Unanticipated Multiple Seam Stresses From Pillar Systems Behaving As Pseudo Gob – Case Histories

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ABSTRACT

Underground coal mining in the U.S. is conducted in numerous regions where previous workings exist above and/or below an actively mined seam. Miners know that overlying or underlying fully extracted coal areas, also known as gob regions, can result in abutment stresses that affect the active mining. If there was no full extraction, and the past mining consists entirely of intact pillars, the stresses on the active seam are usually minimal. However, experience has shown that in some situations there has been sufficient yielding in overlying or underlying pillar systems to cause stress transfer to the adjoining larger pillars or barriers, which in turn, transfer significant stresses onto the workings of the active seam. In other words, the overlying or underlying pillar system behaves as a "pseudo gob." The presence of a pseudo gob is often unexpected, and the consequences can be severe. This paper presents several case histories, summarized briefly below, that illustrate pseudo gob phenomenon:

- Pillar rib degradation at a West Virginia mine at 1100-foot (335 m) depth that contributed to a rib roll fatality.
- Pillar rib deterioration at a Western Kentucky mine at 570-foot (175 m) depth that required pillar size adjustment and installation of supplemental bolting.
- Roof deterioration at an eastern Kentucky mine at 1300-foot (400 m) depth that stopped mine advance and required redirecting the section development.
- Coal burst on development at an eastern Kentucky mine at 1700-foot (520 m) depth that had no nearby pillar recovery.
- Coal burst on development at a West Virginia mine at the relatively shallow depth of 1100 feet (335 m) that also had no nearby pillar recovery.

The paper provides guidance so that when an operation encounters a potential pseudo gob stress interaction the hazard can be mitigated based on an understanding of the mechanism encountered.

INTRODUCTION

The U.S. underground coal mining industry has conducted mining in multiple seam environments, where the active mining has underlying or overlying old workings at varying interburden distances, throughout its history. Often no serious consequences arise from the multiple seam mining. However, sometime mines have been confronted with hazards from underlying or overlying workings that include localized roof and rib failure, pillar system failures through propagating roof falls and floor heave, and also pillar bursts.

The major underground coal mining basins in the U.S. are shown in Figure 1. Historically, the Central Appalachian region, consisting of southern West Virginia, eastern Kentucky, and southwestern Virginia has encountered the most significant multiple seam mining issues. This is attributable to the more than 100 years of underground mining, existence of numerous mineable seams in the respective stratigraphic sequences, and the predominant use of pillar recovery that concentrates mining stresses. While less frequent, multiple seam interactions occur in all the other coal mining regions as well (Mark et al., 2007).

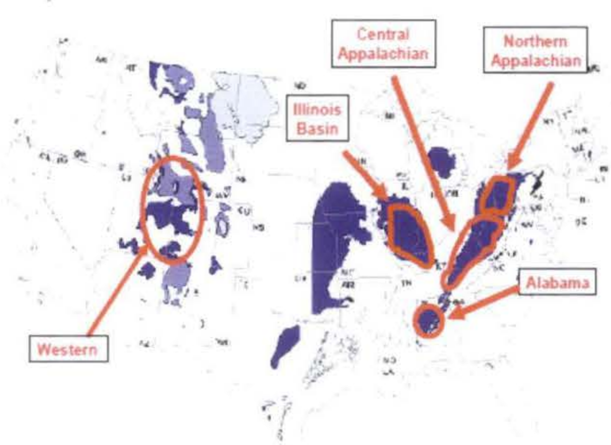

Figure 1. The U.S. major underground coal mining regions (from Mark et al., 2007).

