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Insights into the Relationships Among the Roof, Rib, Floor, and Pillars of Underground Coal Mines

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Abstract
Ground control failures continue to be one of the leading causes of injuries and fatalities in underground coal mining. The roof, rib, floor, and pillars are four areas of potential ground failures that miners, engineers, and consultants are continually evaluating. Quite often, these four underground structures are evaluated independently. A recent push to consider them as a system and in a similar manner as design engineers evaluate mechanical systems has highlighted the need to fully understand the interrelationship among the roof, rib, floor, and pillar. This relationship combines the geometry of the mine layout, geological environment, installed support, and even the timing of the coal extraction. Several studies using field observations and instrumentation show that these relationships can be independent at times, while being dependent in other scenarios. Cases with good roof conditions while the rib and floor deteriorate are contrasted with cases where the roof, rib, and floor deteriorate at the same time. The presented cases in this study demonstrate the importance of understanding the geological environment and mine design to ensure that the proper support is installed.

Keywords Coal mining · Longwall mining · Roof · Rib · Floor · Pillar

1 Introduction

Underground coal mine designs are driven by three primary considerations: ventilation needs, production necessities, and ground control requirements. The ventilation needs include minimum air quality standards to support mine workers, dilution of methane, removal of dust from working areas, and temperature and humidity regulation. The production necessities include providing access for miners, equipment, and supplies to the working areas of the mine; the ability to extract coal; the movement of the coal from the extraction faces to the surface facilities; and the optimization of the productivity and extraction costs. The ground control requirements assist in meeting some of the production and ventilation needs while providing a safe working area for the miners.

The ground control requirements can be subdivided into four areas of potential failure: roof, rib, floor, and pillars as seen in Fig. 1. Each area has been studied for decades, and the studies have developed several design methodologies, best practices, engineering guidelines, and even software packages to assist in underground coal mine design. Several pillar design equations have been developed, as have software design packages, to assess pillar designs that have been widely used in the coal industry ([3, 9], and [8]). There are also numerous roof support design methods, equations, and a few software programs available to aid roof control specialists [5, 10, 14]. Rib support and stability has been a priority of researchers for the past 10 to 20 years and has thus far lead to useful design guidelines [13] and a software package for Australian coal mines titled "Analysis and Design of Rib Supports" [2]. Rib failures have accounted for almost 35% of underground coal mine ground-control-related fatalities for the past decade.

The roof, rib, floor, and pillar can be considered as four structures of importance to the stability of underground openings and ultimately the safety of underground mines. Traditionally, the roof, rib, floor, and pillar stability have been assessed individually with little to no concern of the other. This is evidenced by the discussion of these four structures throughout the history of underground mining and the established design methods, criteria, and software. Over the past 10 years, numerous mine visits, test areas, instrumentation studies, visual observations, and condition mapping research endeavors provided opportunities to

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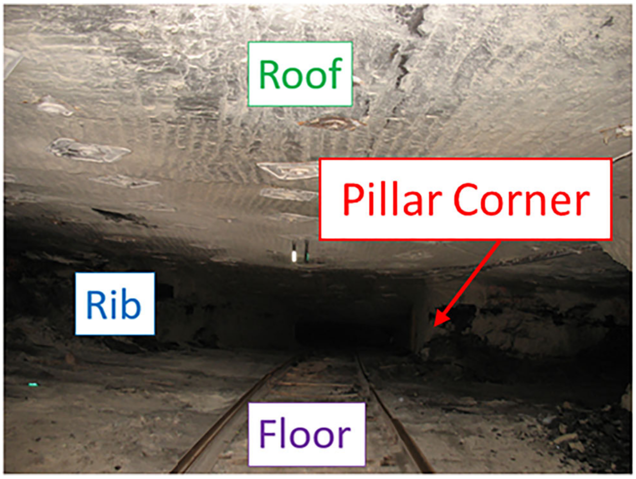

Fig. 1 Photo of an underground coal mine entry showing the roof, rib, floor, and the corner of a pillar

investigate and develop a conceptual relationship among these four structures.

2 Previously Observed and Reported Relationships

Over the past 100-plus years, underground coal mine designs have been improved in three of these four areas, including roof support, rib support, and pillar design. The floor stability has seen the least amount of attention in past research efforts. In several instances, the four underground structures—the roof, ribs, floor, and pillars—have been the subject of research efforts. Several of these efforts established relationships among these four underground structures.

