Longwall Mining-Induced Abutment Loads and Their Impacts on Pillar and Entry Stability

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ABSTRACT

Longwall mining-induced abutment loads on the surrounding coal pillars can be grouped into two categories in terms of the relative position of the coal pillars and the longwall face. They are the front and side abutment loads. Even though a lot of research and efforts have been made to study the nature and behavior of these longwall mining-induced abutment loads, their influence zones and magnitude are still not well defined and fully understood due to the complexity of geological conditions and the longwall mining-induced overburden strata movement. The uncertainty about the mining-induced abutment loads often forces consultants and mining engineers to employ a conservative approach in designing coal pillars and entry roof control plans. The problems with this approach are that: (a) it increases CM development-longwall retreat footage ratio, (b) it decreases coal recovery, and (c) it increases the operating costs. However, a more liberal approach may create safety issues and result in loss of production. Therefore, the importance of accurately defining the influence zones and magnitude of the front and side abutment loads induced by longwall mining can never be over emphasized.

The authors in this paper attempt to define the influence zones and discuss the magnitude of the longwall mining-induced abutment loads by analyzing the field data measured at RAG American Coal Company's longwall mines. In addition, the relationship between entry stability and the balance among roof/floor conditions, pillar design, and roof control plan is also briefly discussed.

Key words: Abutment loads, pillar design, and roof control

INTRODUCTION

For the last several years, Mine A has been employing the current chain pillar configuration (a yield-and-abutment pillar system) to successfully mine 10 longwall panels under a cover depth of less than 1,200 ft. As the depth of cover increases up to 1,300+ ft in the future panels, the question is that can the current chain pillar configuration still successfully be used without causing roof control problems in both the longwall headgate and tailgate entries, and without inducing tailgate pillar bounces or floor bumps? If not, what pillar configuration should be employed? To answer this question, a joint research project to measure panel and pillar stresses was initiated with NIOSH in 2000 and was completed in May 13, 2002. The field data from this project and others in which stress and entry convergence data were collected in last several years at RAG longwall mines are used to analyze the longwall mining-induced abutment loads and their impacts on pillar design and entry roof control plan for different roof and mining conditions.

STRESS AND ROOF COVERGENCE MONITORING SYSTEMS AT RAG LONGWALL MINES

To better understand the nature of overburden strata movement and the impacts of abutment loads on the stabilities of pillars and entries during longwall retreat, borehole pressure cells and convergence meters have been used to measure pillar stress and entry convergence at our four longwall mines in the U. S.

Stress Monitoring Systems at Mines A and B

Mine A is located in Colorado and mining the Wedge seam, which has a thickness ranging from 8 to 9 ft and a cover depth ranging from 800 to 1,650 ft. As illustrated in Fig. 1, a yield-abutment pillar system with three entries is employed between longwall panels. The yield pillar is 35 ft wide and 80 ft long and the abutment pillar is 80 ft wide and 180 ft long. A total of 8 borehole pressure cells (BPCs) were installed across the chain pillar system and 3 BPCs were installed inside each panel. At the monitoring site, the coal seam thickness was 8.7 ft and the depth of cover was 1,310 ft

Mine B is located in Utah and mining the D seam, which has a thickness ranging from 8 to 23 ft and a cover depth ranging from 1,000 to 3,000 ft. As illustrated in Fig. 2, a yield pillar system
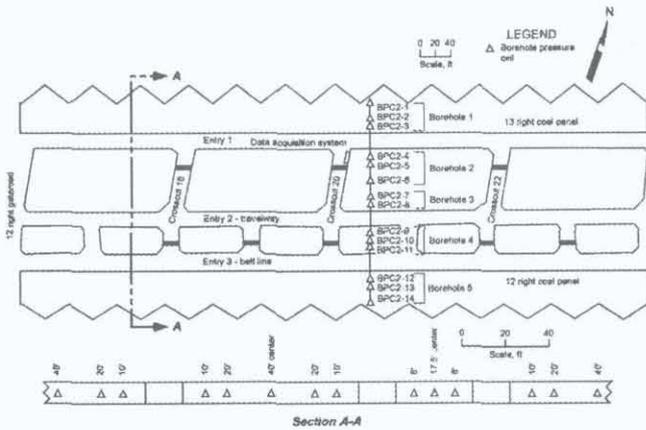
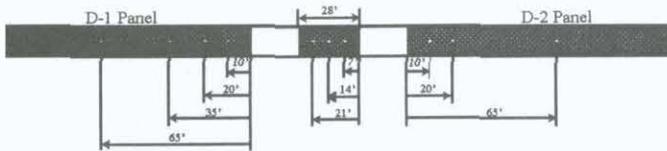Fig. 1 Stress Monitoring System at Mine A