EVALUATION OF MULTIPLE SEAM INTERACTION

For decades the stresses that arise from multiple seam mining scenarios and the impact on the seam being mined has been the subject of much research. In 2007 the National Institute for Occupational Safety and Health (NIOSH) developed the Analysis of Multiple Seam Stability (AMSS) program to help reduce the risk of ground failures from potential interactions. The NIOSH study reviewed previous multiple seam mining research, established an extensive database of multiple seam mining case histories, applied LaModel 2D to establish multiple seam stress levels, and incorporated these stress levels to Analysis of Retreat Mining Pillar Stability (ARMPS) and Analysis of Longwall Pillar Stability (ALPS) computations. The computations and statistical analyses of the database helped determine the significant parameters that need to be accounted for in a multiple seam mining environment. The AMSS program offers criteria for an appropriate pillar design and guidance for the installation of supplemental roof and rib support (Mark et al., 2007). A significant finding from the AMSS research is that when there is no full extraction, and the past mining in an overlying or underlying seam consists entirely of intact pillars, interactions with the active seam are usually minimal unless the interburden is less than 30 to 50 feet (10 to 15 m).

AMSS has been used extensively in the U.S, underground coal mining industry. After the Crandall Canyon mine disaster in 2007 (MSHA, 2008), the Mine Safety and Health Administration (MSHA) has instituted technical review procedures to ensure that appropriate pillar designs are used in underground coal mines. The most numerous category of MSHA technical review are multiple seam mining scenarios evaluated with AMSS by the operator and/or MSHA (Gauna and Tyrna, 2011).

Multiple Seam Interaction Factors. The NIOSH study found that the most important factors affecting the intensity of a multiple seam interaction were the depth of cover, whether the past mining was conducted above or below the active seam, the immediate roof geology of the active seam, the interburden thickness between the active seam and the previously mined seam (or seams), and type of remnant structure in the overlying and/or underlying seam. Remnant structures in the previously mined seam(s) are typically created when coal is left in place adjacent to areas of full extraction, also known as gob areas. Isolated remnants, with worked out areas on two or more sides, have the most hazardous stress concentration, while less severe stress concentrations occur along gob-solid boundaries (Mark, et al., 2007; Mark and Gauna, 2015).

By definition, remnant structures exist in conjunction with gob areas which are de-stressed and have transferred load to the remnants. Regions in which all the pillars are intact are usually presumed to have minimal stress concentrations. However, a number of situations have been encountered where severe stress concentrations have occurred without the presence of full extraction mining in the overlying and/or overlying seam. In these cases, smaller developed pillars in old works have apparently yielded and transferred much of their load onto larger nearby pillars or barriers. In other words, the documented pattern of roof, rib, and floor degradation observed in these situations suggests that the small pillars are behaving as a "pseudo gob."

MULTIPLE SEAM PSEUDO GOB CASE STUDIES

The case studies presented below all involve pseudo gob situations. They illustrate the range of unanticipated multiple seam mining hazards that can be encountered.

Pillar Rib Deterioration-West Virginia. The mining operation is located in Boone County, West Virginia in the Central Appalachian coal mining region. In 2006, a 46-year old roof bolting machine operator was fatally injured when a large portion of the rib fell (MSHA, 2006). The accident was investigated by the Mine Safety and Health Administration, Technical Support (MSHA –TS).

The mining unit investigated consisted of a five entry configuration being developed to establish a pillar recovery panel. The mine portals were in the No. 2 Gas Seam with the mining area accessed via an in-mine slope from the No. 2 Gas Seam down to the Powellton Seam. The pillars on the mining unit were established on 80 x 110 to 150-foot centers (24 x 34 to 46 m) with approximately 9 x 19-foot (3 x 5.5 m) mining dimensions. Depth of cover was approximately 1100 feet (335 m).

The section was overlain by development mining in the No. 2 Gas Seam with 65 feet (20 m) of interburden (Figure 2). U.S. multiple seam mining research has shown that when overlying seams have no pillar recovery and consist of development mining, this interburden distance normally will have minimal stress interaction. The investigation revealed that pillars located under the No. 2 Gas Seam chain pillars showed no or minimal evidence of rib spall (Figure 3). In contrast, ribs located beneath the edge of the overlying barrier pillar exhibited intense rib sloughing (Figure 4). The accident occurred in the Powellton Seam # 5 entry face area after it had advanced beneath the overlying barrier. The accident site was subjected to an elevated intensity of rib sloughing and the rib side had a thick shale parting that had a tendency to roll out as large blocks.

