Development of Ground Response Curves for Longwall Tailgate Support Design

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ABSTRACT: Longwall tailgates in coal mines are often subject to severe mining induced loading and deformation. Innovative tailgate supports have been developed over the years to provide safe and economical access and a ventilation pathway at the tailgate. The support capacity and yield capabilities of the supports need to be matched to the loading imposed by the surrounding rock mass. The ground response curve can be used to represent the rock mass response to mining and its effect on support systems. The FLAC finite difference code was used to supplement field results by simulating a longwall tailgate and the associated ground response. The ground response curve is developed by modeling tailgate excavations with different internal support pressures and recording the resulting convergence. Ground response curves are developed for two typical longwalls operating in the Pittsburgh seam with weak and strong immediate roof. An additional model is presented in which the effect of weak overburden strata is simulated. The ground response is shown to be significantly affected by the strength of the immediate roof as well as the main roof. The importance of yield capacity of standing support is demonstrated. Gob height and compaction are found to affect the amount of convergence in the tailgate. The potential exists to develop site specific tailgate design curves by combining model results with field observations.

1. INTRODUCTION

Longwall tailgate entries can be subject to severe loading and deformation associated with the approach and passing of the longwall face. The tailgate entry is required to remain open so that a safe escape way and a reliable return airway is maintained at the tailgate corner of the advancing longwall face. In gassy mines it is also advantageous if the tailgate entry remains open behind the face, allowing ventilation air flow to the first crosscut in the gob area. Depending on the chain pillar size, this can be up to 60 m behind the advancing face. Innovative support methods have been developed to maintain the stability of the tailgate under these severe conditions. At present, standing supports are widely used as tailgate support in U.S. longwall mines [1, 2].

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. The load-deformation characteristics of standing supports are well known, and can be tested in the laboratory [3]. 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 using numerical models. The objective of the study was to improve the understanding of both the ground response and the required yielding capability of standing supports. The work forms part of the strategic goals of the National Institute for Occupational Safety and Health (NIOSH) research program that addresses safe ground control practices for coal mines.

2. STANDING SUPPORT CHARACTERISTICS

There is a wide variety of standing support systems currently available for longwall tailgate application. Although their performance characteristics vary, they can be classified into four basic types, as illustrated in Figure 1: (1) brittle, (2) constant load, (3) strain hardening, (4) strain softening behavior. Examples of each of these types of supports are the concrete donut crib (brittle), conventional 4-point wood crib (hardening), pumpable roof support (softening), and the Can support (constant load).

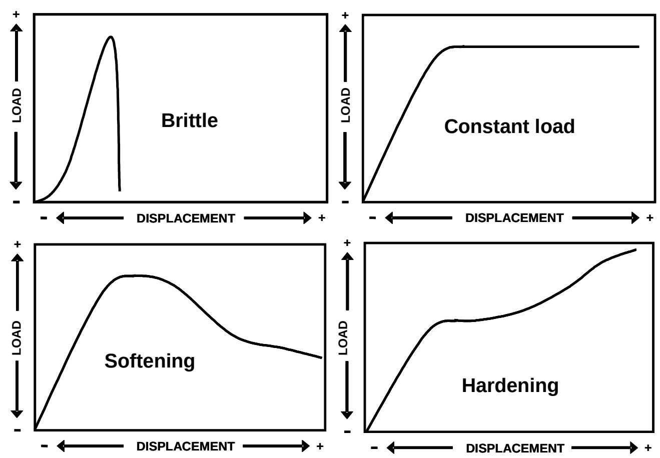

Fig. 1. Four basic types of loading characteristics for standing roof support systems.

Two of the support types were selected for discussion relative to the ground response curves. The first is a strong support exhibiting brittle behavior, similar to the concrete donut crib. The support has a peak capacity of approximately 500 tonnes after 25 mm of compression, but loses its strength after a further 25 mm of compression. The second is a softening support, such as the pumpable roof support. It is a grout-filled support that is formed in the mine entry by pumping a specialized grout into a fabric bag that is hung from the mine roof. This support type typically has a peak strength of about 150 tonnes after 25 mm compression, and loses about 50% of its strength after 300mm of compression.

3. OBSERVED GROUND RESPONSE IN LONGWALL TAILGATE ENTRIES

Longwall tailgate entries are subject to four distinct loading stages, shown in Figure 2. The loading stages are defined as follows: A) Development: loading condition before the effects of longwall retreat mining; B) Side Abutment: the entry is subject to an increase in vertical loading from the side abutment of the first panel mining, the horizontal stresses can decrease owing to the relaxation of the strata towards the gob; C) Face Abutment: the entry is subject to a further increase in loading as the second panel face approaches; D) Full Extraction: the loading condition after the longwall has passed and the entry is located in the gob area.