Fig. 2 Stress Monitoring System at Mine B

with two entries is employed between longwall panels. The yield pillar is 28 ft wide and 80 ft long. A total of 10 BPCs were installed at the motoring site. At the monitoring site, the coal seam thickness was 23 ft thick with the top 10 ft mined and the depth of cover was 2,290 ft (1). In addition, at Mine B another stress monitoring line including seven BPCs was also installed inside the 350 ft wide barrier pillar along the D-1 panel's setup room, where the depth of cover was 2,000 ft.

Entry Convergence Monitoring Systems at Mines C and D

Both Mines C and D are located in Pennsylvania and mining the Pittsburgh seam, which has a thickness ranging from 6.5 to 7.5 ft and a cover depth ranging from 450 to 1,050 ft. As illustrated in Fig. 3, a two-stable pillar system with three entries is employed between longwall panels. In general, Mine C has a thicker seam ranging from 7 to 7.5 ft and a deeper cover ranging from 650 to 1,050 ft. The width of the chain pillar system at Mine C is 200 ft center-to-center with a 16 ft wide entry. Mine D has a thinner seam ranging from 6.5 to 7 ft and a shallower cover ranging from 400 to 850 ft. However, a wider chain pillar system of 230 ft center-to-center was used at the time that the entry convergence was monitored in 1995. The entry width at Mine D was also 16 ft wide.

At Mine C, four COR-P convergence meters (2) were installed 100 ft apart in the headgate entry immediately outby the stageloader and one COR-P convergence meter was installed in the future tailgate entry to measure the total entry closure during longwall retreat. At the monitoring site, the coal seam thickness was 7 ft and the depth of cover was 850 ft.
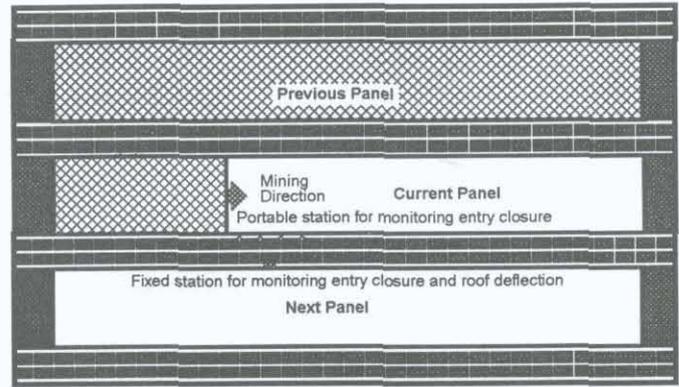

Fig. 3 Entry Activity Monitoring System at Mines C and D

At Mine D, two COR-P convergence meters were installed in the future tailgate entry to measure both the total entry closure and roof deflection. To measure entry roof deflection, an expansion shell was used to anchor the bottom of the convergence meter into the main floor (3 ft deep). At the monitoring site, the coal seam thickness was 6.5 ft and the depth of cover was 600 ft.

RESULTS AND DISCUSSIONS

The stress data from Mine A were collected through two adjacent panels' mining and are plotted in Figs. 4 thru 9. Since the stress changes in the abutment pillar and 13 Right panel reflect a complete cycle of the longwall mining process, the influence zones and magnitudes of the front and side abutment loads induced by the whole mining process can be derived.