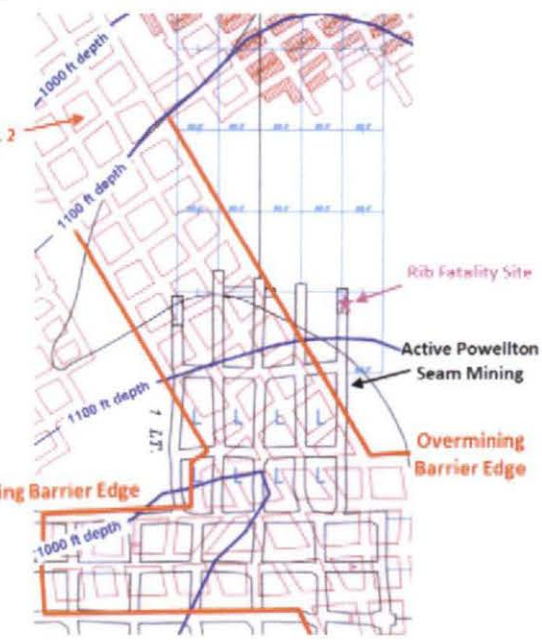

Figure 2. Powellton Seam mining completed (black) with overlying development mining in the No. 2 Gas Seam (red).

The ARMPS SF calculated for the chain pillars in the overlying No. 2 Gas Seam was 2.3, a value that would normally indicate a stable pillar configuration (Mark 2010). Nonetheless, it is apparent that some factor allowed the No 2 Gas Seam pillar system to yield and transfer loads onto the surrounding barrier. An AMSS evaluation, not yet developed at the time of the investigation, of the

Figure 3. Powellton Seam mining under the No. 2 Gas Seam chain pillars showing no evidence of rib spall; photo view shown by arrow on embedded map.

Figure 4. Powellton Seam mining within the overlying barrier pillar exhibiting intense rib sloughing; photo view shown by arrow on embedded map. Photo illustrates thick shale parting that tends to roll out as large blocks.

Powellton Seam mining shows that if the No. 2 Gas Seam chain pillars are treated as gob, pillar SF = 2; however, a "condition yellow" cautionary warning is generated indicating the likelihood of rib instability.

Rib control measures were subsequently instituted in the high stress region. In-cycle rib bolting was instituted to protect the personnel. Also, the mine operator purchased "inside control" dual boom bolting machines, with drill station controls located between the drill booms, so that roof bolt machine operators could work in a zone where they were protected from the rib hazard.

Pillar Rib Deterioration-West Kentucky. The two-seam mining operation is located in Webster County, Kentucky in the Illinois Basin coal mining region. Highly localized zones of severe rib sloughage occurred in the active workings of the overlying mine, and these were investigated in 2015 by MSHA–TS.

The operation originally started in the Springfield (West Kentucky No. 9) Seam. Upon depleting those reserves, mining moved into the overlying Baker (West Kentucky No. 13) Seam. Interburden between the two seams is roughly 100 feet (30 m).

The pillars in the active, overlying mine range in size from 70 x 70-foot centers (21 x 21 m) to 100 x 100-foot centers (30 x 30 m), depending on their use as production panels or mains. Mining dimensions are approximately 10 x 20-foot (3 x 6 m). The mining height involves two benches of the coal seam separated by an approximate 1-foot (0.3 m) mudstone layer.

At the time of the investigation, mining had generally progressed down dip from roughly 140-foot (45 m) depth near the access shafts to a maximum depth of 570 feet (175 m) to the northeast of the shafts. The mining units investigated consisted of ten entry room work without pillar recovery. A robust primary roof support system is used consisting of No. 7 x 8-foot (21 mm x 2.4 m) SRD fully grouted, headed rebar. Intersections have supplemental support consisting of eight 0.6-inch x 12-foot (15 mm x 3.7 m) cable bolts installed 4 across in conjunction with T-channel. Panels of 4-inch grid 5 x 16-foot (10 cm grid 1.5 x 4.9 m) roof mesh are installed in all entries. Wire mesh rib support was routinely installed in the belt entry and supply/travel roadway (Phillipson and Muto, 2015).