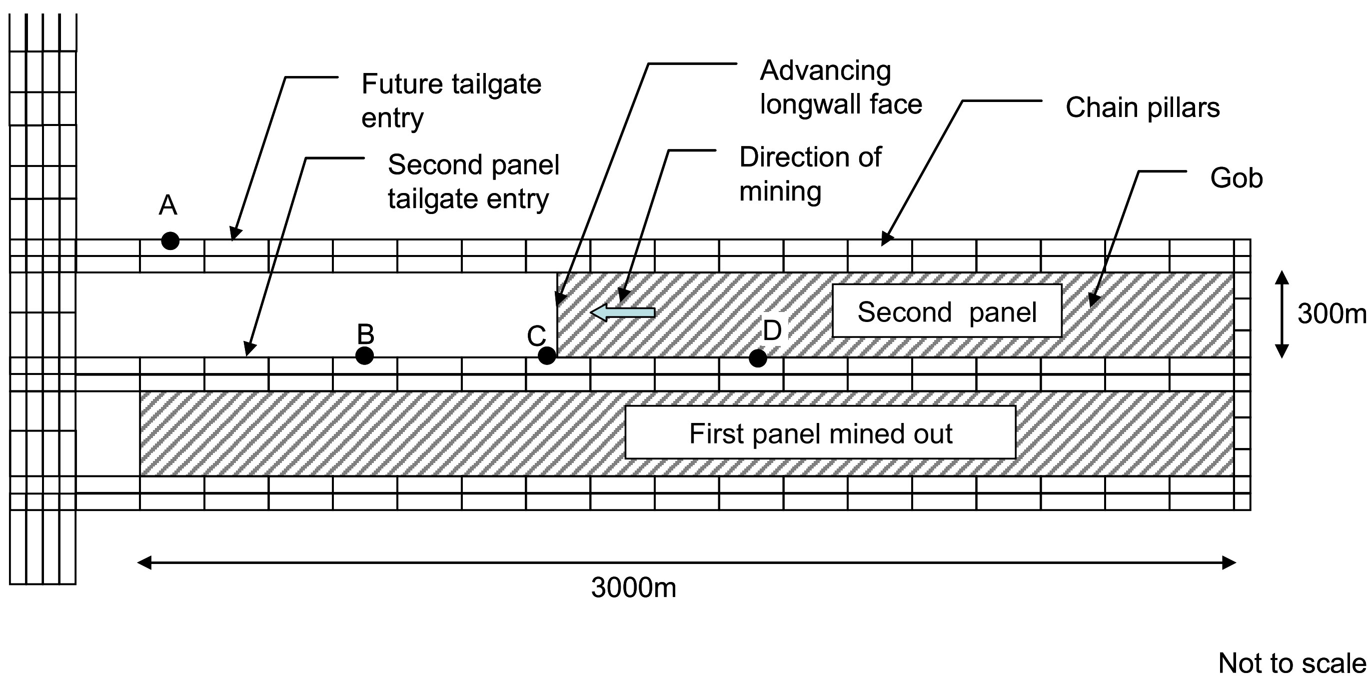

Fig. 2. Example of a longwall panel layout showing dimensions and nomenclature. Points A, B, C and D represent the Development, Side Abutment, Face Abutment and Full Extraction tailgate loading conditions, respectively.

Observations of tailgate entry performance in Eastern U.S. longwalls have shown that limited convergence between the roof and floor occurs between initial development and the Side Abutment loading stage. Convergence values of less than 10mm have been measured [4]. The Face Abutment loading stage can result in convergence of up to 50 mm [1, 5]. Convergence measurements are difficult to obtain behind the face, but a further 50mm is not uncommon within the first 10m behind the face [6], provided the support system remains functional. Mucho et al. [1] measured convergence of 100 mm at distances of up to 30 m behind the face in a tailgate entry supported with wood cribs.

The success of tailgate support can be compromised by issues such as side loading by gob fragments, lateral movement between the roof and floor and disintegration of the roof around the supports. These issues, though important, were not addressed by the current study.

4. 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 [7]. 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 [1, 2, 8, 9, 10, 11].

The ground response curve plots the support pressure against the excavation convergence, as shown conceptually in Figure 3. 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).

