intersecting the ground reaction curve but still has enough post yield capacity to intersect the curve at point B. The minimum amount of support required to maintain the opening is achieved by designing the supports to intersect the curve at point C. However, there is no margin of safety in such a design. Further, a very accurate knowledge of the ground and support behavior would be required. A previous study has suggested another point on the ground reaction curve that could be used for design, the support design threshold (Barczak, et al., 2008). This is the point on the ground reaction curve where the curve changes from being linear to nonlinear or where the rock begins to fracture and yield. Another important consideration in support design is the amount of uncontrolled convergence that can occur. The uncontrollable convergence is the convergence that the support cannot control or limit (Barczak, 2006 and Barczak, et al., 2008). The convergence that occurs along the linear portion of the ground reaction curve to a large extent cannot be controlled by the levels of support that are used. Ground reactions that cannot be resisted include the main roof-to-floor convergence. However, the support must be designed to withstand this convergence and still provide the required resistance to intersect the ground reaction curve at the appropriate location.

The ground reaction curve depends on the load path taken by the rock mass. Since in a longwall tailgate situation the loads on the rock mass continually change especially as the face approaches, theoretically there are an infinite number of loading conditions and therefore ground reaction curves that would need to be considered. However, for tailgate support design and evaluation, four fundamental loading conditions can be identified for which ground reaction curves could be developed. These loading conditions are; development loading, side abutment loading from adjacent panel mining, front abutment loading at the face and full extraction loading inby the face (Barczak, et al., 2008). Figure 2 shows the generalized location of the four loading condition points with respect to the panel layout. Essentially, for tailgate standing support design only these four loading conditions need to be considered.

MINING AND GEOLOGIC SITUATION

The mine where the study was conducted is located in the Herrin No. 6 coal seam in southern Illinois at a depth of 500 ft with a seam thickness between 7 and 8 ft. The immediate roof consists of about 3 ft of black carbonaceous shale that is overlain by a 5-ft-thick limestone (Brereton). On top of the limestone is about 40 ft of the Anvil sandstone. Above the sandstone the main roof consists mainly of shale with some coal seams up to the glacial deposits that are about 60-ft thick. The immediate floor consists of about 3 ft of weak underclay.

The mine uses a three-entry gate road system with abutment pillars. The crosscuts at the test site area were on 150-ft centers while the pillar width was 70 ft. The longwall panels are 1,050 ft wide.

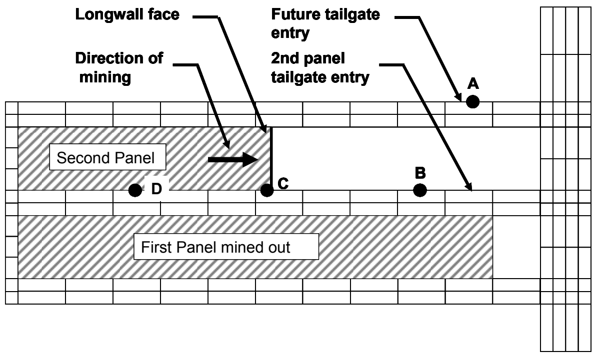

Figure 2. Generalized longwall panel layout indicating the four locations where the ground reaction curves should be determined. The points represent the following loading conditions: A-development, B- side abutment, C-front abutment at the face, and D-full extraction.

Tailgate Support

Tailgate support at the mine normally consists of a double row of 4-point conventional wood cribs constructed using mixed hardwood with a 6x6x36-in block size. The cribs were spaced on approximately 10-ft centers.

As part of the study, an engineered wood crib, identified as the ATLAS 100, were also installed along a 150-ft section of the tailgate. These cribs were placed in a double row configuration and spaced on about 10-ft centers. These ATLAS cribs were developed by Southern Illinois University (SIU) (Chugh, 2008). This crib is similar to a 4-point wood crib but with a large portion of the connecting wood between the load points having been removed (Figure 3). The load contact points are 5.75 in by 7.75 in. This crib design reduces the weight of the crib blocks for material handling while the open crib design allows for improved ventilation.