The underlying Springfield Seam mining was also mined without pillar recovery. The production pillar centers appear to range from 50 x 50-foot (15 x 15 m) to 65 x 65–foot (20 x 20 m). Panels were separated by barriers that could be 100 foot (30 m) wide. Multiple seam interactions were being encountered above these barrier pillars. It seems likely that the Springfield Seam pillars have failed, perhaps by punching into clay floor. Consequently, due to load transfer, the Springfield Seam barrier pillars separating the smaller pillars behaved as underlying gob-solid or remnant structures that impact the active mining in the Baker Seam. The stress interactions became noticeably more significant at depths exceeding 460 feet (140 m).

An example of the Baker Seam mining encountering underlying remnant structure at 570-foot (174 m) depth is shown in Figure 5. In the example, mining is on 80 x 80-foot (24 x 24 m) centers with crosscut center increased to 120-foot (37 m) over an underlying remnant barrier in the Springfield Seam. As noted on Figure 5, roof pot-outs tend to flank the perimeter of the barrier and were consistent with roof flexure from the subsidence troughs that flanked the underlying barrier (Phillipson and Muto, 2015).

The roof support system did not require modification. However, pillar rib sloughing was severe and persistent directly above and in the vicinity of the underlying barrier to the extent that rib support was installed to control further deterioration using wire mesh panels secured with 4-foot (1.2 m) fully grouted bolts and 6 x 16-inch (15 x 41 cm) plates (Figure 6). The investigation involved other portions of the mine and revealed that there is also a depth dependency to rib deterioration where there is an absence ofmultiple seam structure. As a consequence a two phase rib support program was established (Phillipson and Muto, 2015):

- Entries or crosscuts that cross a Springfield Seam barrier at any depth, or lies within 50 feet (15 m) of its vertical projection, have rib support installed in the upper coal bench.
- At depths greater than 500 feet (152 m), all critical entries (defined as escapeways, intake entry, belt entry, supply/travel entry, and 1 return entry per mining unit) as well as crosscuts that host equipment caches and power centers where workers congregate, have rib support installed in the upper coal bench.

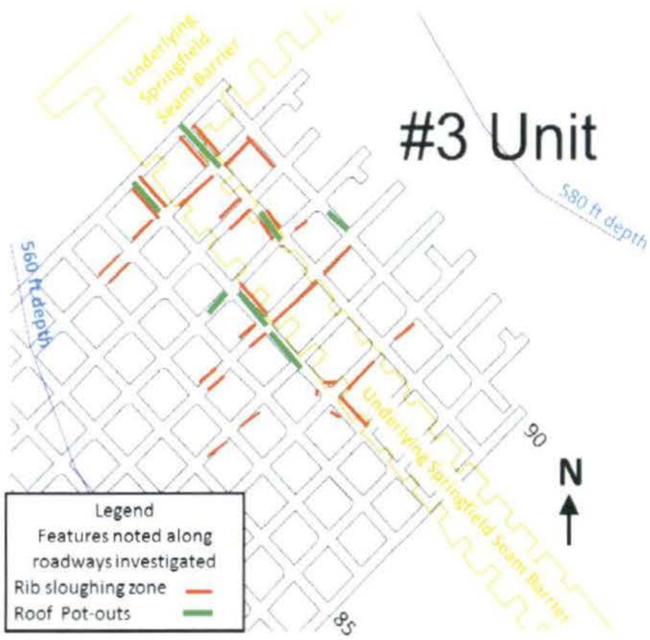

Figure 5. Baker Seam mining (black) on 80 x 80-foot (24 x 24 m) centers with crosscut center increased to 120-foot (37 m) over underlying remnant barrier (tan) in the Springfield Seam. Rib sloughing and roof pot-outs plotted from an intermittent traverse where all roadways are not mapped (Phillipson and Muto, 2015).

Figure 6. Typical Baker Seam rib conditions in the vicinity of an underlying barrier requiring welded wire mesh and rib bolting in the upper bench - mudstone layer of the seam (Phillipson and Muto, 2015).