The effect of the support system can also be plotted on Figure 3. Line PQB represents a yielding support that is installed after initial convergence (δ). As the convergence increases, the support resistance increases, in proportion to the support stiffness. The support reaches its peak resistance at (Q). The support then yields and the support pressure is sufficient to arrest further convergence at point B. Ideally, support should 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.

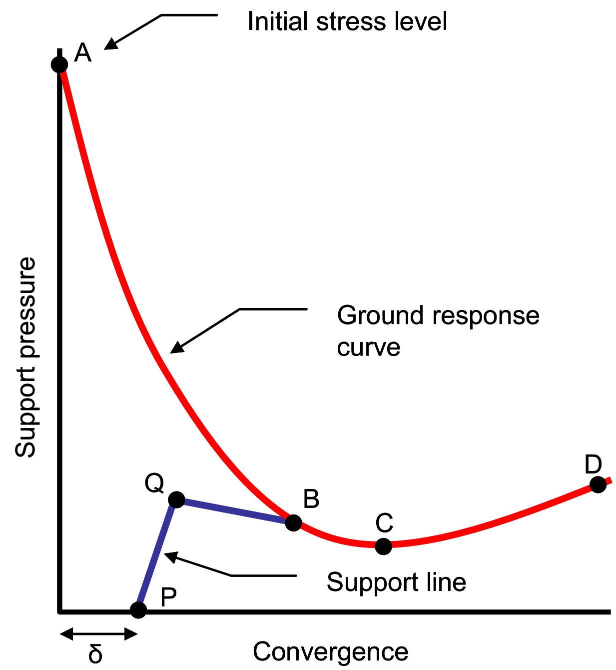

Fig. 3. Idealized ground response curve and support line.

In a longwall tailgate entry, the stress in the surrounding rock does not remain static. The advancing longwall 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 loading 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.

5. MODELING METHOD TO DEVELOP GROUND RESPONSE CURVES

The finite difference software FLAC [12] was used to develop ground response curves for a tailgate entry in various loading conditions and geological settings. The software is able to realistically model rock behavior from the initial elastic response to the large displacements and deformations that are associated with rock failure. It has the capability to model strength anisotropy found in the bedded coal measures and can simulate strain related weakening of failed rock. The software also has a built-in programming language that allows the user to control loads and displacements in the model. This facility was used to apply internal pressure within the modeled tailgate entry excavation so that the ground response curve could be determined.

Being a two-dimensional method, the software cannot model the conditions just behind the longwall face where a three-dimensional geometry exists. The results for the fully extracted loading stage are only applicable at a location remote from the longwall face, where two-dimensional conditions exist. Inspection of three-dimensional model results [11] using the Lamodel software [13] shows that two dimensional conditions are restored approximately 120 m behind the face for a longwall layout similar to that evaluated in this study. Simple linear interpolation was used to estimate the convergence between the Face Abutment stage and the Full Extraction loading stage.

A further limitation of the modeling method is that 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 rocks around standing supports and support loading by detached blocks were therefore specifically excluded from this study.

5.1. Model Layout

The overall finite difference model geometry and boundary conditions are shown in Figure 4. 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, which was 5 m wide by 1.8 m high. The extent of the model was 180 m wide by 100 m high, which allowed a 300 m wide longwall panel as well as the adjacent tailgate entry and the center entry to be modeled, by employing symmetry. The element size was 20 cm in the vicinity of the tailgate entry.

Three different geological settings were simulated, shown in the left margin of Figures 5 to 9. The first was a coal bed 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 second model is similar to the first, except that a strong sandstone bed was modeled in the immediate roof, typical of mining under a sandstone channel in the Pittsburgh seam. The third model simulated weak overburden, in which the limestone beds are absent and the overburden consists mainly of shale and siltstone beds.

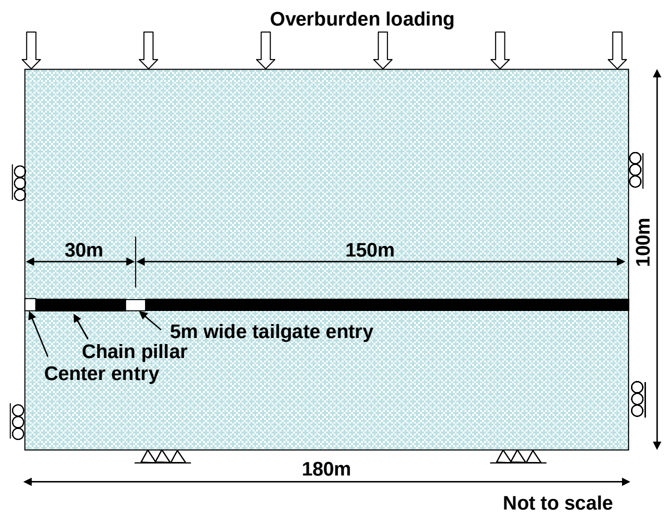

Fig. 4. Finite difference model showing general model layout and boundary conditions.