One such relationship is that of the roof and rib. Through observations, engineering judgment, and numerical modeling, it has been shown that when the coal pillars spall, the roof span increases, causing the strength of the roof to weaken [12], ultimately resulting in the potential of stability issues. Another relationship is between the rib and floor. In a recent case study by researchers at the Bulga Underground Operations extracting the Blakefield seam in Australia observed upward floor movement leading to increased rib spalling [11].

An important relationship that has been mentioned numerous times in the past is that of the floor and roof properties and their impact on pillar strength. Babcock [1] suggested that there are two factors of pillar strength related to roof and floor strength: (1) if the roof and floor rock are strong or weak, a given pillar will become stronger or weaker, and (2) the effect of end constraint can make a pillar stronger or weaker depending upon the strength or weakness of the roof or floor. Su and Hasenfus [15] found that a weak floor could reduce the peak pillar strength by as much as 50%. A weak floor does not guarantee a reduction in pillar strength.

There have also been numerous accounts of the relative timing of the roof, floor, rib, and pillar deterioration in field studies of the past relative to each other and the retreating of longwall panels. In one such study, Maleki [7] stated, "Upon retreat of the first longwall panel, pillar ribs gradually spalled, followed by floor heave and local roof falls," further supporting the idea that rib deterioration can lead to floor deterioration and roof deterioration. Van Dyke et al. [17] stated, "In addition, two rows of 4.9-meter cable bolts were utilized to improve roof stability in areas where deep cover and severe rib sloughage were present," indicating that the roof condition affects the rib conditions.

3 Instrumentation Studies

Three recent instrumentation studies conducted by the National Institute for Occupational Safety and Health (NIOSH) demonstrate the interrelationships among the roof, rib, floor, and pillars of underground coal mines. At two sites, research was conducted in longwall gateroads, and at the third and fourth sites research was conducted at a room-and-pillar retreat mining section. One of the longwall sites (site 1) was a deep-cover longwall mine extracting the Pocahontas #3 seam, and the other longwall site (site 2) was under shallow cover extracting the Lower Kittanning seam. The room-and-pillar retreat mine had two sites: (site 3) at shallow cover and (site 4) at deep cover extracting the Jawbone coal seam.

There are three primary types of instruments employed in the four study sites: borehole pressure cells (BPC) to measure stress changes in the pillars, multi-point borehole extensometers (MPBX) to measure rib dilation, and multi-point roof extensometers (RFEXT) to measure roof sag. The intent was to install and monitor all three types of instruments at all three of these sites to measure the roof, rib, and pillar response to longwall and pillar extraction.

Study site 1 was conducted on the first headgate of a new district from development through first panel extraction and ending just after the second longwall passed the instrumentation site. The gateroad system was a yield-abutment-yield system with pillar centers of 15.2 m by 45.7 m and 53.3 m by 137.2 m for the yield and abutment pillars, respectively. The depth of cover at the site was 624.8 m, and the longwall panel was 213.4 m by 3658 m [6].

Study site 2 was conducted on the second headgate of a new district from development through first panel extraction and ending just after the second longwall passed the instrumentation site. The gateroad system was a three-entry system with equal-sized pillars on pillar centers of 30.5 m by 45.7 m. The depth of cover at the site was 182.9 m, and the longwall panel was 365.8 m by 2133 m [4].

Study sites 3 and 4 were conducted about mid-panel of two room-and-pillar retreat sections from development through extraction of the instrumented pillar or until the instrumentation was mined out and wiring was damaged. The retreat section at study site 3 consisted of six entries with equal-sized pillars on 22.9-m by 32-m centers. The depth of cover at study site 3 was 198 m. For study site 4, there were seven entries with pillars on 19.8-m by 27.4-m centers. The depth of cover at study site 4 was 282 m.

Study site 1 had technical difficulties with the MPBX due to operational and installation issues and only has reliable data for the BPC and RFEXT. Figure 2 shows the results of the BPCs and roof extensometers during the retreating of the first longwall panel with two boxes highlighting interesting behavior of the roof extensometers. Box 1 shows the early increase in roof sag compared with the BPC pressure increase for some of the roof extensometers, and Box 2 shows a secondary increase in roof sag once BPC pressure has stabilized after the first face passed. Figure 3 presents the results of the average BPC and average roof sag during the same period as Fig. 2 with five highlighted areas. The onset of roof sag begins slightly before the increasing of BPC pressure as highlighted by areas 1 and 2. There is also a slight delay in the main increase in BPC pressure (arrow 3) versus roof sag (arrow 4) and the secondary increase in roof sag rate after the BPC pressure has stabilized (Box 5).