The load-displacement curves for the ATLAS 100 crib and for a conventional 4-point mixed hardwood crib are shown in Figure 4. These curves were developed by testing the support in the Mine Roof Simulator (MRS) at the Pittsburgh Research Laboratory. In these tests, a vertical load was applied to the support under displacement control at a rate of 0.5 in per min. The tested cribs had a similar height to those installed at the test site. Up through about 6 in of displacement, the performance of the two cribs is very similar. However, beyond 6 in, the ATLAS crib becomes unstable and begins to strain soften and shed load. In comparison to other types of standing supports used in tailgates, the conventional and ATLAS cribs can be considered a relatively soft and lower capacity support (Barczak, et al., 2008, STOP, 2004).

Test Site

To evaluate the standing support performance and ground reaction, both roof-to-floor and support convergence was measured in the tailgate. The roof-to-floor measurements were made in between the standing supports and provide a measure of the amount of local convergence the support was controlling. Figure 5 shows the location of the instrumentation used to monitor the standing support and tailgate convergence. To measure the support

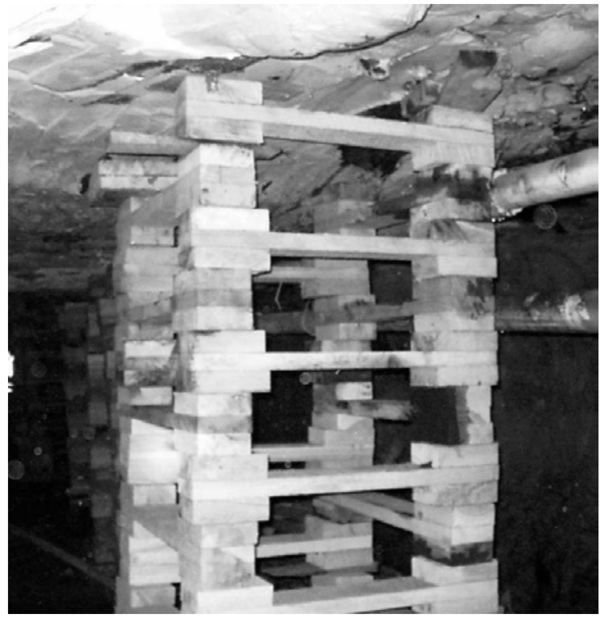

Figure 3. The ATLAS 100 engineered crib installed in the tailgate.

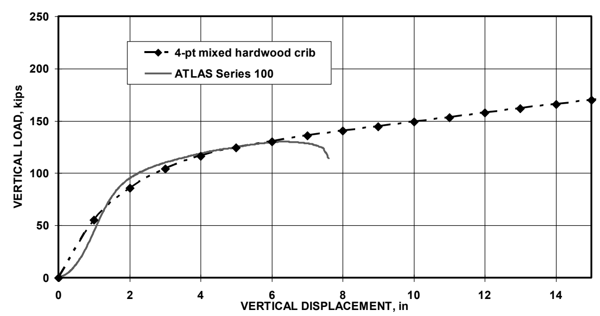

Figure 4. The load-displacement for the ATLAS 100 and conventional 4-point mixed hardwood crib as determined in the laboratory. The crib height is 7 ft.

convergence, displacement transducers were installed near the top of the cribs with a wire connecting the transducer to an anchor point located near the bottom of the support. The loads on the support were estimated based on the measured convergence and the load-displacement curves developed from the laboratory testing of the support. Roof-to-floor convergence was measured by attaching the displacement transducer to a roof bolt with a wire connecting the transducer to an anchor installed in a shallow drill hole in the floor. Because of the relatively soft nature of the floor, only one roof-to-floor convergence anchor survived inby the longwall face. A permissible data acquisition system was used to record the data.

The standing support and instrumentation were installed prior to the adjacent panel being mined with the test site on the headgate side of the first panel. This allowed for the side abutment loading effects to be measured. Convergence measurements were also obtained for the front abutment loading and inby the face where the effects of full extraction could be observed.

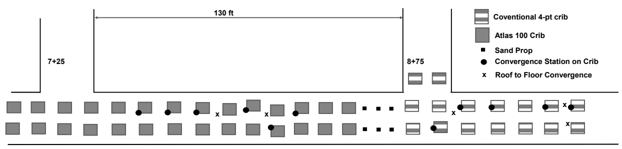

Figure 5. Tailgate test site with the location and type of the cribs and instrument location being noted. The sand props were not part of the study.