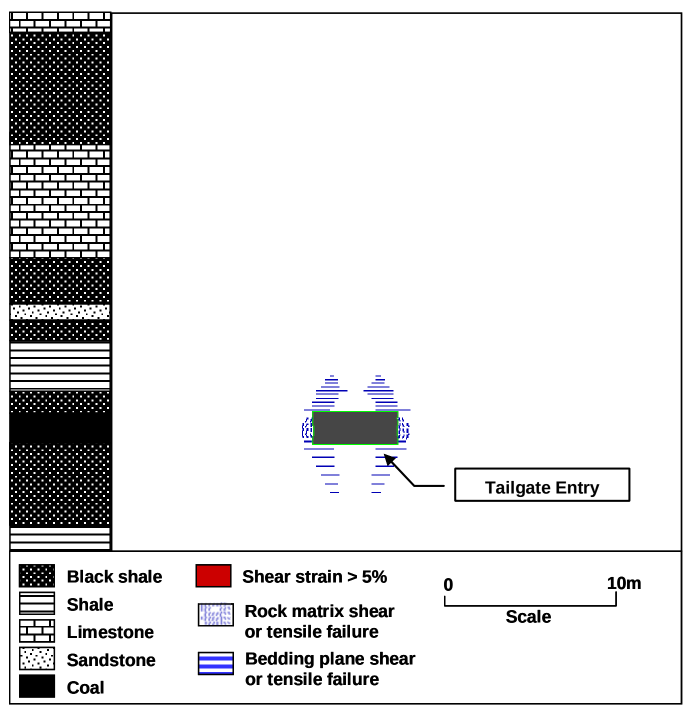

Fig. 5: Model with weak immediate roof and strong overburden beds. Rock failure around tailgate entry at the Development loading stage (Point A, Figure 2).

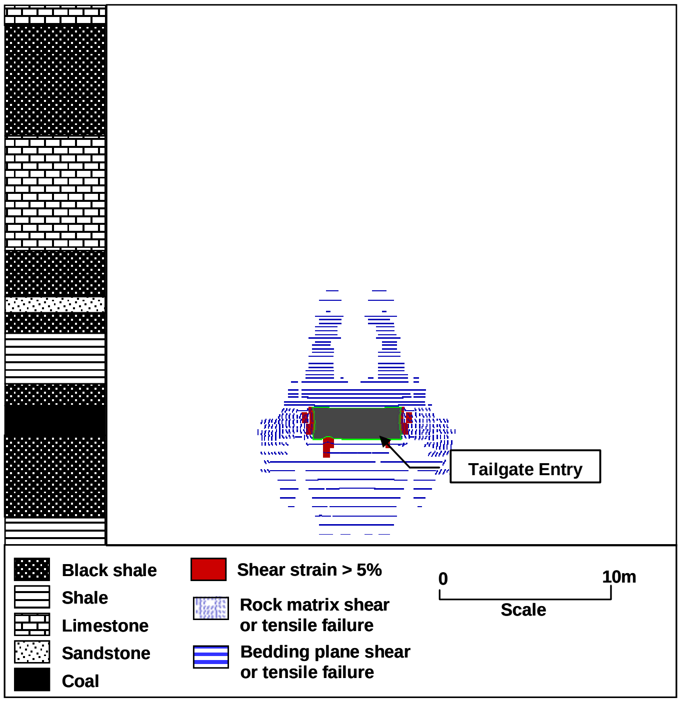

Fig. 6. Model with <u>weak</u> immediate roof and <u>strong</u> beds in the overburden. Rock failure and shear bands around tailgate at the Face Abutment loading stage, (Point C, Figure 2).