At the shallow-cover case in the Lower Kittanning seam, the extensometers showed a much different result in terms of the relative timing of roof sag compared with the increase in BPC pressure as the face approached the site, as shown in Fig. 4. The roof sag and BPC pressure began increasing at approximately the same time relative to face position; however, most of the increase due to the first panel passing occurred much quicker for the BPC than the roof extensometer. The rib monitoring at the same study site showed a delayed onset of the rib dilation in relation to the BPC pressure as shown in Fig. 5, similar to the roof sag measured at the site. The rib dilation appears smoother than the roof sag or BPC pressure increases.

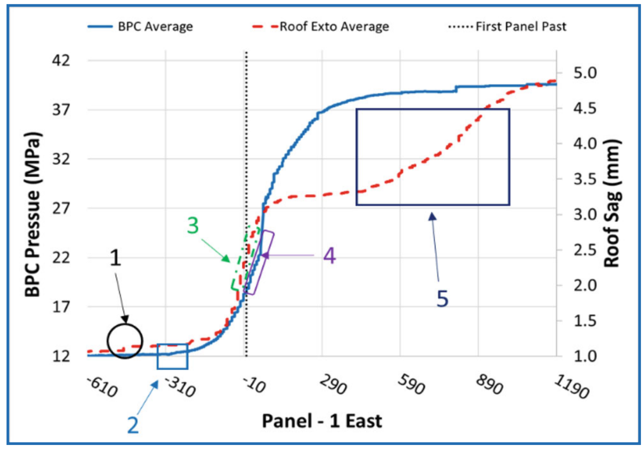

Fig. 3 Study site 1 average BPC pressure reading compared with average measured roof sag versus face position

For both study sites 3 and 4, the roof extensometers showed almost no movement, and a comparison of the onset of the roof sag and the BPC pressure increase could not be completed. However, in a general sense it is apparent that the roof sag must have been lagging the BPC pressure increase due to the lack of measured roof sag. Since these two study sites were at room-and-pillar retreat mines, the *y*-axis for Figs. 6 and 7 is the number of pillars extracted rather than a date or distance. For study site 3, the instrumented pillar was number 23, and for study site 4 the instrumented pillar was number 141. The rib dilation showed different trends under shallow and deep cover. For study site 3, shallow cover, the rib dilation began slightly before the BPC pressure began increasing, as seen in Fig. 6. For the deeper cover site, study site 4, the rib dilation began slightly after the BPC pressure began increasing, as seen in Fig. 7.

Although the average trends can easily demonstrate the onset of pillar dilation, pillar loading, roof sag, individual instruments, or measurements provide a range of results for the timing of change initiation, rate of change, and final

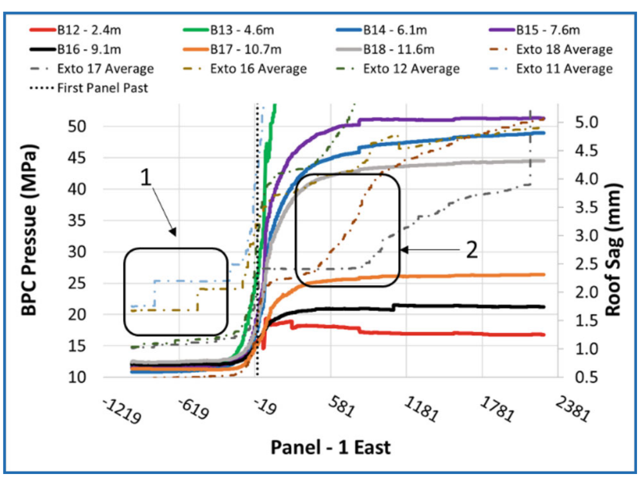

Fig. 2 Comparison of BPC and roof extensometer measurements versus face position at study site 1

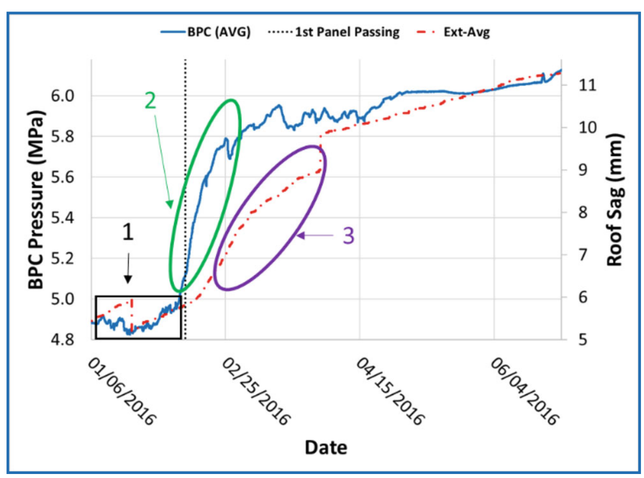

Fig. 4 Study site 2 average BPC pressure compared with average roof sag measured versus time