RESULTS OF THE CONVERGENCE MEASUREMENTS

Based on the support convergence measurements a comparison between the two different standing supports can be made. Figure 6 shows the average support convergence developed from the side and front abutments along with the combined total both for the conventional wood and ATLAS 100 cribs. For the side abutment load, the convergence on the conventional wood cribs was about 0.07 in higher than the SIU cribs. For the front abutment loading, the difference was only about 0.01 in. Further, there is only about 0.5 to 0.6 in of support convergence from both the side and front abutments when the support was adjacent to the longwall face for both cribs.

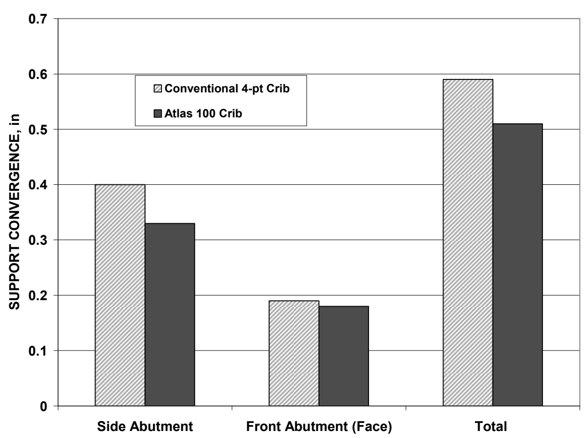

Figure 6. Convergence from the side abutment, the front abutment with the support at the face and the total from both abutments measured on the support for both the ATLAS 100 and the conventional 4-point wood cribs.

Because the convergence resulting from the two supports systems was so close, a combined support convergence could be developed. The combined support convergence is given in Figure 7 along with the roof-to-floor convergence for three loading conditions including the side and front abutment and the inby loading conditions. The roof-to-floor convergence was higher than the support convergence but only by about 0.1 in for the side and front abutment loading phases. Further, there was twice as much convergence from the side load as from the front abutment load when the test site was in the tailgate. Inby the face, there was over 3.5 in of support convergence and over 4 in of roof-to-floor convergence. However, significant levels of convergence did not occur until well inby the face. Figure 8 shows the support convergence on two of the conventional wood cribs and roof-to-floor convergence near these cribs. At the face, there was less than 0.5 in of roof-to-floor and less than 0.1 in of support convergence from the front abutment. The large and rapid increase in convergence did not begin to occur until the supports were between 90 to 100 ft inby the face.

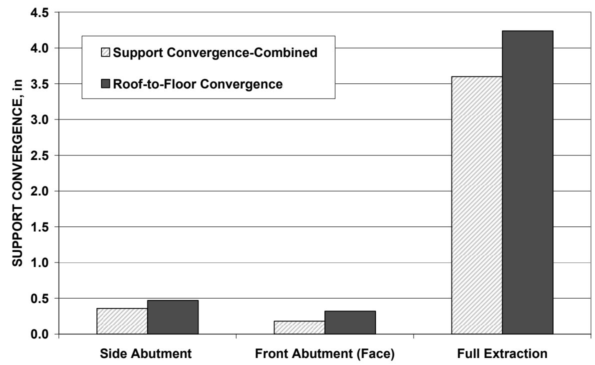

Figure 7. Average convergence measured on both types of cribs for three different loading conditions, side abutment, front abutment for support at the face and full extraction with the support inby the face. Roof-to-floor convergence is also given.

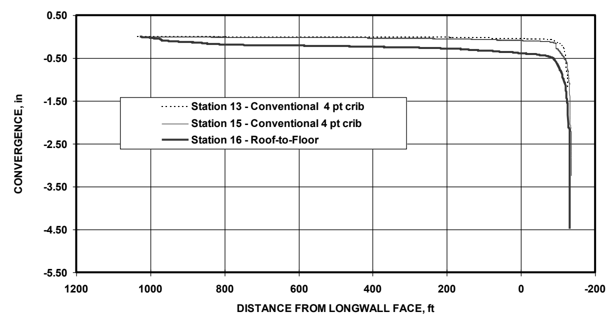

Figure 8. Measured support and roof-to-floor convergence plotted with respect to the longwall face position. Positive distance numbers indicate the measurements are outby the longwall face and negative distance numbers indicate the measurements are inby the longwall face.