The stress data from Mine B were collected for one-panel's mining. Since the yield pillar yielded about 60 ft outby the longwall face and D-2 panel was only 48 ft away from the D-1 panel's gobline, the data from D-2 panel and the yield pillar cannot be used to serve the purpose of this study. Therefore, only the pressure data from the BPCs inside D-1 panel were used to analyze the magnitude and influence zone of the front abutment load (Fig. 10).

The seven BPCs within the barrier pillar were installed at 25, 55, 120, 150, 190, 227, and 323 ft away from the setup room. The stress increments (difference between the initial reading and the final reading when the D-1 panel's face was advanced 1,030 ft away from its setup room) inside the barrier pillar were collected and are plotted in Fig. 11. The stress data from this monitoring site can be used to determine the influence zone of the side abutment load and the trend of its distribution curve.

At Mine C, the entry convergence data recorded in the headgate entry are plotted in Fig. 12. Since the convergence meters were located in the belt entry and used to reflect the entry convergence, the data from this monitoring site can only be used to deduce the influence zone of the front abutment load. However, the entry convergence data collected in the future tailgate entry
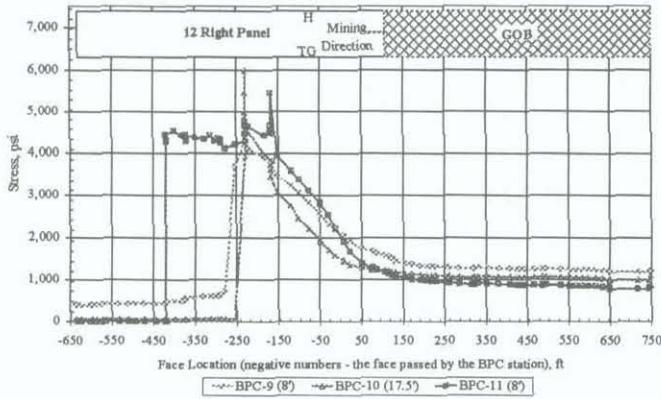
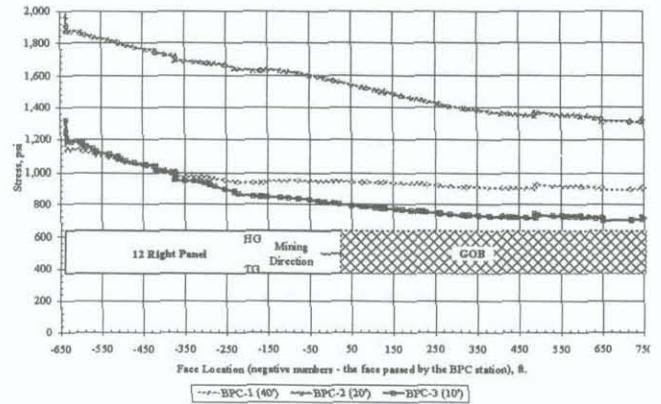Fig. 4 Yield Pillar Stress vs. 12 Right Face Location (Mine A)

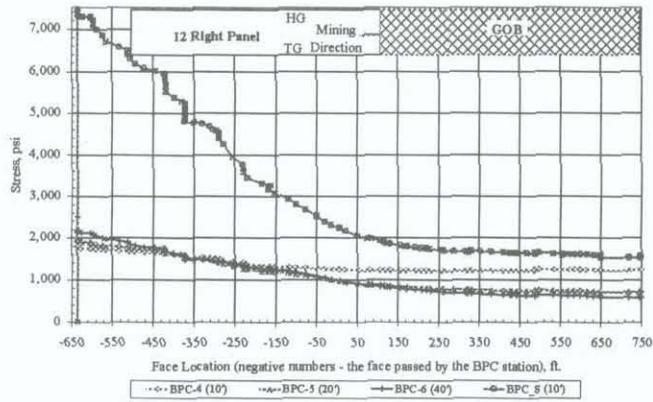Fig. 7 13 Right Panel Stress vs. 12 Right Face Location (Mine A)