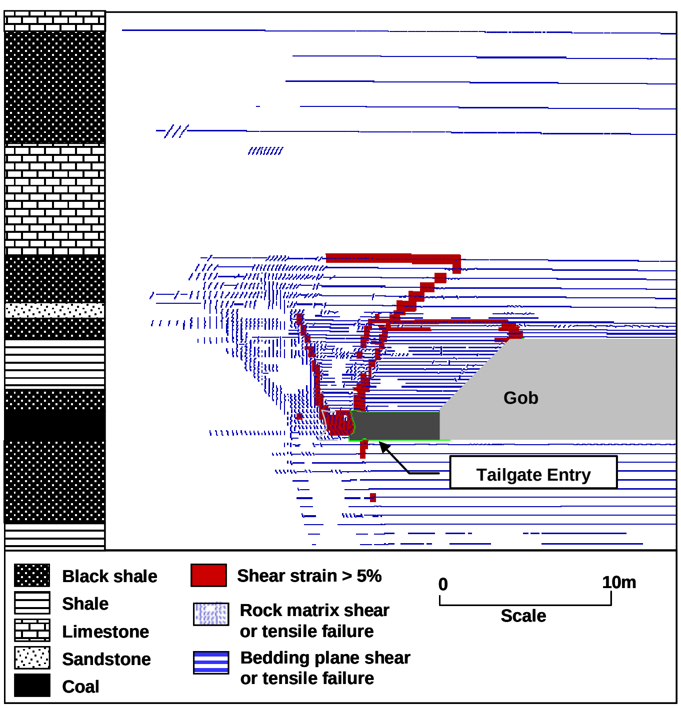

Fig. 7: Model with <u>weak</u> immediate roof and <u>strong</u> overburden, Rock failure and shear bands around tailgate entry at the Full Extraction loading stage (Point D, Figure 2).

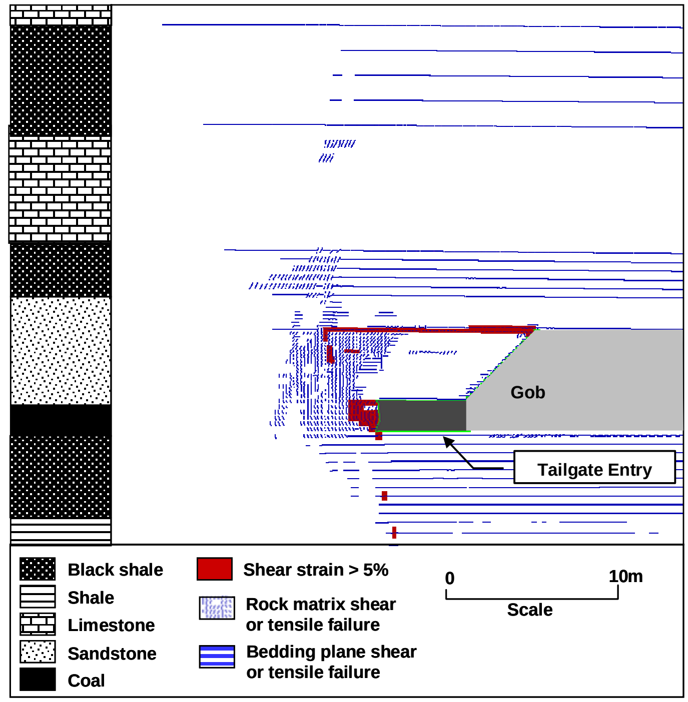

Fig. 8. Model with <u>strong</u> immediate roof and <u>strong</u> overburden, rock failure and shear bands around tailgate entry at the Full Extraction loading stage (Point D, Figure 2).

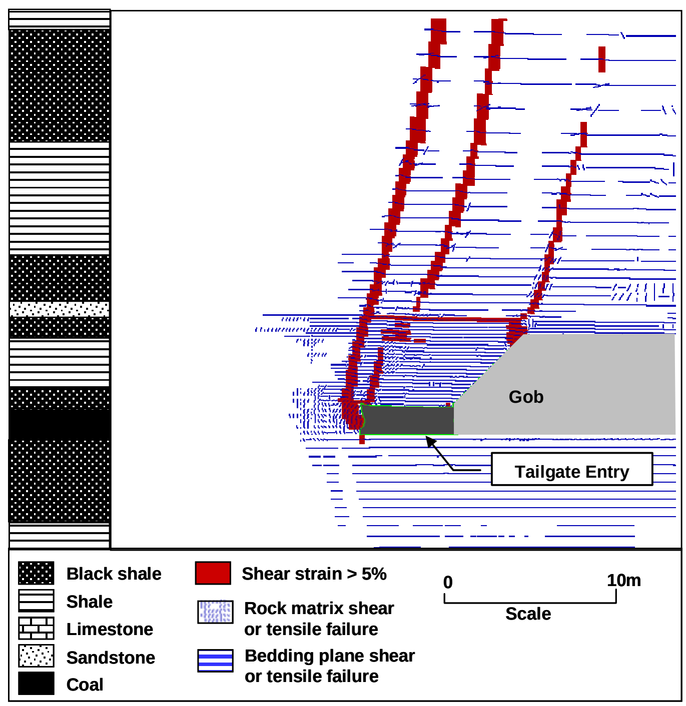

Fig. 9. Model with <u>weak</u> immediate roof and <u>weak</u> overburden, rock failure and shear bands around tailgate entry at the Full Extraction loading stage, (point D Figure 2).

