A First Step In Developing Standing Roof Support Design Criteria Based on Ground Reaction Data For Pittsburgh Seam Longwall Tailgate Support

Thomas M. Barczak, Senior Research Engineer
Gabriel S. Esterhuizen, Sr. Research Fellow
John L. Ellenberger, Lead Research Scientist
NIOSH-Pittsburgh Research Laboratory
Pittsburgh, PA

Peter (Yunqing) Zhang, Sr. Geotechnical Engineer
Pennsylvania Services Corporation (affiliate of Foundation Coal)
Waynesburg, PA

ABSTRACT

Roof support systems are designed for roof control to prevent unplanned falls. It sounds logical and has been the conventional thinking in support design since supports were first installed. In order to determine which support system should be used or which would be the most effective, the degree of control provided by the support system must be known. This question embodies the concept of a ground response curve, which is a measure of support control by assessment of the convergence in the mine entry as a function of the support capacity. In this National Institute for Occupational Safety and Health (NIOSH) study to optimize standing roof support design, ground response curves were developed for longwall tailgate conditions from numerical models of Pittsburgh Coal Seam geology. The models were calibrated against tailgate convergence measurements that were made in two Pittsburgh Coal Seam mines as the depth of cover varied during the panel extraction. Ground response curves were developed for four loading conditions: (1) development, (2) side abutment, (3) front abutment near the longwall face, and (4) full extraction inby the face. In general, the tailgate convergence and required support capacity increase through each of these loading stages.

It was concluded that prior to failure of the rock mass, the support system regardless of its capacity has relatively little impact on tailgate convergence. Recognizing that the support cannot prevent much of the (pre-failure) convergence that is occurring is an important part of support design. Supports that exhibit high loading stiffness but cannot sustain that loading through a displacement compatible with the ground response curve will not provide adequate roof control because they can fail prematurely. The required capacity depends on the loading plus yielding characteristics of the support and the amount of rock failure that has occurred. The loading plus yielding character establishes where the support loading intersects the ground response curve. Design criterion for support capacity based on the identifying the onset of strain-soften rock response leading to "damaged roof" is proposed as a foundation for assessing support design requirements. The capacity without accounting for the loading and yielding character of one support should not be used to assess the capacity requirement of an alternative support design, particularly when the loading and yielding characteristics are significantly different. A sensitivity study was made to evaluate the impact of mining height and overburden depth. As expected, the results show that convergence increases with increase in mining height and increase in overburden depth. Some specific support examples are also analyzed. Although this is a first step and the two-dimensional numerical models have limitations, these initial studies provide valuable insight into the control provided by the roof support system and will ultimately lead to optimizing support design based on specific mine site conditions.

INTRODUCTION

Longwall tailgate entries can be subjected to severe loading and deformation associated with the approach and passing of the longwall face. The tailgate entry is required to remain open so a safe travel way and a reliable airway is maintained at the tailgate corner of the advancing longwall face. In gassy mines it is also advantageous that the tailgate entry remains open behind the face, allowing ventilation air flow to the first crosscut in the gob area for passage into the bleeder entry. Innovative support methods have been developed to maintain the stability of the tailgate under these typically severe conditions. At present, standing supports are widely used as tailgate support in U.S. longwall mines (Barczak, 2003).

The design of standing supports requires knowledge of the loads that the ground will impose on the supports and the roof-to-floor convergence that will occur. This allows the support capacity and yield capability of the supports to be matched to the expected ground response (Mucho et al., 1999). The load-displacement characteristics of standing supports are well known and can be tested in the laboratory (Barczak, 2003). The ground response, however, is poorly understood and is not easily measured in the field, especially in the gob area behind the longwall face.

This paper presents the results of a study into the ground response around tailgate entries for Pittsburgh Seam longwall mines using numerical models that have been calibrated with in-mine measurements of tailgate convergence. The objective of the study was to improve the understanding of both the ground response and the required load and yielding capability of standing supports. The work forms part of the strategic goals of the NIOSH research program that addresses safe ground control practices for coal mines.

GROUND RESPONSE CURVES

The concept of a ground response curve was originally developed for the civil tunneling industry where the timing and method of ground support is determined by monitoring the support pressure and excavation convergence during construction (Brown et al., 1983). The ground response approach has found application in both hard rock and coal mining as a method to better understand the interaction between the rock mass and the support system (Hoek and Brown, 1980; Brady and Brown, 1984; Mucho, et al., 1999; Barczak, 2003; Medhurst and Reed, 2005; Barczak, et al., 2005).

The ground response curve plots the support pressure against the excavation convergence, as shown conceptually in figure 1. If the excavation boundaries are subject to support pressure equal to the stress in the surrounding rock, no convergence will occur (Point A). As the support pressure is reduced, the excavation 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 the required support resistance begins to increase as self-supporting capacity is lost and the dead-weight of the failed ground must be resisted (point D).

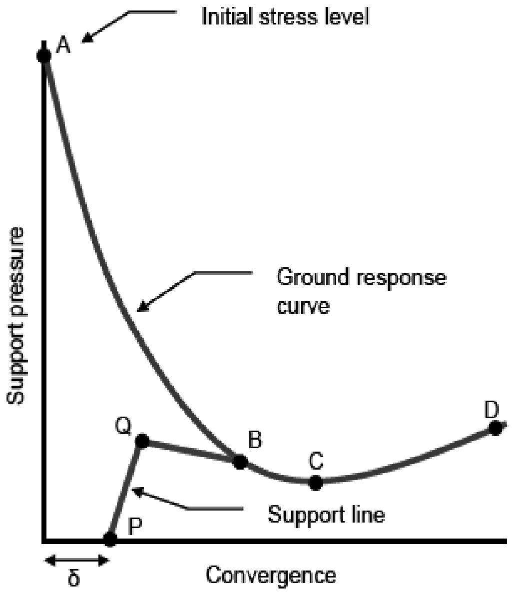


Figure 1. Idealized ground reaction curve and support response.

The effect of the support system can also be plotted on figure 1. Line PQB represents a yielding support which is installed after initial convergence (δ). As the convergence increases, the support loading increases in proportion to the support stiffness. The support reaches its peak resistance at (Q). The support then yields and the support load resistance is sufficient to arrest further convergence at point B. Theoretically, support could be designed and installed to operate as close as possible to point C, which allows the available strength of the rock mass to be utilized while minimizing the load carried by the support system. However, unless accurate knowledge of the ground response is known, a more prudent approach would be to leave some margin of safety by employing a higher support capacity to ensure that point C is never reached.