The investigation led to the operation applying AMSS to insure that the Baker Seam pillars that cross the underlying multiple seam structures have adequate pillar stability to achieve global stability. An assessment of the AMSS procedures by MSHA-TS led to establishing a site specific Baker Seam AMSS evaluation for this mine's multiple seam environments. In the example shown in Figure 5, the 80 x 80-foot (24 x 24 m) center pillar system had crosscuts extended over the barrier to 120-foot (37 m) center and establishes an acceptable AMSS derived stability factor. However, the AMSS warning remains that stress interaction will be significant to where robust roof and rib support will likely be required to have local stability. The conditions noted in the underground investigation validate the need for robust ground support even with increased pillar stability which is a common situation in multiple seam mining scenarios.

Roof and Rib Deterioration-Kentucky. The mining operation is located in Letcher County, eastern Kentucky, in the Central Appalachian coal mining region. An underground area with severe rib sloughage was investigated in 2013 by MSHA – TS. The mining unit investigated consisted of a six entry submain being developed with 84 x 104-foot (26 x 32 m) center pillars to establish pillar recovery panels at 1,200 to 1,400-foot (370 to 430 m) depth of cover (Figure 7).

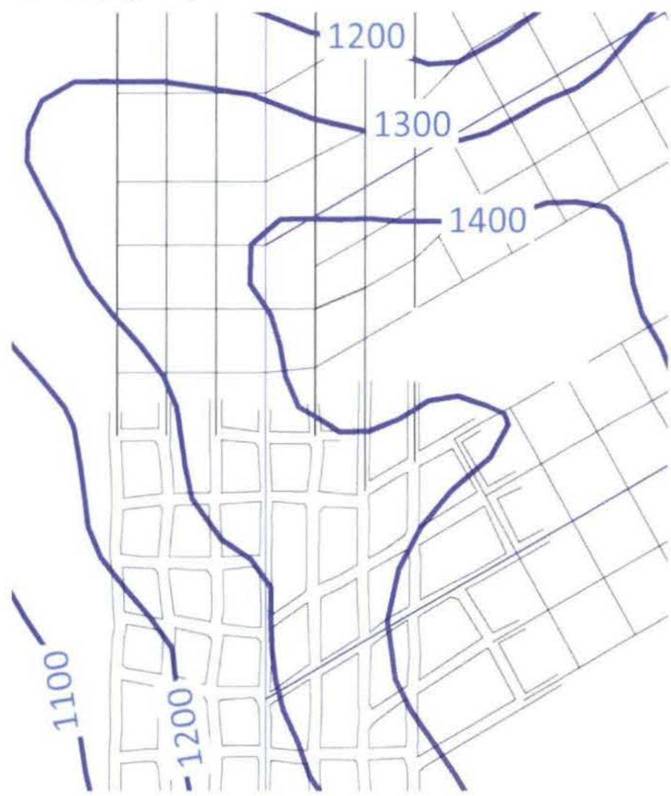

Figure 7. Kellioka Seam six entry submain being developed to establish pillar recovery panels at 1200 to 1400-foot (370 to 430 m) depth of cover.

The mine is in the Kellioka Seam (B Seam). Previous mining has been conducted in the following three seams: Imboden Seam approximately 300-foot (91 m) below, Low Splint Seam (F Seam) approximately 200-foot (60 m) above, and the Owl Seam (D Seam) approximately 85-foot (25 m) above. The Imboden Seam mining in the investigation area consists of four entry development and barrier pillars. The Low Splint Seam mining consists of a large barrier pillar with full extraction mining on one side. The Kellioka Seam mining showed no evidence of multiple stress interaction from either the underlying Imboden Seam or from the overlying Low Splint Seam.

However, multiple seam stress interaction became apparent from overlying Owl Seam workings. The Kellioka Seam submain is also in a transition zone where the development advanced under an Owl Seam barrier that adjoins a seven entry panel having 72 x 95-foot (22 x 29 m) center pillars (Figure 8). The Owl seam panel was reported to have experienced floor failure, which would have shifted considerable load to the adjacent barrier pillar. The investigation revealed that the Kellioka Seam mining under the Owl Seam barrier exhibited elevated stress that generated rib spall and roof degradation (Figures 9 and 10). In contrast, the mining under the failed Owl Seam pillar system offered a de-stressed region with a clear definition of where the de-stressed zone is and the position of the overlying edge of the barrier (Figure 11).