5.2. Material Properties used in the Models

The rock mass was modeled as a strain softening, ubiquitous joint material, using the built-in constitutive model available in the finite difference software. This model 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 by the strain softening Coulomb constitutive model. Strength data for the different rock types included in the models were based on published data for to coal measure rocks [14, 15]. A summary of the average material properties used in the models is presented in Table 1. Rock strength variability was simulated in the models by allowing variations of up to 30% above and below the average values. 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.

Table 1 Average Mechanical Properties of Rock Types

Rock class	Cohesion (MPa)	Friction angle (^{o})	Poisson ratio	Elastic modulus (gpa)
Weak rock: Black shale, mudstone	4.5	25	0.25	6.0
Moderate rock: Shale	8.0	28	0.25	8.0
Strong rock: Sandstone	12.0	32	0.25	12.0
Very strong rock: Limestone	20.0	36	0.25	20.0
Coal	1.9	31	0.25	2.5

Table 2. Average Strength Properties of Bedding Planes

Bedding plane description	Cohesion (MPa)	Friction a ngle (^{o})
Very weak – clay filled discontinuity	0.055	21
Weak – open discontinuity	0.5	21
Moderate – weakly healed discontinuity	3.3	24
Strong – healed discontinuity	5.5	26
Very strong – strongly healed discontinuity	10.0	28

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 to 10% of the initial value after 0.5% plastic strain. The friction angle remained constant during yield. Dilation angle was constant at 15 degrees for all rock types. Owing to element size dependence of strain softening models, the element sizes were unchanged in all the analyses.

The model simulating the fully extracted conditions included the gob on one side of the tailgate entry. The gob was modeled as a soft elastic material. The bulk modulus of the gob was set at 18 MPa, determined by trial and error to allow approximately 90 cm of subsidence over the center of the longwall panel, similar to observed subsidence in Pittsburgh seam longwalls [16].

5.3. *Model Loading*

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. The initial vertical stress in the model was set at 5 MPa to simulate a tailgate entry at a depth of approximately 200 m 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 ratio of each rock layer plus a tectonic component which depended on the elastic modulus of the rock [17, 18]. The input parameters were selected so that the horizontal stress in the moderately strong shale beds was 8 MPa, similar to measured values in Eastern U.S. coal mines [18].

The loading induced by the Side Abutment and Face Abutment stages were simulated by increasing the vertical loading of the model by 1 MPa and 6 MPa, respectively. The stress increments were based on the results of three-dimensional models of longwalls using FLAC^{3D} [19]. Out-of-plane stress rotation near the longwall tailgate corner could not be included in the two-dimensional models.

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 assumed to extend three times the mining height above the roof of the mined coal seam. The extraction of the coal and associated gob formation was simulated as a single step in the model.

5.4. *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. The model was run to equilibrium at each loading stage and the average 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 1.0 kN/m^2 up to 2,500 kN/m^2 were applied to provide a range of results that would bracket the typical range of standing support capacities. Ground response curves were developed by plotting the support pressure against the tailgate entry convergence for each loading stage.

6. MODEL RESULTS

6.1. Rock failure and convergence

The model results for the Development, Face Abutment and Full Extraction loading conditions are presented in Figures 5 to 7 for the model which simulated typical Pittsburgh seam geology. The support resistance for this set of results was 75 kN/m^2, that approximates a single row of standing supports with 90 tonnes capacity, spaced 2.4 m apart along the length of a 5m wide entry. The Figures indicate the extent of failure of the intact rock and bedding planes around the tailgate entry. Shear band development is shown by highlighting the zones where the strain exceeds 5%.

It can be seen in Figure 5 that the Development loading stage results in bedding slip in the immediate roof and floor of the entry, and limited failure in the coal seam. Failure and convergence increases considerably at the Face Abutment loading stage, shown in Figure 6. About 32 mm of additional convergence occurs, which is similar to that observed in a Pittsburgh seam longwall using standing supports of a similar capacity [1]. The convergence in the model is largely the result of elastic relaxation and bulking of the failed rock into the excavation.