In a longwall tailgate entry, the stress in the surrounding rock does not remain static. The advancing longwall face causes changes in the loading condition as it approaches and ultimately removes one side of the entry excavation. These changes will result in a unique ground response curve for each mining stage. Support installed during the initial loading stages can therefore experience further convergence as the ground responds to the new loading condition. In this study, families of ground response curves were developed, each corresponding to one of the four loading stages of the tailgate entry illustrated in figure 2. These four distinct loading stages are described as follows:

- **Development (A):** The loading condition before the effects of longwall retreat mining is the beginning of the loading cycle.
- **Side Abutment (B):** The entry is subjected to an increase in vertical loading from the side abutment of the first panel mining and the horizontal stresses can decrease owing to the relaxation of the strata towards the gob.
- **Face Abutment (C):** The entry is subjected to a further increase in loading as the face from the second panel approaches creating further loading from front abutment pressure.
- **Full Extraction (D):** The loading condition after the longwall face has passed and the gob area from the active panel extraction is formed.

IN MINE MEASUREMENTS OF TAILGATE CONVERGENCE

Tailgate convergence measurements on a three-entry gate road system were taken at two Pittsburgh Seam longwall mines operated by Foundation Coal Corporation. The mine properties border one another and have similar geological conditions. Convergence data was collected from two different longwall panels from one mine and four different panels from the second mine over a four-year period. The goal was to collect data at various locations where the depth, which ranged from 650 ft to 950 ft, changed during the course of the study. The abutment (chain) pillars were 100 ft wide and 184 ft long, providing an Analysis of Longwall Pillar Stability (ALPS) tailgate stability factor ranging from 1.4 to 2.4 for the depth of cover examined in this study, above the minimum acceptable stability factor of 1.25 (Mark, 1992). Both mines used pumpable roof supports for tailgate support, so the support was similar in all cases, except one mine used two rows of supports instead of one.

The convergence measurements were made from displacement transducers that were connected to a permissible data acquisition system for sampling and collection of tailgate convergence on a near continuous basis. The displacement transducer was mounted on the outside surface near the top of the pumpable support and a string attached to an anchor near the base of the support in order to measure the displacement induced in the support by the roof-to-floor tailgate convergence (see figure 3). Load measurements on some supports were also made by a hydraulic cell placed beneath the pumpable support. Displacement measurements were also taken between the pumpable supports by anchoring a transducer on a roof bolt plate and with a steel wire attached to a plate anchor resting on the floor to measure roof-to-floor convergence. One of the support measurements was typically taken at an intersection. Data collection started when the supports were about 300 ft outby the face and continued until the face passed by the instrument

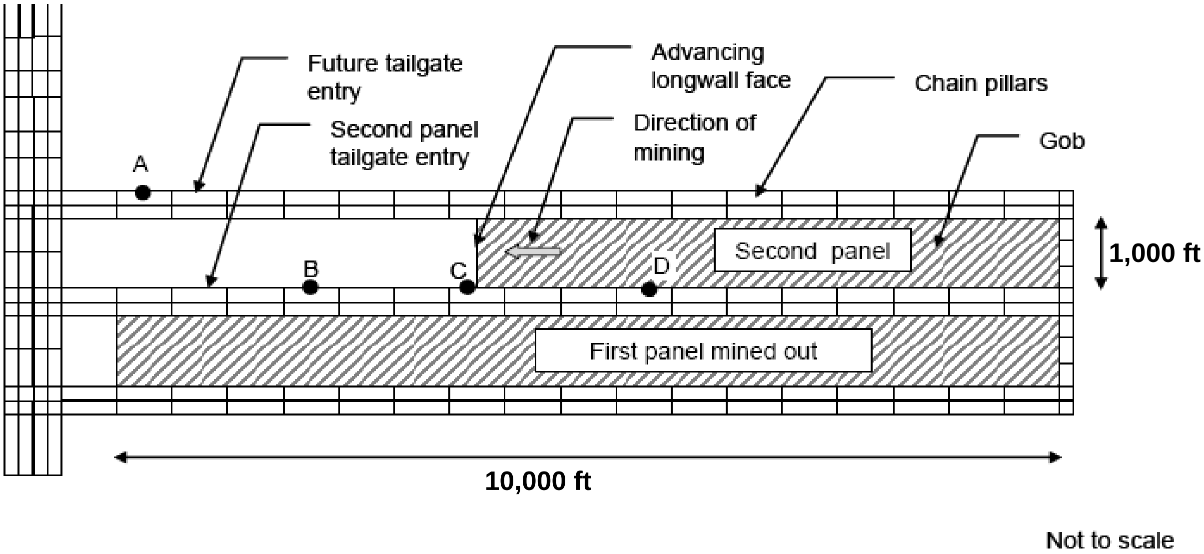


Figure 2. Example of a longwall panel layout showing dimensions and nomenclature. Points A, B, C, and D represent the Development, Side Abutment, Face Abutment, and Full Extraction (Inby) loading conditions, respectively.

Figure 3. Convergence instrumentation shown on pumpable roof support in longwall tailgate.

locations, at which time data acquisition was lost or corrupted as the coal or gob debris interfered with the displacement sensor.

The convergence ranged from less than 0.1 in to as high as 3.0 in at the tailgate T-junction, position C in figure 2. Figure 4 shows the distribution for 750-ft depth of cover. The convergence data is normally distributed with a mean of 0.48 in and a standard deviation of 0.26 in. The average data shows a correlation with depth of cover as shown in figure 5. One set of tailgate convergence data was taken as the panel approached within 20 to 165 ft of a pre-driven recovery room at the end of the panel. The convergence measured at this site was somewhat higher than that observed at the other locations. Excluding this data, a linear correlation suggests that the tailgate convergence increases about 0.6 in for every 100-ft depth of cover change. A nonlinear correlation indicates that the increase in convergence accelerates with respect to increasing depth (see figure 5). Figure 6 shows two other trends. The convergence increased by about 10 pct when only one row of supports was used instead of two. It should be noted that two rows were used at one mine and one row at the other mine; however, the geological conditions were similar. More convergence (25 pct increase) was measured on average between the supports compared to measurements taken on the support itself.

MODELING METHOD TO DEVELOP GROUND RESPONSE CURVES

The finite difference software FLAC (Itasca Consulting Group Inc., 2005) was used to develop the 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 using the Coulomb constitutive properties built within the model. The software also has a built-in programming language which allows the user to control loads and displacements in the model.