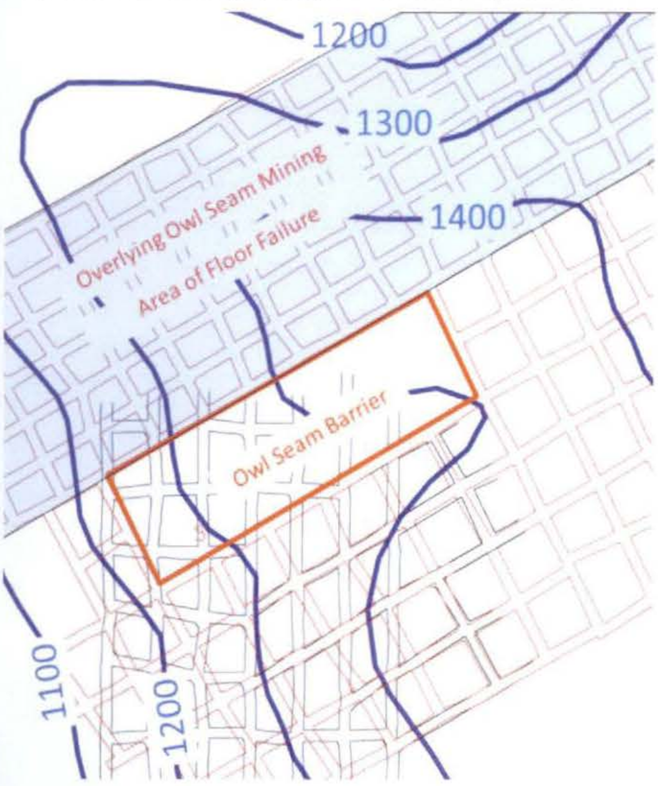

Figure 8. Kellioka Seam six entry submain (black) overlain by Owl Seam pillars and barrier (red) showing Owl Seam panel having reported floor failure (shaded).

The ARMPS SF calculated for the overlying Owl Seam pillars was 2.5, which would normally indicate a stable pillar configuration. However, floor failure was noted, and later adjoining mining employed larger pillars for Owl Seam development (Figure 8). An AMSS evaluation of the Kellioka Seam mining assuming the Owl Seam failed panel as gob, indicates

Figure 9. Kellioka Seam pillar showing rib sloughing from multiple seam stress interaction (view shown by arrow on embedded map).

Figure 10. Kellioka Seam roof geologic structure, small drag fold, degradation and pillar rib sloughing from multiple seam stress interaction.

a stable pillar system (SF = 1.58); however, a cautionary warning exists indicating the possibility of interaction affecting roof and rib stability which did occur as noted in the investigation.

The need to install roof-to-floor support to cope with roof deterioration stopped the section advance (Figure 9). To avoid the problem area, the mine elected to advance the development elsewhere. Kellioka Seam entries were superimposed under Owl Seam entries and mining under the intact Owl Seam barriers was avoided. Mining then advanced into the destressed zone under the overlying panel, and then tied back into the stopped entries to establish ventilation using reduced mining widths and robust roof support.

Figure 11. Kellioka Seam mining having de-stressed conditions under the he failed Owl Seam pillar system and also showing a definite location of the overlying edge of the Owl Seam barrier.

Multiple Pillar Burst-Kentucky. The mining area is located in Harlan County, Kentucky in the Central Appalachian coal mining region in the Kellioka Seam Two adjoining mining operations encountered three multiple pillar burst events in December 1999, September 2001, and November 2002 that were investigated by MSHA - TS. The bursts events in 1999 and 2001 are attributable to a pseudo gob situation in an underlying seam at one of those operations (Figure 12).

Figure 12. Coal pillar and immediate roof material filling entry after the 2001 Kellioka Seam burst event.