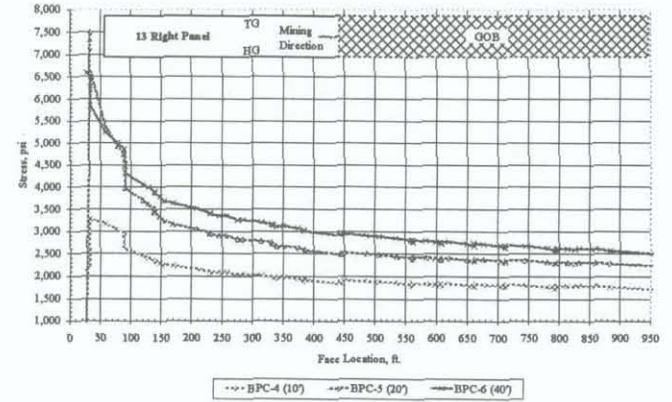Fig. 5 Abutment Pillar Stress vs. 12 Right Face Location (Mine A)

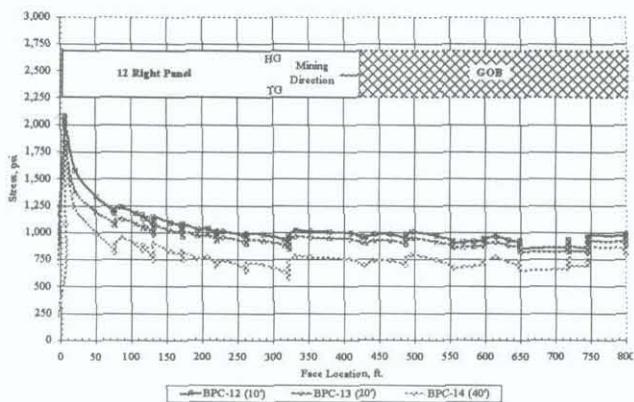Fig. 8 Abutment Pillar Stress vs. 13 Right Panel Face (Mine A)

Fig. 6 12 Right Panel Stress vs. 12 Right Face Location (Mine A)
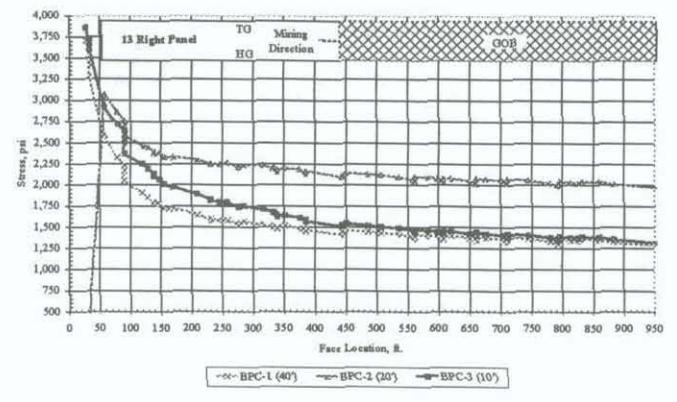

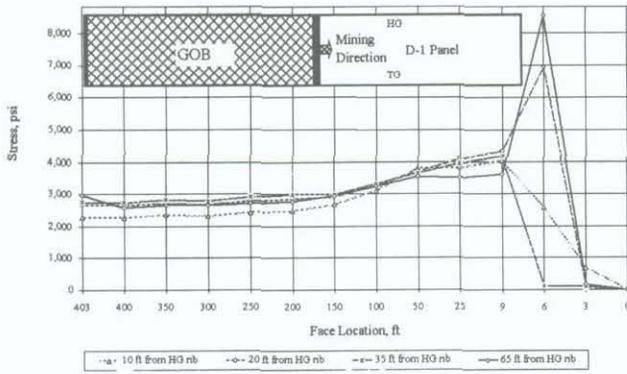Fig. 9 13 Right Panel Stress vs. 13 Right Face Location (Mine A)