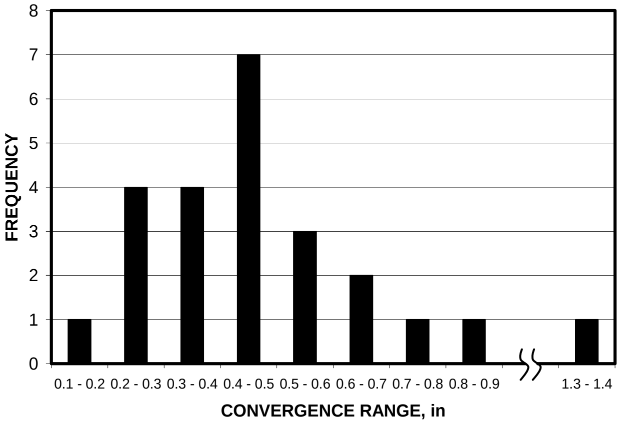


Figure 4. Distribution of tailgate convergence for front abutment load condition (Point C in figure 2) at 750 ft depth of cover

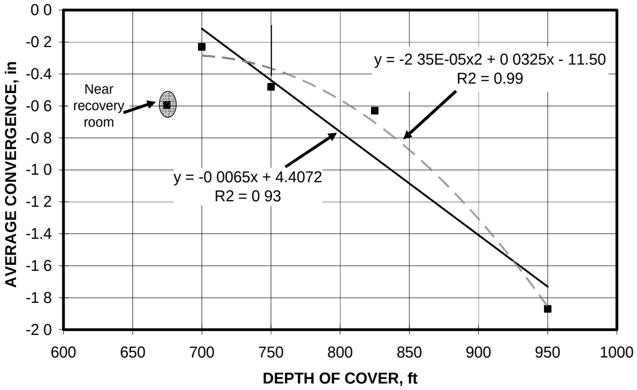


Figure 5. Correlation of tailgate convergence to depth of cover.

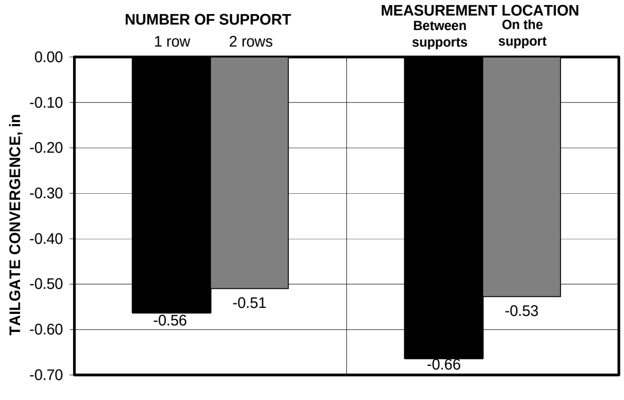


Figure 6. Convergence increased by 10 pct when 1 row of supports used instead of 2 rows (left portion of graph) and 25 more convergence occurred between supports than on the supports.

This feature was used to apply internal pressure within the modeled tailgate entry excavation so that the ground response curve could be determined.

Model Layout and Material Properties

A typical three-entry gate road design used in the Eastern U.S. longwall operations was evaluated in the study. The model was constructed to analyze the tailgate entry specifically. The extent of the model was 600 ft wide by 325 ft high, which allowed a 1,000-ft-wide longwall panel as well as the adjacent tailgate entry and the center entry to be modeled by employing symmetry. The element size was 8 in, near the vicinity of the tailgate entry.

The geological profile simulated in the model is shown in figure 7. The coal bed is overlain by weak shale strata and alternating weak and strong beds, typical of the Pittsburgh Seam in Western Pennsylvania. A significant feature of this lithology is the presence of thick, strong limestone beds in the roof strata. The rock mass was modeled as a strain softening, ubiquitous joint material, using the built-in constitutive model available in the finite difference software. Strength data for the different rock types included in the models were based on published data for coal measure rocks (Rusnak and Mark, 1999; Zipf, 2005). A summary of the average material properties used in the models is presented in table 1. The average values of the bedding plane strength used in the models are summarized in table 2. The bedding strength was loosely related to the intact rock strength, the weaker rocks having weaker bedding planes. Strain softening of the rock matrix and bedding planes was modeled by implementing cohesion weakening. The cohesion of all the rock types and bedding types was specified to reduce by 90% of the initial value after 0.5% plastic strain to simulate the strain-softening response of the rock. This measure is based on laboratory triaxial testing of rock core specimens from one of the Pittsburgh Seam mines (Strata Testing Services, 2003).

The model simulated the fully extracted conditions including the gob on one side of the tailgate entry. The gob was modeled as a soft elastic material. The stiffness of the gob was determined by trial and error to allow the appropriate degree of subsidence (60-65% of seam height) over the center of the longwall panel, similar to observed subsidence in Pittsburgh Seam longwalls (Luo and Peng, 1992).

Model Loading

The initial vertical stress in the model was set at 825 psi to simulate a tailgate entry at a depth of approximately 750 ft below the ground surface. Since the model did not extend to the ground surface, vertical loads were applied to the top of the model to simulate the overburden up to the ground surface. The initial horizontal stresses were calculated from the Poisson's ratio of each rock layer plus a tectonic component which depended on the elastic modulus of the rock (Mark and Mucho, 1994; Dolinar, 2003). The input parameters were selected so that the horizontal stress in the moderately strong shale beds was 1,200 psi, similar to measured values in Eastern U.S. coal mines, (Dolinar, 2003).

The loading induced by the Side Abutment and Face Abutment stages were simulated by increasing the vertical loading of the model by 20% and 120%, respectively. The Full Extraction loading condition was modeled by simulating the extraction of the coal on one side of the tailgate entry and simulating gob formation. The gob was modeled in two stages. The lower section is a low modulus material to simulate full caving, while the upper section is modeled with an unchanged rock matrix but the joint cohesion is minimized to simulate partially caved rock. This was done to provide sufficient confinement of the immediate roof resulting in more realistic inby pillar response and roof activity. .