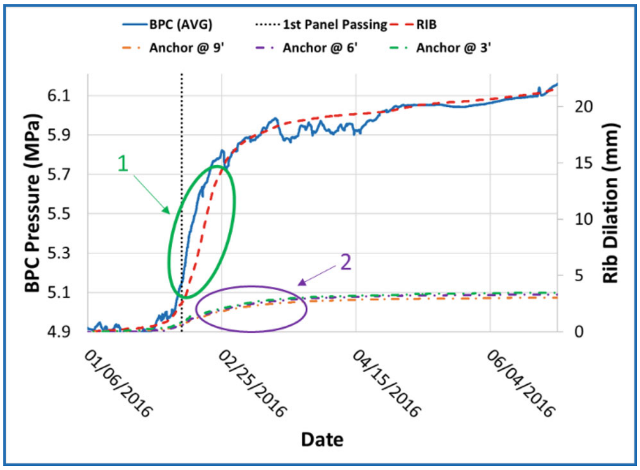

Fig. 5 Study site 2 average BPC pressure compared with average rib dilation measured versus time

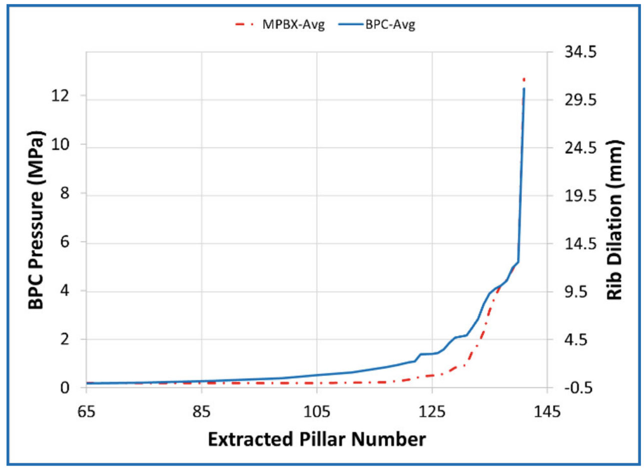

Fig. 7 Study site 4 average BPC pressure compared with average rib dilation versus pillar extraction

changes. The variation of the individual instrument readings for study site 1 can be seen in Fig. 2. The other study sites and instrument types have similar divergence from the average.

4 Observations and Condition Mapping

In-mine entry condition mapping provides many useful comparisons that can be used to look at geology and installed supports over time. There are different conditions to look for and consider when performing the condition mapping. The major elements to observe are rock type, structural conditions, and stress-induced features from mining. Other factors should be considered that are not observed underground but that impact entry conditions, such as surface topography, overburden, bodies of water, and gas wells.

In-mine mapping can capture entry deterioration caused by different conditions such as stress increases, geologic changes,

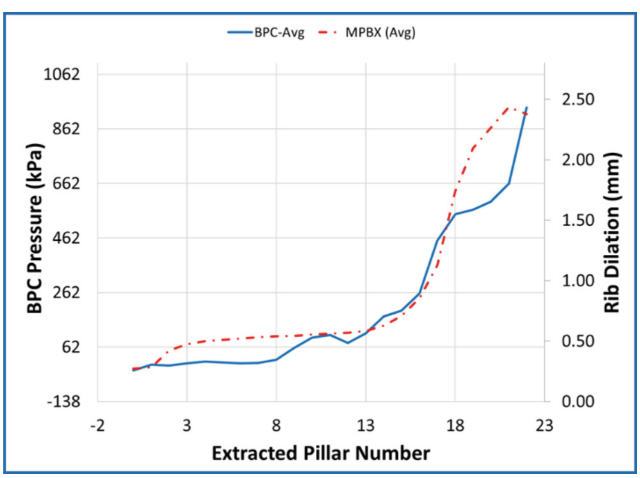

Fig. 6 Study site 3 average BPC pressure compared with average rib dilation versus pillar extraction

changes in mining, or by general time-dependent weathering. Many times, these conditions can change a specific part of the entry while leaving the rest of the entry unchanged. The change in conditions will typically affect the most vulnerable part of the entry system first. The pillars, roof, and floor act as one system to maintain the stability of the entry. For most coal mines the roof is the weakest part of the system followed by the ribs, which is the reason mines install support in these areas.