GROUND REACTION CURVES

The full ground reaction curves for the four different loading conditions were developed by numerical modeling. The finite difference model FLAC was used to develop these ground reaction curves (Itasca Consulting Group Inc., 2005). A detailed discussion of the numerical modeling to develop the ground reaction curves was given by Barczak (Barczak, et al., 2008). Figure 9 shows the basic layout for the model designed to specifically evaluate the tailgate. The model extended from the surface above the seam to 100 ft below the seam, a distance of 600 ft. Horizontally, the model simulated a section of the panel and gateroads that extended from the center of the middle entry to the middle of the panel for a distance of 650 ft. There was an axis of symmetry about a vertical axis through the center of the middle entry.

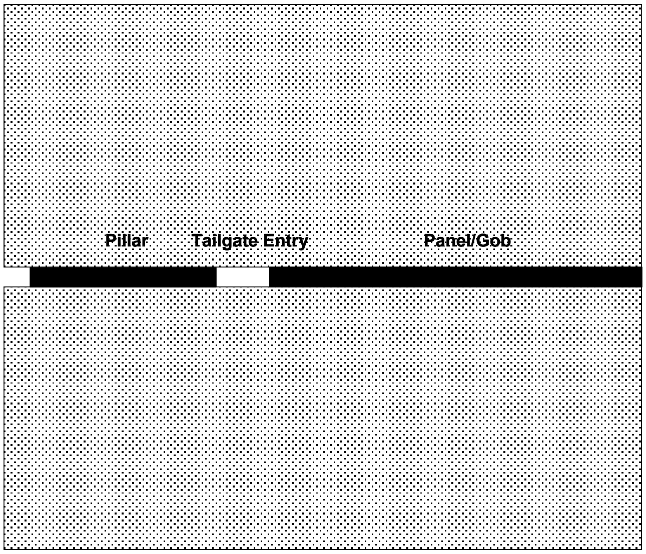

Figure 9. Basic numerical model layout used to develop ground reaction curves for the four different tailgate loading conditions. Only a portion of the layout is shown.

For the development loading condition, a vertical load was applied to the model that resulted in a vertical stress at the coal seam of 550 psi. The side and front abutment loading conditions were simulated by increasing the vertical load by 10 pct and 60 pct respectively. These levels of vertical load were developed by matching the model results to the in situ convergence measurements. For the full extraction condition, the panel in the model was removed and replaced by a soft elastic gob. The stiffness of the gob was based on matching the amount of subsidence in the model to the typical subsidence that occurs over the Herrin seam (subsidence factor of 65 to 70 pct). A horizontal stress of 1,100 psi was applied to the model based on the low strain model for horizontal stress developed for the eastern United States (Dolinar, 2003).

A Coulomb constitute model for the physical properties was used to simulate failure within the models. The model properties used for the coal seam and immediate and intermediate roof and floor are given in Table 1. A strain softening model was used for both the rock and bedding planes where the cohesion for all rock types and bedding planes was reduced by 90 pct of initial values at 0.5 pct plastic strain.

To simulate support in the models, vertical support pressure was applied to the roof and floor in the tailgate entry that ranged from 10 to 3,000 tons. This was equivalent to 1.25 tons/ft to 375 tons/ft of support along the entry. This resulted in a total of 9 points being used to establish each ground reaction curve. The models were run to equilibrium with the opening convergence being noted. For the four loading conditions, the convergence and the support pressure were then plotted to develop the ground reaction curves. The field results were used to calibrate the models.

Figure 10 shows the ground reaction curves that were developed for the four loading phases that needed to be considered. Exponential regression curves were fit through the numerical modeling results. The convergence and support loads that were measured and calculated from the test sites are also shown. Support loads were developed as the average load for the two supports for a given convergence based on the laboratory tests conducted on the two supports. From the test site data, the support loads per foot of entry for the side abutment were 17.6 tons (2.2 tons/ft), for the front abutment at the face, 26.4 tons (3.3 tons/ft) and for full extraction 96.0 tons (12.0 tons/ft). Both the side and front abutment conditions produced very steep, near linear ground reaction curves. Only the full extraction curve showed significant convergence and nonlinear behavior.

The ground reaction response developed in the Illinois basin can be compared to those developed from the Pittsburgh seam (Barczak, et al., 2008). Figure 11 shows ground reaction curves from the two regions for a depth of 500 ft for the front abutment and full extraction conditions. The Pittsburgh seam case for a depth of 500 ft was based on numerical modeling only with no field confirmation. The front abutment ground reaction curves are nearly identical with only slightly greater convergence for the same level of support in Illinois. For the full extraction condition, there is a much large difference in the position of the ground reaction curves but in this case, the curve developed for the Pittsburgh seam shows more convergence for the same amount of support.