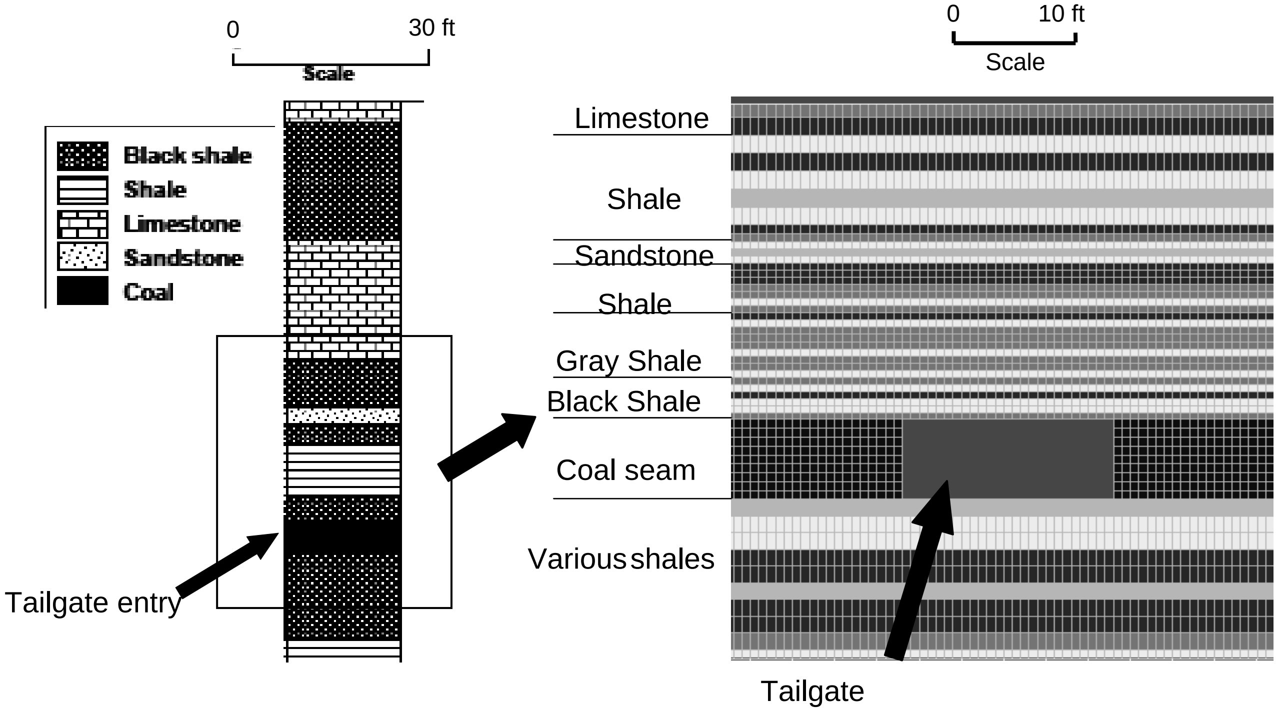


Figure 7. Geological profile simulated in numerical model.

Table 1. Material properties used in the model.

Rock class	Cohesion (psi)	Friction angle (deg)	Poisson ratio	Elastic modulus (ksi)
Weak rock: Black shale, mudstone	650	25	0.25	1,700
Moderate rock: Shale	1,200	28	0.25	2,300
Strong rock: Sandstone	1,700	32	0.25	3,500
Very strong rock: Limestone	2,900	36	0.25	5,800
Coal	275	31	0.25	360

The friction angle remained constant during yield.

Table 2. Bedding plane properties used in model.

Bedding plane description	Cohesion (psi)	Friction angle (deg)
Very weak – clay filled discontinuity	8	21
Weak – open discontinuity	75	21
Moderate – weakly healed discontinuity	500	24
Strong – healed discontinuity	800	26
Very strong – strongly healed discontinuity	1,450	28

Procedure for Developing Ground Response Curves

The ground response curves were developed by simulating a uniform support pressure on the roof and floor of the tailgate entry while sequentially modeling the four external loading stages. In this approach, intrinsic support (i.e., roof bolts) is not explicitly modeled. The model was run to equilibrium at each loading stage and the resulting convergence in the tailgate entry was recorded. In this manner, failure and convergence that occurred during the earlier stages are preserved and included in the later loading stages. Repeat analyses were carried out in which the internal support pressure was varied, so that the ground response curve could be developed. Internal pressures of 0.08 tons/ft^2 to 23 tons/ft^2 equating to unit support loads of 10 to 3,000 tons were applied to provide a range of results that would bracket the possible range of standing support capacities. Ground response curves were developed by plotting the support pressure against the tailgate entry convergence for each loading stage.

GROUND RESPONSE CURVES

Figure 8 shows the suite of ground response curves for the four different load stages for the base case condition at 750 ft of overburden and a 7.5-ft coal seam height. Average in-mine tailgate convergence measurements are also shown on the graph. The curves shift to the right in the plot indicating increases in convergence with each loading stage. Again, these curves represent snapshots in time at specific points in the loading cycle of a longwall tailgate (see figure 2). The migration of the curves occurs because the loading on the tailgate is not constant but changes with time as the panel is mined. Another notable observation is that (at this scale) the development, side abutment, and face loading curves are nearly vertical (very high slope) and fairly linear. This indicates that the standing support resistance has very little impact on the tailgate convergence for these stages.

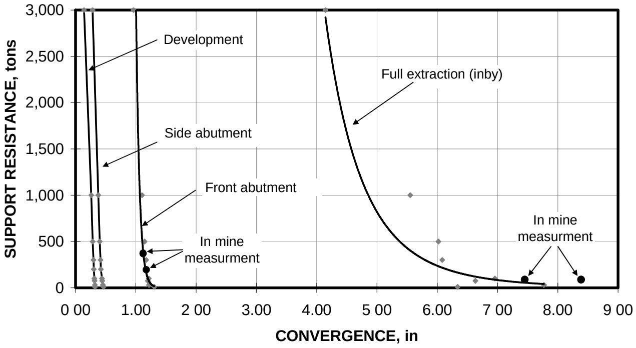


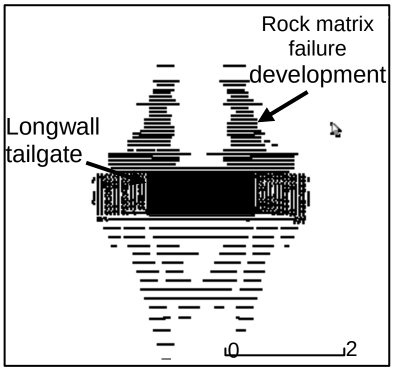
Figure 8. Suite of ground reaction curves for the four loading stages for the base configuration at 750 ft of overburden and a 7.5 ft coal seam height.

Conversely, the full extraction (inby) loading curve is nonlinear with decreasing slope as the support resistance decreases, meaning increases in support capacity from low capacity to higher capacity can produce significant reductions in convergence. It can also be seen that model responses are less consistent for the inby loading than they are for other three loading stages.