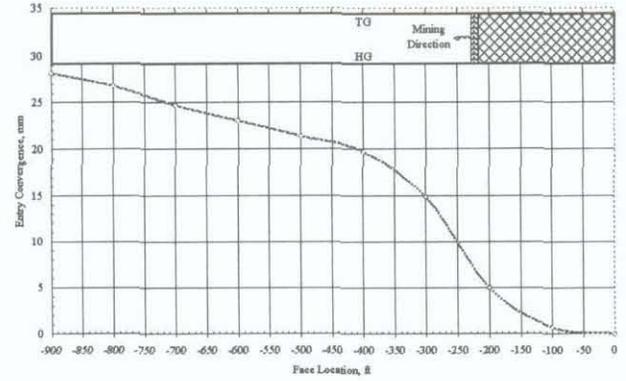Fig. 10 D-1 Panel Stress vs. D-1 Face Location (Mine B)

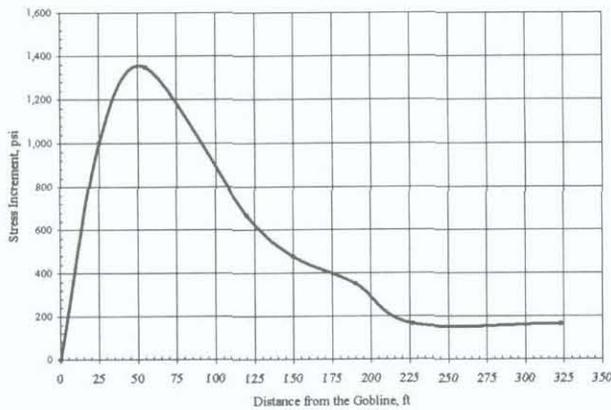Fig. 13 Future TG Entry Convergence vs. Face Location (Mine C)

Fig. 11 Influence Zone of the Side Abutment Load
(Mine B, depth of cover = 2000 ft)
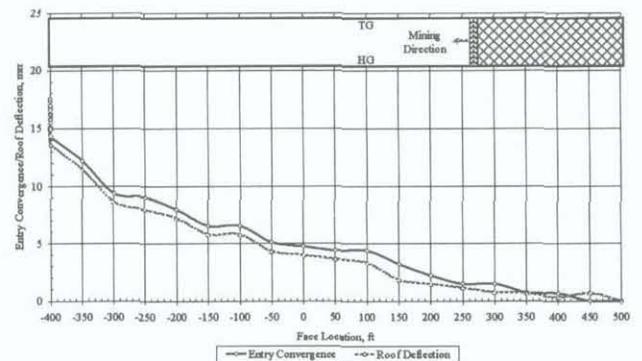
Fig. 14 Future TG Entry Convergence and Roof Deflection vs.
Face Location (Mine D)

(200 ft away from the headgate entry) can be used to determine the influence zone of the side abutment load across the chain pillars. The convergence data in the future tailgate entry vs. the face location are plotted in 13.

To determine the impacts of the front and side abutment loads on the convergence, roof deflection, and floor heave of the future tailgate entry, two convergence meters at Mine D were installed at the entry center with one being anchored into the main floor. The results from this monitoring site are illustrated in Fig. 14.

Influence Zones of the Front and Side Abutment Loads

Influence zone of the front abutment load

As illustrated in Fig. 4, the yield pillar stress started to increase when the 12 Right panel's face was approaching 650 ft inby the monitoring site. However, the stress changes of the three BPCs inside the yield pillar were minimum or negligible within the zone of 650 to 350 ft inby the monitoring site. Then, an obvious

Fig. 12 HG Entry Convergence vs. Face Location (Mine C)

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pillar stress change occurred when the face was less than 350 ft inby the BPCs. A dramatic stress increment can be observed when the face was less than 150 ft inby the monitoring site. This trend of stress increment was continuing until the face reached the monitoring site.

It should be noted that once the face passes by the monitoring site, any change of BPC pressure at the site is under the influence of the side abutment load. It can be seen from Fig. 4 that the yield pillar started yielding on the gob side (BPC-11, 8 ft from the gobline) when the face was 160 outby the monitoring site and the whole pillar yielded when the face was 240 ft passing by the BPCs.

For the influence zone of the front abutment load during the 12 Right panel's mining, the similar trend of pressure changes can also be found among the BPCs except BPC-4 inside the abutment pillar, as illustrated in (Fig. 5). It should be noted that the monitoring site was 635 ft inby the recovery room of 12 Right panel. In order to see the full impact of the side abutment load, the pressure values of the BPCs inside the abutment pillar were collected in seven and half months later after the 12 Right panel's face reached the recovery room or when the 13 Right panel's face was about 1,000 ft inby the monitoring site.