The Full Extraction stage, shown in Figure 7, results in 256 mm of convergence and considerable failure of the surrounding rock mass. The limiting effect of the strong limestone beds on vertical failure development is clearly demonstrated. A semi-detached block is formed in the roof that is held in place by the support pressure. In practice such a detached block is likely to also transfer some of its weight to the gob, resulting in reduced loading of the standing supports. Further inspection of the model results showed that during the Full Extraction loading condition, the convergence is largely caused by the upper strata settling onto the gob and the chain pillars. As a result, the gob stiffness will have a direct effect on the amount of convergence in the tailgate entry behind the face.

Figure 8 shows the rock failure associated with the Full Extraction loading condition for the strong roof case. It can be seen that the strong sandstone roof has failed to a lesser degree and convergence is 169 mm. A horizontal shear band forms within the sandstone, near the top of the gob. The vertical extent of rock failure is again inhibited by the overlying limestone bed.

The results for the weak overburden case, under Full Extraction loading conditions, are presented in Figure 9. The results show extensive shear band development in the absence of the strong limestone beds. Convergence in the tailgate entry is much larger now, at 381 mm. Closer inspections of the results showed that the shear bands in the overburden result in a stepped displacement profile. Consequently the immediate entry experiences a greater amount of convergence. The weak immediate roof is seen to be failed and forms a detached block, delineated by the shear banding.

6.2. Ground Response Curve Results

The resulting ground response curves for the three cases analyzed are presented in Figures 10 to 12. Each case shows the support pressure versus convergence curve for the four longwall loading stages. Three additional curves are shown in which the convergence at 10m, 30m and 60m behind the face (inby) was estimated by linear interpolation. The support pressure is plotted on a logarithmic scale, starting at 10 kN/m^2. It is assumed that the primary support, which is installed during development, will provide this level support prior to the installation of standing supports.

The two idealized standing support curves, previously discussed, are also shown in each chart. Support line A represents the idealized brittle support, and B represents the softening support. The supports are assumed to be installed after convergence caused by the Development loading stage has occurred.

Figure 10 shows the set of ground response curves developed for the weak roof, strong overburden case. The results show that, up to the Face

Abutment loading stage, the ground response curves are steep and convergence is limited to less than about 75 mm. At the Full Extraction loading stage the convergence increases to more than 100 mm for 2,500 kN/m² support pressure, and apparent collapse is indicated if the support pressure is reduced to less than 25 kN/m².

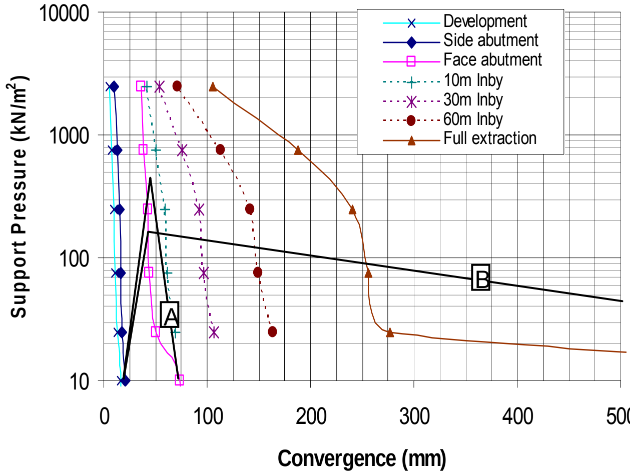

Fig. 10. Ground response curves derived from the model of a tailgate entry under a <u>weak</u> immediate roof with <u>strong</u> beds in the overburden. Dotted lines indicate interpolated curves. Lines A and B represent brittle and softening supports, respectively.

Considering the two idealized standing support curves, we see that the brittle support (A) will be able to control convergence up to the Face Abutment stage, when it reaches its maximum load. However, it will shed its entire load before it reaches the 10 m inby location. The lower capacity softening support (B) will provide adequate support up to the Full Extraction loading stage. At this stage the convergence will be about 260 mm. To control the roof up to the 60 m inby mark, if required for ventilation purposes, would require about 150 mm of yield capability. It is interesting to note that even if the capacity of the softening support is increased tenfold, it would need to yield by about 150 mm in response to the convergence at the Full Extraction loading stage.

In the case of the strong roof model, Figure 11, the ultimate convergence is less than 175 mm for the Full Extraction loading condition. The brittle support (A) reaches its peak load at the 10 m inby condition. The yielding support (B) can arrest the convergence up to the Full Extraction stage by yielding about 145 mm and would require about 90 mm of yield capability to support the roof up to the 60 m inby mark, if required for ventilation purposes.