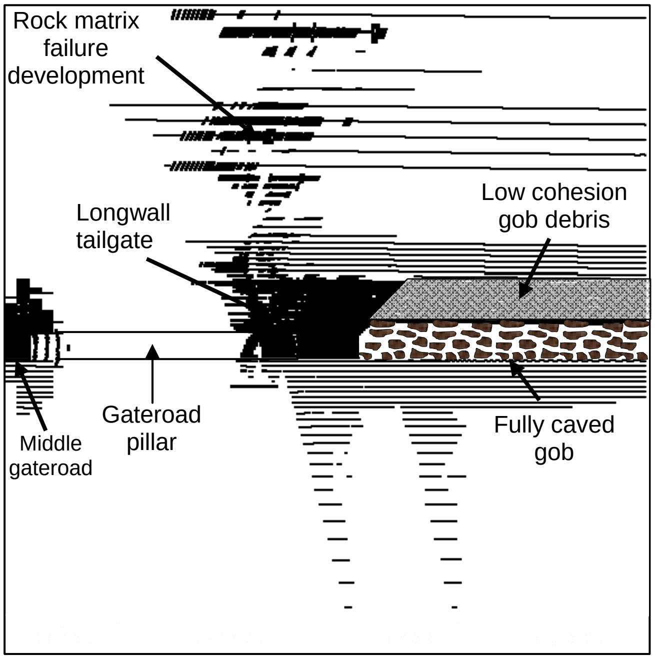
These differences in the inby behavior can be explained by the rock mechanics associated with the different loading stages. Outby the advancing longwall face, the tailgate is always flanked by a pillar on one side and an unmined longwall panel on the other side. A softened or damaged rock zone develops above and to a degree below the tailgate as the stress is transferred to the solid abutments on each side (see figure 9a). This roof beam bridging across the tailgate entry and supported by the solid abutments on each end will deform downward into the tailgate entry producing convergence. The deformation will generally increase as the rock strength is exceeded resulting in a strain softened rock response. Likewise, the floor can move upward, also creating convergence. Inby the longwall face, the panel abutment is replaced by the gob material, which exhibits a much softer response. In this condition, the roof is acting more like a cantilevered beam (see figure 9b), supported on one end by the pillar abutment. Here, larger deflections occur creating more damage to the immediate roof and more opportunity for the support system, which tries to act as a breaker line, to influence the roof failure process. As such, the impact of the support resistance is greater inby the face. In general, the impact of the support on the ground response will increase once the rock is damaged and strain softened. Prior to this, the elastic response of the rock or coal is not significantly influenced by the support system.

A sensitivity study was conducted with the numerical models to evaluate the impact of depth of cover, seam height, and applied stress. These results are summarized as follows.

Depth of cover: The overburden stress directly increases with increasing the depth of cover at a rate of 1.1 psi/ft. Examining the response for the front abutment loading near the longwall face as shown in figure 10, it is seen that the ground response curves become further apart as the depth of cover increases, indicating that the tailgate convergence grows progressively larger as the depth of cover increases. With 500 tons of support resistance, the modeling indicates that the convergence increases by 0.5 in as the depth of cover increases from 500 to 750 ft, and increases by 0.6 in as the depth of cover increases from 750 to 1000 ft and by nearly 0.7 in from 1,000 to 1,250 ft. It is also seen that the nonlinearity in the ground response curves progressively increases at support resistances below 500 tons with increasing depth of cover. This indicates that the impact of the support capacity relative to reducing tailgate convergence increases as the depth of cover increases. This supports the hypothesis that the capability of the support to control the ground response increases as the rock damage intensifies. Inby the face, the tailgate convergence increases in proportion to the depth of cover, but the ground response curves have a similar profile. This suggests that the support control is about the same regardless of the depth of cover at least for the ranges evaluated in this model.



Face abutment condition (cross section of tailgate entry)



Full extraction (inby) condition (cross section)

Figure 9. Rock response around tailgate opening for face abutment (a) and full extraction (b) loading conditions (750-ft overburden and 7.5-ft mining height).

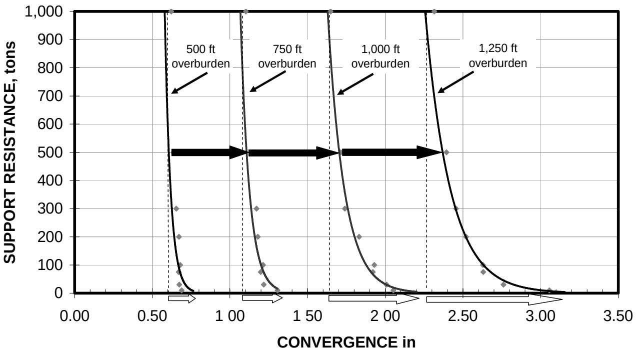


Figure 10. Ground response curves become further apart as the depth of cover increases, indicating that the tailgate convergence grows progressively larger as the overburden depth increases with 7.5-ft mining height.

Mining (coal seam) height: The base case mining height of 7.5 ft was increased and decreased by 2.5 ft for the sensitivity study to evaluate the impact of pillar response. The ground response curves near the longwall face location for these three mining heights are shown in figure 11. The tailgate convergence also increases with increasing mining height, approximately 0.25 in for each 2.5-ft increase in mining height. As such, the impact of mining height over this range was less than that observed for 250-ft increments in depth of cover. The ground response curves also have the same profile, indicating the support impact is about the same regardless of seam height. Inby the longwall face, the ground response curves tend to coalesce (see figure 12), indicating that seam height does not influence convergence much in this area and has significantly less impact than other factors.

Abutment Stress: The face abutment stress was increased from the base case of 2.2 times the overburden load to 2.5 times the overburden load and then incrementally increased by an additional 0.5 factor to a maximum of 5.0 times the overburden load. This is done to evaluate the impact of pillar deformation and yielding. The tailgate convergence at the face location increased linearly with these stress multipliers until the factor reached 4.0 (see figure 13). Beyond this, the convergence began to increase to a greater degree. Beyond a stress multiplier of 4.5, the pillar failure was extensive as was the immediate roof and floor damage in the tailgate entry.

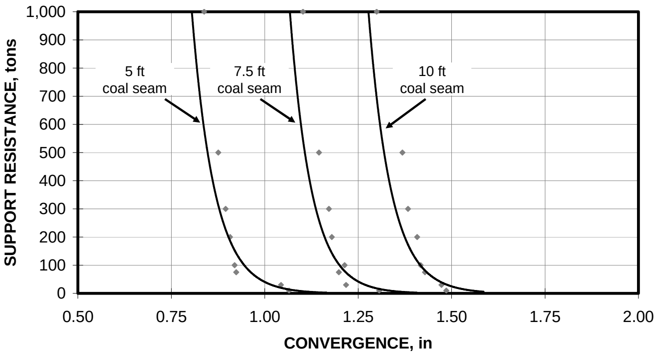


Figure 11. The tailgate convergence increases with increasing mining height, approximately 0.25 inches for each 2.5-ft increase in height with 750 ft of overburden.