When additional stresses are applied to the entry system, then the weakest part of the system will degrade first. In one such circumstance highlighted in a case study by Van Dyke et al. [18], the bleeder entries were mapped for entry conditions before, during, and after the longwall had completed mining a panel shown in Fig. 8. In this case, the ribs were the weakest link in the entry system and experienced the most damage caused by rear abutment stress near the center of the panel in the bleeder entries.

Changes to entry conditions can be geologically dependent, which can be less predictable than changes in stress due to mining. Geologic anomalies can occur in a relatively small area of 15.2 m or less and have a large effect on the conditions of the ribs, roof, and floor. Figures 9 and 10 show the deterioration of the local roof because of the thinning of the roof coals and the introduction of a moisture-sensitive clay.

Another observational experience was encountered while conducting a study site at a western Kentucky room-and-pillar retreat mine extracting the Darby and Kellioka coal seams [16]. Throughout the mine, the roof, rib, and floor were observed with several areas showing no signs of deterioration and others showing deterioration of the roof, rib, and floor. A series of six photos demonstrate the varied conditions observed throughout the mine in Fig. 11 through Fig. 16. This series of photos begins with little to no deterioration (Fig. 11), then roof deterioration (Fig. 12), rib deterioration (Fig. 13), floor deterioration (Fig. 14), roof and rib deterioration (Fig. 15), and finally roof, rib, and floor deterioration in the same location (Fig. 16).

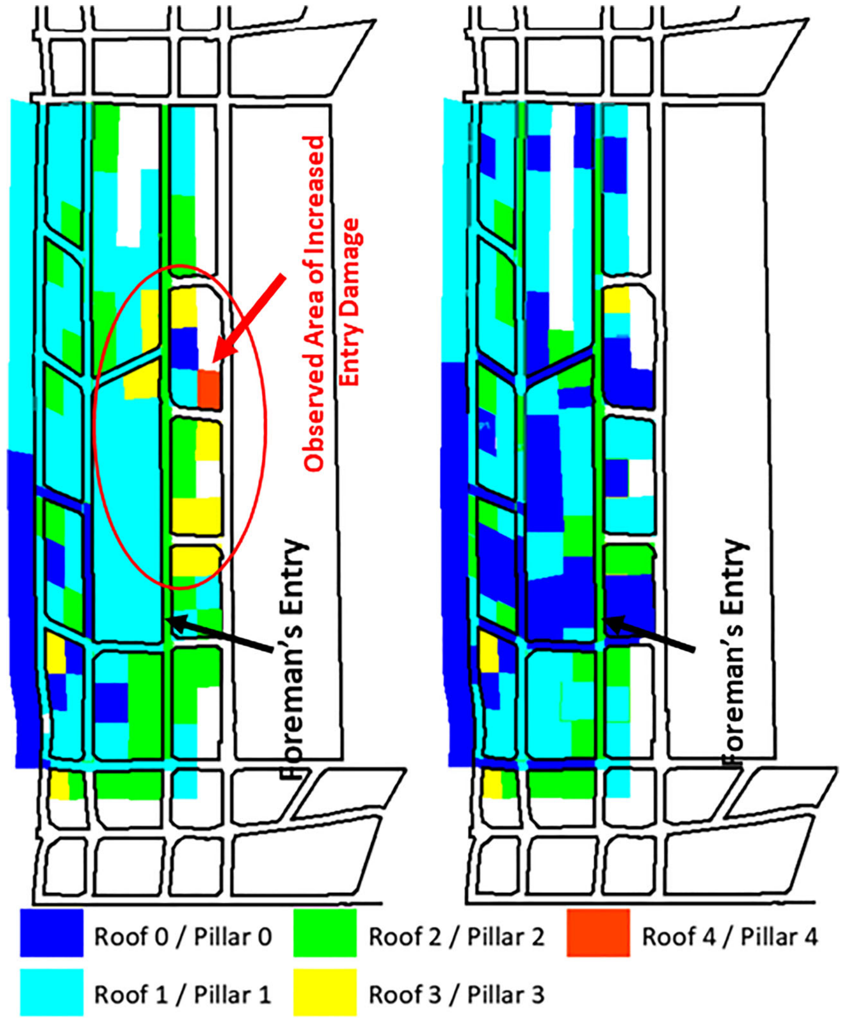

Fig. 8 Changes in entry conditions before (right) and after (left) mining the longwall [18]

Some of the deterioration was caused by multiple seam interactions, abutment stress due to pillar extraction, and geological changes in the immediate roof and floor.