The effect of the front abutment load on both panels ahead of the 12 Right panel's face can also be roughly divided into three zones discussed earlier during the 12 Right panel's mining, as illustrated in Figs. 6 and 7. The peak load was reached when the face was 7 ft inby the BPCs (Fig. 6).

In summary, the influence zone of the front abutment load induced by the first panel's mining can be divided into three different zones in terms of the pressure increment rates of the BPCs ahead of the longwall face and the face locations. They are:

Zone I: Initial influence zone – 650 to 350 ft
Zone II: Obvious influence zone – 350 to 150 ft
Zone III: Significant influence zone – 150 to 0 ft

Examination of the pressure changes inside the abutment pillar and 13 Right panel when the 13 Right panel's face was approaching indicates that the influence zone of the front abutment load can reach as far as 950, as illustrated in Figs. 8 and 9. However, zones II and III are almost identical to those induced by the first panel's mining. In addition, the abutment pillar started to yield at a depth of 10 ft into the pillar from the tailgate when the 13 Right panel's face was 33 ft inby the monitoring site, as illustrated in Fig. 8 (BPC-4). However, the stress at the pillar center (BPC-6) kept increasing until the wire of BPC-6 was cut due to the deteriorated roof and rib conditions when the face was 27 ft inby the monitoring site. By the time when the wires were cut and the data logger was removed, no panel rib's yielding was observed or recorded (Fig. 9, BPC-1, 10 ft deep from the tailgate entry). However, BPC-2, which was 20 ft deep into the panel, did show a pressure drop when the face was 60 ft inby the face. This may be caused by local weakness of the coal seam around BPC-2.

Analysis of the pressure changes inside D-1 panel at Mine B shows the similar trend of the front abutment load effect (Fig. 10). It can be seen from Fig. 10 that the yield zone depth ahead of the longwall face ranges from 6 to 9 ft.

As illustrated in Fig. 12, the headgate entry convergence data recorded at Mine C indicate that the effect of the front abutment load on the headgate entry convergence can be felt as far as 650 ft at COR-P3 and as near as 300 ft at COR-P1 and COR-P2, depending upon the local roof and floor conditions.

Based on the analysis of the field data, it can be concluded that (a) the influence zone of the front abutment load can reach as far as 650 ft outby the longwall face during the first panel's mining and 950 ft outby the longwall face during the second panel's mining, and (b) the yield zone depth ahead of the longwall face ranges from 6 to 9 ft.

Distribution and influence zone of the side abutment load

The distribution and influence zone of the side abutment load within chain pillars or barrier pillars surrounding a longwall gob or gobs are critical to determine if the future tailgate entry, the adjacent tailgate-end face, a bleeder entry, or a main entry is under the influence of the side abutment load. Depending on its function, service life, and roof/floor conditions, an entry can be developed within or beyond the influence zone of the side abutment load if a sound roof control plan is made and implemented.

According to Peng and Chiang (3), the maximum influence zone of the side abutment load mainly depends on the overburden depth of a coal seam and can be estimated by the following equation:

$$D = 9.3 \sqrt{h} \qquad (1)$$

where D is the maximum distance from the gobline, in ft and h is the depth of cover, in ft.

For a cover depth of 1,310 ft at Mine A, the maximum influence zone of the side abutment load may reach as far as 336 ft by Eq. 1. Since BPC-1 inside the 13 Right panel was only 195 ft from the 12 Right panel's gobline (Fig. 7), it is obvious that BPC-1 was within the influence zone of the side abutment load induced by the 12 Right panel's gob, which could be verified by the relative stress increment indicated in Fig. 7.