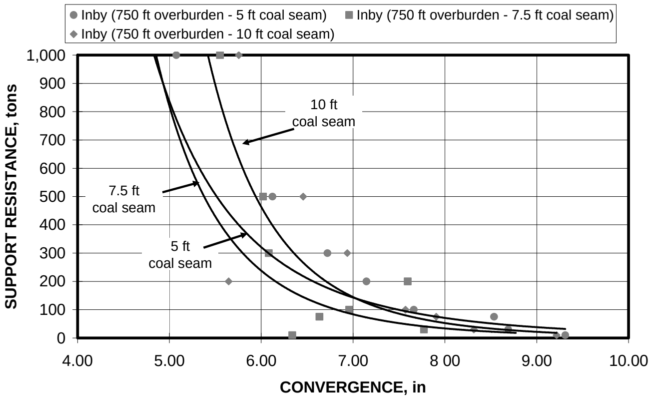


Figure 12. Inby the longwall face, the ground response curves tend to coalesce, indicating that seam height does not influence convergence much in this area.

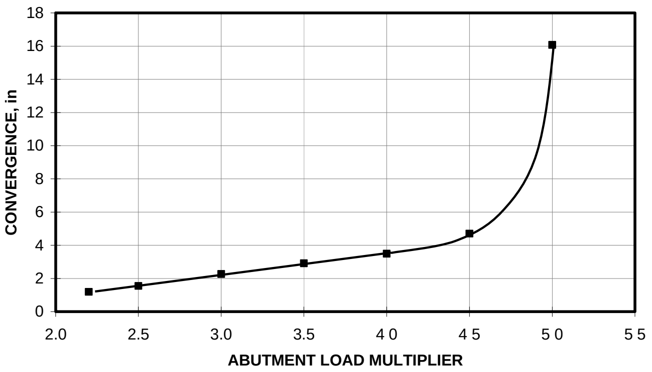


Figure 13. The tailgate convergence increases linearly with face abutment stress up to a multiplier of 4.0. Beyond this, the convergence began to increase to a greater degree.

MODELING DISCUSSION

Modeling of the elastic response of rock masses has been effectively achieved, but modeling of rock failure remains a complex and daunting task even with the advancements in model capabilities in recent years. The development of ground response curves requires modeling of the rock response beyond the elastic range of loading. FLAC has several properties that facilitate this task, including representing the inelastic response and strain related weakening of failed rock, but limitations remain in being able to capture the behavior of the rock structure through failure. The final dead-weight loading by loosened or detached roof rocks is not well represented. The software was designed to simulate continuous materials but does not efficiently simulate discrete particles such as detached blocks in the roof of the entry. Issues such as disintegration of the roof rock structure around standing supports and support loading by detached blocks were therefore specifically excluded from this study. Likewise, failure that involves buckling of delaminated strata is also not considered in this analysis. Buckling occurs at lower stress and through a different failure mode than the intact rock matrix allows in this analysis.

Some of the other issues that were examined in this study are discussed as follows.

Gob modeling: The formation of the gob and reaction of the caved material is not an easy process to model. After several approaches were examined, it was concluded that a two-stage gob model provided the most realistic results. The lower section of roof is fully caved and is modeled with a low modulus material, while the upper gob has an unchanged rock matrix but the joint cohesion was removed (see figure 9).

Material modulus: The rock matrix consisted of four primary rock materials as depicted in table 1. A range of material properties exists for all rock materials. The elastic modulus was varied by a factor of 2 as part of the effort to calibrate the model to the observed tailgate convergence during the field studies. The higher modulus values were found to provide convergence most closely related to the field measurements.

Horizontal stress: It was assumed that the longwall gate roads are aligned parallel to the major horizontal stress, thus reducing the out-of-plane stresses in the two-dimensional models. Horizontal stress can significantly impact the roof response. For this study, the horizontal stress was decreased by 20% during the side abutment loading and then increased 20% during the face abutment loading.

Two-dimensional limitations: Only two-dimensional models were utilized in this study. Aside from the fact that the two-dimensional modeling cannot account for the spacing of the support along the tailgate entry, it is believed that the two-dimensional approach is reasonably accurate for the development and side abutment stages of the loading cycle. The most severe limitations occur at the tailgate corner as the longwall face passes by the area of interest. Here the stress field can be complex and the intersection of the front and side abutments can create out of plane stresses that are not properly modeled in a two-dimensional environment. As a result, the face loading stage is best described as behavior just outby the face line. The behavior just inby the face directly behind the shield line where the gob forms also has these same issues. Likewise, the inby behavior modeled by the two-dimensional approach is best described after the gob has fully formed. Although not an issue in this situation, two dimensional modeling would also have limitations regarding panel geometry effects, such as sub-critical conditions that could occur for deeper cover conditions.

SUPPORT DESIGN DISCUSSION POINTS

Uncontrollable convergence: Clearly, prior to failure of the rock mass, the support system regardless of its capacity, has relatively little impact on tailgate convergence. This behavior has been referred to as "uncontrollable convergence" in previous publications (Barczak et al., 2005). Referring back to figure 8, increasing the unit support capacity from 100 to 500 tons (400% increase) reduced the convergence near the longwall face by only 5% (0.06 inches). Recognizing that the support cannot prevent much of the convergence that is occurring in these conditions is an important part of support design. Supports that exhibit high loading stiffness but cannot sustain that loading by yielding through a displacement compatible with the ground response curve will not provide adequate roof control. The support must be able to survive the "uncontrollable convergence" in order to provide roof support if failure of the rock mass occurs later in the loading cycle. Several examples of very high capacity support systems with limited yield capability that fail prematurely due to the "uncontrollable convergence" component have been documented in previous publications (Barczak, 2006).

Establishing capacity threshold based on the ground response curve: One approach to establishing the support design capacity requirement is to identify the nonlinearity portion of the ground response curve. Then assuming this area represents strain softened or "damaged rock" response, the required support capacity to prevent the onset of this condition can be determined. Figure 14 illustrates this concept for the front abutment (face) loading condition. In this example, the support design threshold would be approximately 225 tons, equating to a support load density of 28 tons/ft of tailgate entry for an 8-ft support spacing. Providing capacity above the support design threshold provides little improvement in ground control since the convergence is reduced by only a slight amount. Conversely, providing capacity less than the support design threshold can lead to progressively higher risk of roof instability and the potential for roof falls..