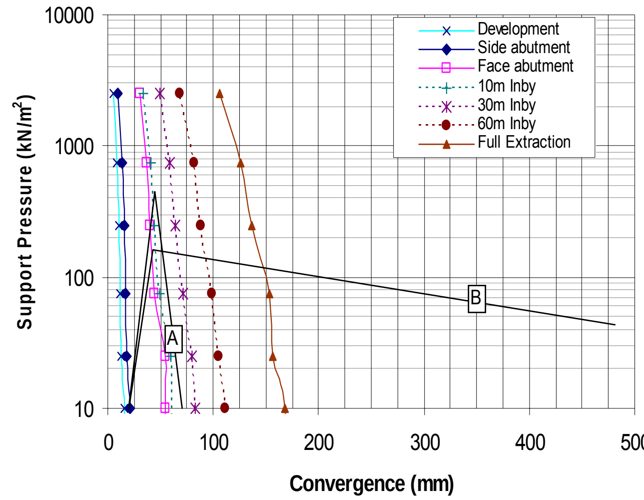

Fig. 11. Ground response curves derived from the model of a tailgate entry under a <u>strong</u> immediate roof with <u>strong</u> beds in the overburden. Dotted lines indicate interpolated curves. Lines A and B represent brittle and softening supports, respectively.

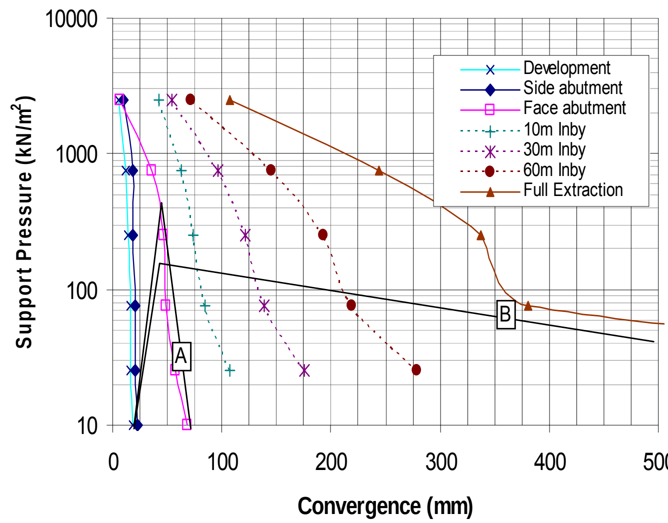

Fig. 12. Ground response curves derived from the model of a tailgate entry under a <u>weak</u> immediate roof with <u>weak</u> beds in the overburden. Dotted lines indicate interpolated curves. Lines A and B represent brittle and softening supports, respectively.

The results for the weak overburden model, Figure 12, show that convergence will be substantially higher than for the previous two cases. In addition, the roof apparently starts to collapse when the support resistance drops below 75 kN/m^2, which is higher than the strong overburden case. The results show that the brittle support (A) will be adequate up to the Face Abutment loading stage, but would fail soon afterwards. The softening support (B) is not able to arrest convergence up to the Full Extraction stage because the ground support curve exceeds its capacity. This support is, however, able to control the roof up to the 60 m inby loading stage.

7. DISCUSSION AND CONCLUSIONS

The finite difference model results presented in this paper have provided valuable insight into the loading mechanisms and associated convergence in longwall tailgate entries. The method can be used to investigate the effect of various loading conditions, longwall geometries and geological scenarios on the ground response.

Although the two-dimensional modeling technique used in the study has limitations, especially for capturing rock response near the longwall tailgate corner, satisfactory agreement was obtained between field observations and model behavior.

The results showed that up to the Face Abutment loading stage, the convergence in the tailgate entry is largely the result of bulking associated with rock failure and bedding plane shear in the surrounding strata.

In the Full Extraction loading stage, convergence is additionally caused by settlement of the overburden onto the gob and chain pillars. The gob stiffness and height of gob formation will therefore have an impact on the convergence of the tailgate behind the face.

The strength of the overburden strata is shown to have a significant effect on the amount of convergence in the tailgate entry and on the support required to restrict the convergence. Weak overburden strata tend to shear at the edge of the chain pillar, resulting in greater convergence in the tailgate entry and a higher load demand on the standing supports.

The ground response curves, developed from the model results, show that convergence in the tailgate entry cannot be prevented by standing supports. A significant proportion of the tailgate convergence is driven by loads which far exceed the capacity of typical standing supports.

The results presented in this paper should not be used as standing support design curves since they were developed for a specific set of geological and geometric conditions using simplified two-dimensional models. In addition, further work is required to investigate issues such as ground response in the vicinity of the face corner and the effect of loosened or detached roof rocks.

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