For a cover depth of 2,000 ft at Mine B, the maximum influence zone may reach as far as 416 ft away from the gobline. Therefore, the BPC located 323 ft away from the D-1 panel's gobline was also within the influence zone defined by Eq. 1. However, the stress increments at locations of 227 ft and 323 ft were far less than those at the locations that were near the gobline. In addition, the monitoring results within the barrier pillar at Mine B once again indicated that an exponential distribution curve of the

side abutment load is expected in the coal blocks surrounding a longwall gob or gobs.

Even though the entry convergence or roof deflection data in the future tailgate entries at Mines C and D cannot be used to determine the magnitude of the side abutment load, they can be used to deduce the influence zone of the side abutment load. At Mine C, the future tailgate entry was 184 ft away from the longwall gobline and under a cover depth of 900 ft. Since the maximum influence zone of the side abutment load may reach 279 ft for a cover depth of 900 ft, the future tailgate entry was within the influence zone of the side abutment load. At this monitoring site, a 28 mm of entry convergence after the face was 900 ft outby the monitoring site was recorded with obvious roof sagging and broken roof around the convergence meter.

At Mine D, the future tailgate entry was 214 ft away from the longwall gob and under a cover depth of 600 ft. Since the maximum influence zone of the side abutment load was 228 ft for a cover depth of 600 ft, the future tailgate entry was also under the influence zone of the side abutment load with a 17.5 mm of entry convergence 8 days after the face reached the recovery room, which was about 38% less than that recorded from the future tailgate entry at Mine C due to the distance difference from the longwall gobline.

In summary, the filed data collected from Mine D further proves that the maximum influence zone of the side abutment load can reach as far as predicted by Eq.1.

Magnitudes of the Front and Side Abutment Loads

Theoretically, the side abutment load can be estimated, depending on panel width, depth of cover, and shear angle of the overburden strata along the gobline (4,5). However, no analytical method is available to determine the front abutment load. Based on the USBM's limited field instrumentation, the front abutment stress on pillars at the headgate side (or called the first front abutment stress) can be estimated by:

$$\sigma_{hf} = 0.5\,\sigma_s \qquad (2)$$

and the front abutment stress on pillars at the tailgate side (the accumulated front abutment loads) is determined by:

$$\sigma_{tf} = 0.7\,\sigma_s \qquad (3)$$

where σ_s = side abutment stress.

To verify the accuracy of Eqs. 2 and 3, the average abutment stresses in the chain pillars and 13 Right panel at Mine A were used to calculate the ratio of the front and side abutment loads and listed in Table 1. It can be seen from Table 1 that during the first panel's mining (12 Right) the magnitudes of the front and side abutment stresses were the largest in the yield pillar before it yielded and the smallest in 13 Right panel. This again indicates that the degree of impact of the longwall mining-induced abutment loads on longwall chain pillars and the adjacent panel is mainly determined by the distance between the individual pillar of interest or the future panel and the active panel.

Since the yield pillar had yielded before it was exposed to the full side abutment load, the ratio of the front and side abutment stresses is of less interest for conventional pillar design. In addition, during the 12 Right panel's mining, the absolute stress increment rather than the front/side abutment ratio in 13 Right panel affects the stability of the future tailgate-end face and thus is our major concern in determining the width of the chain pillar system between panels. Therefore, only the ratio of the front and side abutment stresses of the abutment pillar is meaningful to serve the purpose of longwall chain pillar design.

It is obvious from Table 1 that the first front abutment effect on the abutment pillar or the front abutment stress on pillars at the headgate side is far less than that predicted by Eq. 2. However, the front abutment stress on the tailgate pillar or the second front abutment stress far greater than that predicted by Eq. 3. The

Table 1 Front and Side Abutment Stresses and Their Ratios (Mine A)