SUPPORT DESIGN CONSIDERATIONS BASED ON GROUND REACTION CURVE

The tailgate entry in this study was a low convergence environment until well behind the face. This resulted in very steep ground reaction curve with only a small amount of nonlinear convergence when the support was at the face and subjected to the full front abutment. The small amount of convergence even at low levels of support indicates that the tailgate conditions were in general very stable with very little damage or yield in the rock. With such near linear behavior for the side and front abutment curves, it was difficult to locate the support design threshold, the point where the curve becomes nonlinear because of damage to the rock. Further, with little nonlinear behavior there should be little rock damage and with the damage occurring at low support loads, the support design threshold was of limited importance. Even though the two supports were relatively soft and limited in capacity, they had more than adequate capacity and stiffness in such an environment to maintain tailgate stability. To increase the level of support, even significantly, would have resulted in only a small reduction in the convergence because of the steepness of the curve. The stability of the ATLAS 100 cribs was not a factor with this limited amount of convergence. It should be noted that the convergence measured may be normal or average but there must be sufficient support capacity to withstand unusually adverse ground and geologic conditions that may be encountered.

The amount of uncontrollable convergence from the side and front abutments that the support had to handle when the face passed was just over 0.5 in based on the ground reaction curve. Because the tailgate support was not installed until after the development convergence occurred, it did not see convergence from development loading. From the front abutment only, the uncontrolled convergence was just under 0.25 in. In this case the standing support would not have to resist the development and side abutment convergence. However, the support system must be able to survive the uncontrolled convergence and still provide adequate support. These levels of convergence though were well below the

Table 1. Physical properties of the immediate and intermediate roof and immediate floor rocks used in the numerical models.

Rock	Cohesion, (psi)	Friction angle (deg)	Poisson ratio	Elastic Modulus (ksi)
Coal	275	31	0.25	360
Immediate Floor: Underclay	175	22	0.25	870
Immediate Roof: Black Shale	290	23	0.25	1,160
Immediate Roof: Limestone	650	25	0.25	1,740
Intermediate Roof: Sandstone	2,300	28	0.25	2,300

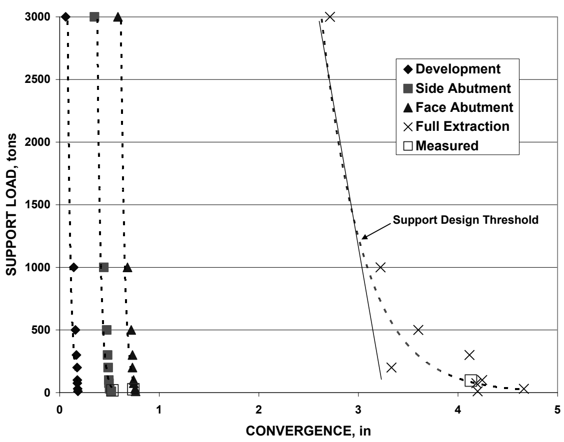

Figure 10. Ground reaction curves from the tailgate of a longwall in the Herrin No. 6 seam in Illinois developed for four loading conditions: development, side abutment, front abutment and full extraction. The support loads from the actual measurements are also given. The dashed lines indicate exponential regression curves fit through the data.

yield and total load capacity of both the conventional and ATLAS cribs.

A significant increase in the rate and amount of support convergence from the full extraction condition only began when the support was at about 90 to 100 ft behind the face. In the case of the full extraction loading, the support design threshold was fairly easily located (Figure 10). To prevent most of the damage to the rock would require a high level of support. However, if there is no need to maintain the tailgate entry that far back into the gob there is no reason to design the support system to the full extraction ground reaction curve.