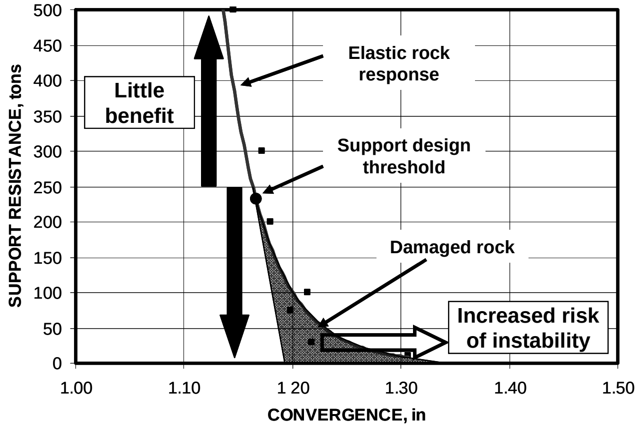


Figure 14. Support capacity design threshold established from onset of strain-soften rock response from ground response curve. In this example for face abutment loading condition, the support capacity requirement is approximately 225 tons.

Required capacity dependent upon support design: The required capacity based on intersecting the ground response curve depends on the loading and yielding characteristics of the support. In general, a support with a higher stiffness will require a higher capacity than a support with a lower stiffness. Therefore, the capacity of one support should not be used to assess the capacity requirement of an alternative support design, particularly when the loading characteristics are significantly different.

Timing of support installation can affect design requirements: Since supports develop load in response to convergence, the timing of the support installation can affect the capacity and yield requirements. Some longwall supports are installed in the active tailgate while others may be installed prior to it becoming an active tailgate. Since convergence occurs throughout the mining cycle, as illustrated in the four loading stages of the ground response curves, the earlier in the loading cycle that the support is installed, the more convergence it will see and must survive to maintain control as the panel mines by the support location in the tailgate. However, since the side abutment loading from first panel mining produces relatively low convergence, this is not likely to be a major concern except in stiff support systems that have very limited yield capabilities.

IMPLEMENTING THE GROUND RESPONSE CURVES INTO THE NIOSH STOP PROGRAM

The ultimate goal is to transfer this information into the NIOSH Support Technology Optimization Program (STOP) to facilitate use as a design tool (Barczak, 2000). The program currently allows ground reaction data to be entered into the program, although additional plans are being made to facilitate the process presented in this paper. For example, the face and full extraction ground response curves for the base case condition of 750 ft of overburden and 7.5-ft coal seam height were entered into the program. Using this as the design criterion, the performance of single and double rows of conventional 4-point wood cribs and 30-in-diameter pumpable supports was examined. Both support systems were installed on an 8-ft center-to-center spacing in the analysis.

The output chart showing the support performance curves and the ground reaction design curve are shown in figures 15a (face abutment condition) and 15b (full extraction condition). Examining the face abutment condition first, the single row of pumpable supports intersects the ground response curve very closely to the 225-ton threshold referenced in figure 14 since the supports are installed on 8-ft center-to-center spacing. Both of the wood crib support systems intersects the ground response curve near the bottom of the curve, indicating significant rock damage has occurred and the probability of unstable ground is much higher. It is also interesting to see that adding another row of wood cribs makes very little difference. Conversely, adding another row of pumpable supports moves the intersection significantly above the support design threshold. Although the added capacity moves the rock response to the elastic range, the reduction in convergence is very small and the support capacity is probably not necessary in this case.

Despite their high capacity, the pumpable supports cannot control the ground movement to prevent yielding of the support system as the full extraction condition develops inby the longwall face. As seen in figure 15b, the single row of pumpable supports now intersects the ground response curve well into the damaged rock zone, while the double row intersects the ground response curve near the support design threshold. Therefore, inby the face, the added capacity provided by the second row of pumpable supports can be justified. The additional row of wood cribs is also more beneficial inby the face compared to previous analysis outby the face, and due to yielding of the pumpable supports, the double row of wood cribs is comparable to the single row of pumpable supports. The single row of wood cribs is again on the low end of the ground response curve, allowing about 7 in of convergence, and as such provides the most risk for poor ground conditions of the supports analyzed in this example.

CONCLUSIONS

The ground reaction concept provides a means to design standing support systems based on the control the support system has on the ground response. Since the goal of support application is to prevent roof falls, this is a logical design philosophy. The ground reaction concept is not new; the difficulty in applying the concept has always been obtaining the curve. In this NIOSH research project, FLAC numerical models were constructed that develop the ground response from simulated support loading in a longwall tailgate and stress conditions induced by the longwall extraction process. The models were calibrated against tailgate convergence measurements during the front abutment loading in two Pittsburgh-Seam longwall mines and inby measurements made at one of two mines, which are valid points on the ground reaction curve for those specific conditions.

This study, along with others, has clearly shown that prior to failure of the rock mass, the support system regardless of its capacity has relatively little impact on tailgate convergence. Recognizing that the support cannot prevent much of the convergence that occurs is an important part of support design. Supports that exhibit high loading stiffness but cannot sustain that loading by controlled yielding through a displacement compatible with the ground response curve will not provide adequate roof control. The support must be able to survive the “uncontrollable convergence” in order to provide roof support if failure of the rock mass occurs later in the loading cycle. It is also clear that the required capacity depends on the loading plus yielding characteristics of the support and the capacity of one support should not be used to assess the capacity requirement of an alternative support design without also assessing its loading and yielding characteristics, particularly when they are significantly different.

Design criterion for support capacity based on the identifying the onset of strain-soften rock response leading to “damaged roof” has been proposed as a foundation for assessing support design requirements. Under 750 ft of overburden with a 7.5-ft mining height, this translates into a support design requirement of 225 tons per row of support, if installed on an 8-ft spacing for supports within the row down the tailgate, for the face abutment loading condition for the study areas. About 255 tons per row for the full panel extraction inby loading condition is required for support design. With less capacity than identified by these thresholds, the risk of instability increases and grows progressively larger as the support density approaches the bottom of the ground reaction curve.