Item	Yield Pillar		Abutment Pillar		13 Right Panel		Comments
	No. of BPCs	Average Stress	No. of BPCs	Average Stress	No. of BPCs	Average Stress	
		(psi)		(psi)		(psi)	
12 Right Panel's Mining							
Initial reading	3	1,021	4	1,045	3	983	650 ft outby the face
Front abutment	3	794	4	324	3	125	Stress increment
Side abutment	3	3,211	4	2,126	3	417	Stress increment
Front/Side ratio		0.25		0.15		0.30	
13 Right Panel's Mining							
Initial reading	n/a	n/a	3	2,169	3	1,525	950 ft outby the face
Front abutment	n/a	n/a	3	3,627	3	2,018	27 ft outby the face
Front/Side ratio	n/a	n/a		1.71		4.84	Stress increment

significant increase of the front abutment stress on the abutment pillar during the 13 Right panel's mining indicates that for the tailgate pillars that have already been exposed to the abutment loads induced by the previous panel's mining, the impact of the second front abutment stress on them will be 10 times greater than that of the first front abutment load, which may be due to the facts that (a) they are immediately adjacent to the second panel's face and (b) the already-disturbed overburden strata above the chain pillars are more sensitive to the approach of the second face.

In summary, the significant deviation of the front abutment stress on longwall chain pillars between the field data obtained through this study and what recommended by Mark (4,5) should be further studied to avoid either underestimate or overestimate the overall pillar stress for longwall chain pillar design.

PILLAR DESIGN VS. ENTRY STABILITY

One of the major purposes of leaving chain pillars between panels is to maintain the stability of the outby tailgate entry during longwall retreat. Underground observations indicate that the stability of the tailgate entry outby the longwall face depends not only on the pillar stability but also the distance from the previous gob or the width of the chain pillar system, geological conditions (roof, floor, and rib), and roof control plan. Therefore, the balance among those factors is very critical in pillar design and roof control design to make a longwall operation more productive and safe. In other words, for a specific geological condition, a productive and safe longwall operation can be realized with a maximum coal recovery and a minimum roof control cost if the longwall chain system between panels and the roof control plan for longwall gate entries are properly designed.

A proper or optimized pillar system and roof control plan can be designed if the roof/floor conditions and the mining-induced abutment stresses and their distributions around a longwall gob or gobs are fully understood. For example, since Mine A has a CMMR (Coal Mine Roof Rating) of 68 to 70, the safety factor of the longwall chain pillar system is only 0.6 under a cover depth of 1,310 ft. The total width of the chain pillar system with 2 pillars and 3 entries is 155 ft (center-to-center). In order to ensure a stable tailgate entry outby the longwall face, an unequal-sized pillar system has successfully been used with a narrower pillar (35 ft rib-to-rib) adjacent to the headgate entry and a wider pillar (80 ft rib-to-rib) adjacent to the headgate entry. In doing so, the stability factor of the tailgate pillar is increased to 0.9, while the yield pillar yields properly inby the longwall face without causing roof control problems in the headgate entry outby the longwall face. In addition, Can cribs and trusses have also being used in the tailgate entry as the secondary roof supports.

However, at Mines C and D the stability factor of the chain pillar system between panels is 1.3 under a cover depth of 900 ft because a much weaker roof condition with a CMMR of 40 to 42. The current pillar system has a total width of 200 ft center-to-center

with two equal-sized pillars. When two rows of wood cribs or fiber cribs were used in a relative tight spacing of 6 to 8 ft, roof deterioration was still expected in the outby tailgate entry where the depth of cover exceeded 900 ft. Since pump cribs were used as the secondary roof support in the tailgate entries, tailgate roof falls have been eliminated.

In summary, to maintain the stability of an underground opening (gate entries, bleeders, or mains), pillar design and roof control plan must be compatible with its roof/floor conditions, service life, and its location or distance from the gobline.

SUMMARY AND CONCLUSIONS

Based on the analysis of the stress and entry convergence data collected from RAG longwall mines, the influence zone of the front abutment load induced by two adjacent longwall panels have been defined. The front abutment stresses on headgate pillars and tailgate pillars are also discussed. Since the magnitudes of the first and second front abutment stresses on the longwall abutment pillar at Mine A are significantly different from what we have been using for longwall chain pillar design, more field data are needed to define the front abutment load.

The maximum influence zone of the side abutment load found in this study agrees well with what predicted by Eq. 1 and has critical implications on barrier pillar design and roof control for the bleeders and mains. A balanced consideration among geological conditions, pillar design, and roof control plan is very critical for the stability of a specific entry and thus may affect the productivity, coal reserve recovery, and safety of a longwall operation.

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