Fig. 9 Photo depicting roof conditions in the same entry 30 ft away from the roof conditions shown in Fig. 10

5 Discussion

Although only a small sample of the instrumentation case studies, observational studies, and past efforts to relate the roof, rib, floor, and pillars of underground coal mines are presented in this paper, it is postulated that the most vulnerable of the four underground mining structures will begin deteriorating first and may or may not be followed by one of more of the other structures. The most vulnerable structure can be identified by determining the residual strength of the four structures throughout the mining process. The residual strength is equivalent to the amount of additional load the structure can resist. Using this residual strength concept, once a structure begins deteriorating, a reassessment of all four structures should be done to reassess the conditions of each at the current state.

Aside from the idea that the weakest of the four structures will approach failure first, the structure with the least residual strength will be impacted next barring a direct connection between the failure of the weakest structure and another structure. An example of the direct link was presented with the

Fig. 10 The roof, shown in Fig. 9, experienced degradation due to the lack of roof coals and the introduction of moisture-sensitive clay

floor heave leading to rib spalling. For this case, the floor rising caused the rib to be pulled away from the remaining pillar, thus resulting in spalling due to floor heave.

Since the historical approach to designing and assessing the stability of underground mine structures relies on individual structure analysis, little to no efforts have been made to determine the effect of one structure deteriorating on another structure. The idea of a system-based design approach could allow

Fig. 11 An area where the roof, rib, and floor showed no signs of deterioration

Fig. 12 Roof deterioration in the form of cutter roof

for the analysis of holistic mine opening design while still accounting for the individual structure stability. How could the presented field studies provide insight into the relationship among the four structures?

Two of the instrumentation studies showed that there is a relationship between the roof and the pillar loading, although not always consistent. For example, the relatively shallow-cover case, site 2, showed the roof sag following the BPC pressure increase, yet the deep-cover case showed the roof sag leading the BPC pressure increase. Both cases showed a step increase in the roof sag and a more consistent slope for the BPC pressure increase. The similarities of the pattern indicate that the roof sag is based on progressive deterioration. The lower roof sag experienced under the deeper cover shows that the residual strength concept could provide insight into the roof condition by observing the pillar loading if enough information is available on the roof strength and mining geometry.

The condition mapping at the Western Kentucky room-and-pillar retreat mine provides support for a residual strength

Fig. 13 Rib deterioration, mostly spalling at the pillar corner

Fig. 14 Area experiencing floor heave with no other obvious deterioration of the roof or floor

concept and a system-based design procedure as well. The ability for the conditions of the opening to change very rapidly in the context of distance from one entry condition to the next identifies the need to assess the structures individually as well as collectively. In the same entry within a few hundred feet, the roof, rib, and floor can go from intact, no change from initial mining condition to noticeable and fairly severe deterioration of one or more of the structures, showing that there is a

Fig. 15 Observed roof and rib deterioration in the same vicinity. Likely due to multiple-seam gob solid boundary effects

Fig. 16 Some of the worst conditions observed, showing roof, rib, and floor deterioration simultaneously

relationship between the structures and that the condition of each may play an important role in the condition of the others.

Another observation at a recent study site was that of the floor heave that appeared to have caused pillar spalling. As the floor heaved, it was pulled towards the center of the entry while moving upward, causing the pillar bottom to be pulled away and spall, as seen in Fig. 17.

6 Conclusions

Based on the past studies, observations, instrumentation studies, and numerical modeling, it is postulated that there is a definable relationship among the roof, rib, floor, and pillars of underground coal mines. In order to develop this relationship, additional studies including field monitoring, measurements, and parametric numerical modeling are needed. It is

Fig. 17 Floor heave causing pillar spalling near the base of the pillar

further recommended that these interactions be studied further and incorporated into future ground-control-based mine design methods and tools. A system-based approach is recommended where the overall system is evaluated for stability as well as the individual components, or structures, themselves. When each structure's stability is evaluated, the effect on the other structures as well as the system should be considered and estimated.

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Compliance with Ethical Standards

Disclaimers The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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