Assessing the level of risk as the support response falls within the soften rock response portion of the ground reaction curve remains part of the research challenge. The rock failure response is the most difficult part of the process to model. The FLAC two-dimensional models used in this study have capabilities to simulate strain related weakening of failed rock using the Coulomb constitutive properties built within the model, but as a continuum model there are still limitations in this regard. With few exceptions, the ground response curves come to equilibrium in the models, implying that “stable ground conditions” can be achieved without any significant support. Perhaps that is true for the conditions analyzed in the model, but it is likely related to the inability of these models to fully simulate discontinuous rock mass. Nonetheless, the ground response curves produced in this study are believed to be a reasonable representation of the ground response and provide a major first step at examining support design from the perspective of ground control. This can help improve the application of roof supports. In the future, additional geological conditions will be examined. The immediate goal is to build a data base of baseline curves for various coal seams and then to refine them through advancements in the numerical models with field measurements for calibration and validation.

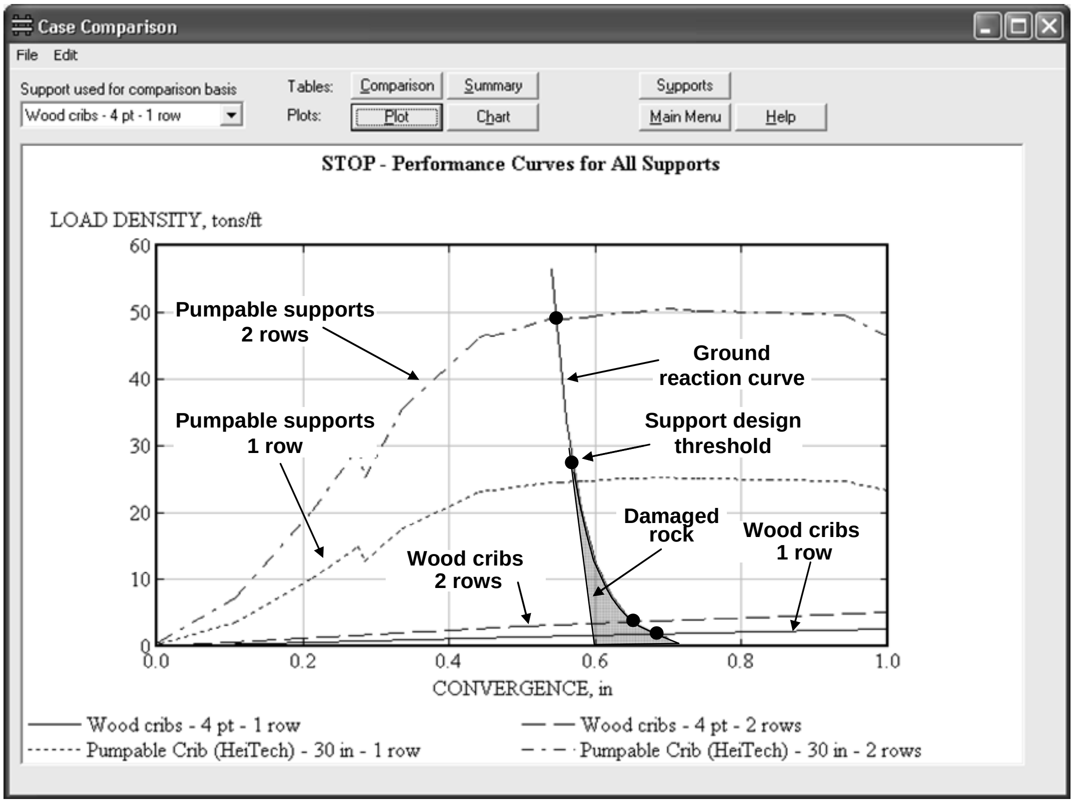


Figure 15a. Support performance assessment for front abutment (face) loading condition (750-ft overburden and 7.5-ft mining height).

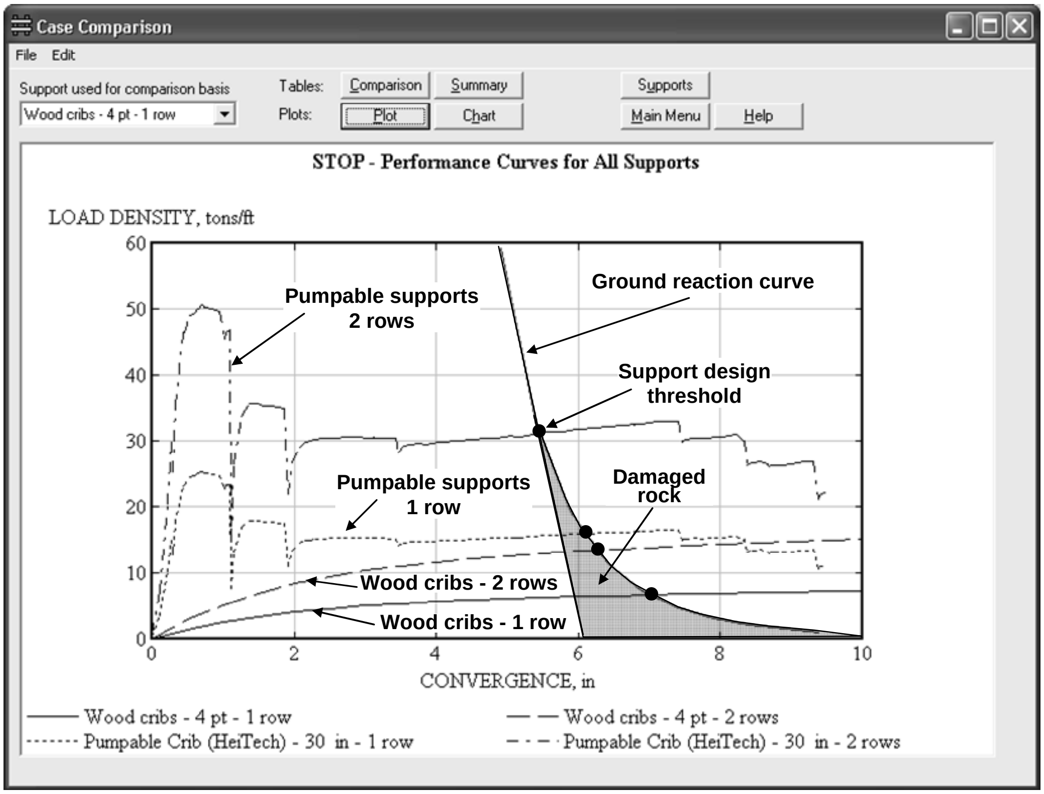


Figure 15b. Support performance assessment for full extraction (inby) loading condition (750-ft overburden and 7.5-ft mining height).

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 any agency determination or policy.

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