The amount of convergence measured on the two supports was very similar. This was to be expected since the load displacement characteristics of the two supports were very similar up through

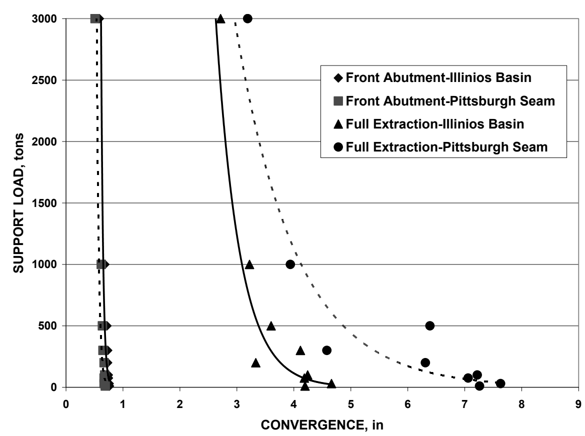

Figure 11. Comparison of the ground reaction curves developed for the Herrin No. 6 seam in Illinois basin and the Pittsburgh seam for the front abutment loading and full extraction.

6 in of displacement. As a result, only one point on the ground reaction curves for each load phase could be determined.

The ground reaction curves for the front abutment loading condition at the face were essentially the same for the Herrin seam and Pittsburgh seam for the depth of 500 ft (Figure 11). However, the vertical load factors used in the numerical models were 10 pct for the side abutment and 60 pct for the front abutment as compared to 20 pct and 120 pct for the Pittsburgh seam (Barczak, et al., 2008). This indicated that in the Pittsburgh seam there was more load transfer to the pillars and longwall face from the side and front abutments than occurred in the Illinois mine. This may be the result of relatively stronger and stiffer beds in the overburden above the caving of the Pittsburgh seam than those above Herrin seam.

For the full extraction loading condition, the Herrin seam showed somewhat less convergence than the Pittsburgh seam. However, in both cases the ground reaction curves showed similar behavior with large amounts of convergence and nonlinear behavior with a long flat tail developing as the level of support was reduced. With such behavior, additional support could limit the amount of convergence if the support characteristics were properly matched to have sufficient support capacity after a large amount of convergence occurred.

CONCLUSIONS

Ground reaction curves for a longwall tailgate were developed for a mine in the Herrin No. 6 seam in Illinois. A combination of in situ measurements of the support and roof-to-floor convergence and numerical modeling was used to produce these curves. Four ground reaction curves were developed that can be used for support design. These were for development loading, side abutment loading from first panel mining, front abutment loading at the face and full extraction loading inby the face. Actual measurements were obtained from the side and front abutment and full extraction loading phases. At the test site where the measurements were made, two different types of cribs, a conventional 4-point wood crib and an engineered wood crib, the ATLAS 100, supported the tailgate.

The laboratory load-displacement characteristics for both types of supports were very close at least through the first 6 in of displacement. This resulted in nearly equal amounts of convergence being measured on the two support systems. Essentially, the performance of the two types of cribs was the same.

The tailgate was a low convergence environment until well behind the face. The estimated amount of uncontrolled convergence was only around 0.5 in from the side and front abutment loading phases and about 0.25 in from the front abutment only. These low levels of convergence were produced by ground and loading conditions that had side and front abutment ground reaction curves that were steep and showed little nonlinear behavior and convergence. This indicated that there was little rock yield or failure. In such an environment, both support systems were well below their capacity and were more than able to adequately support the tailgate through front abutment loading at the face. Because the process of full extraction loading did not begin until well behind the face, standing support design should be based on the front abutment ground reaction curve unless there would be a reason to maintain the tailgate far inby the face.

The support capacity for other such low convergence environments that have similar side and front abutment ground reaction curves as measured in the Herrin No. 6 seam would need only a low load capacity for the standing support. In the case of this study, just over 3 tons/ft of support was needed to maintain the tailgate. This low level of support can be used because there is little rock damage or failure. Because of the steepness of the ground reaction curves, a substantial amount of support would be required to limit the convergence even by a small amount.

Although the front abutment ground reaction curves were nearly identical for the Herrin and Pittsburgh seams at a depth of 500 ft, the vertical loading factors used for the side and front abutment phases in the numerical models for the Herrin seam were only half of those for the Pittsburgh seam. Because of the difference in physical properties of the rock mass and coal of the two seams, a lower amount of increase in the vertical load used to simulate the side and front abutment loading must be applied to the models for the Herrin No. 6 seam to generate the convergence that was measured. This suggests that the amount of load transfer to face and pillars from the side and front abutments was much less in the Herrin No. 6 seam. The reduction in the vertical loads resulted in less rock failure and yield and this in combination with the shallow depth may have contributed to the development of a low convergence condition in the tailgate. Under such conditions only a low capacity support would be required to maintain the tailgate.

DISCLAIMER

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent agency determination or policy.

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