The 1999 and 2001 burst events occurred on five entry developments having 80 x 80-foot (24 x 24 m) pillar centers at similar depths of cover of 1650 to 1700 feet (502 – 518 m). The events were situated under a ridge exceeding 1500-foot (460 m) depth of cover (Figure 13).

In the vicinity of the burst events the Kellioka Seam is underlain by workings in the Harlan Seam with 165 to 175-foot (50 – 53 m) interburden (Harris, et. al. 2014). Investigators

Figure 13. Kellioka Seam burst events with affected pillars identified in MSHA – TS investigations outlined in red. Depth of cover and underlying Harlan Seam workings (magenta) shown. Kellioka workings are surrounding mining at the time of 2001 event.

at the time of the events inferred that the Harlan Seam barriers underlying the Kellioka Seam bursts were highly stressed. It appears that yield in the Harlan Seam pillar systems created a pseudo gob that transferred stress onto the adjacent barriers. When coupled with the depth of cover and Kellioka Seam burst prone geologic conditions, the events occurred when the Kellioka Seam development advanced over the underlying barriers.

The overlying Darby Seam had also been mined with approximately 45-foot (14 m) interburden. However, the closest Darby Seam mining was situated 450 feet (135 m) inby the 1999 burst event and 250 feet (75 m) inby the 2001 burst event. At those distances it seems highly unlikely that the Darby Seam workings contributed to the coal bursts, a conclusion that was also reached by other researchers who have investigated the events (Newman, 2002; Harris, et. al. 2014).

After the 2001 event, no further mining was allowed in areas where the depth exceeded 1500 feet (460 m) and where underlying barriers were present. The subsequent burst in 2002, which occurred at a traditional gob-solid crossing at 1400-foot (425 m) depth of cover, led to further mining restrictions for depths greater than 1000-foot (300 m).

An ARMPS version 6 evaluation of the Harlan Seam pillars involved in the 1999 and 2001 events found an SF that exceeded 2.0, which would normally suggest a stable pillar system. However, a reevaluation by Harris (2013), applying LaModel multiple seam scenarios and strain softening coal properties for the Harlan Seam, determined sufficient yield could take place for stress transfer to the Harlan Seam barriers. A thorough back analysis of the burst events using LaModel 3.0 for the multiple seams determined site specific pillar design criteria considered appropriate to allow pillar recovery in the presence of multiple seam mining structure. The study for site specific criteria included overlying Darby Seam and underlying Harlan Seam workings (Harris, et. al. 2014). Pillar recovery was conducted, primarily at 1000-foot

(300 m) maximum depth, after evaluation of the mining plan for a specific limited area met the established LaModel criteria.

Pillar Burst-West Virginia. The mining operation is located in Boone County, West Virginia in the Central Appalachian coal mining region in the Powellton Seam. In 2006 while advancing an eight entry main, the mine encountered a pillar burst on the right side of the section where the immediate roof consisted of sandstone. Degraded roof conditions were encountered on the left side of the section where the immediate roof consisted of shale (Figure 14). Gauna and Phillipson (2008) concluded that yielding pillars in the overlying seam caused stress transfer to the adjoining larger pillars. Also the example points out that mitigation for future mining can involve historical back analysis of successful and unsuccessful multiple seam mining configurations across the reserve area using empirical pillar design methods to minimize risk.

Figure 14. Powellton Seam mains (black) showing burst pillar area (red hatch) with depth of cover and overlying No. 2 Gas Seam workings (orange); larger overlying remnant barriers identified by orange shading.

The Powellton Seam burst region (Figure 15) and degraded shale roof (Figure 16) were both situated approximately 60 feet (18 m) beneath large pillars, 240 x 225-foot and 190 x 225-foot (73 x 69 m and 58 x 69 m), that had been left in the overlying No. 2 Gas Seam. The No. 2 Gas Seam large pillars are surrounded by much smaller pillars, measuring 40 x 50-foot (12 x 15 m). The apparent lack of loading observed on the Powellton Seam pillar ribs located beneath the overlying small pillars indicated that the small pillars were acting as pseudo gob, transferring load to the large pillars which acted as remnant barriers.

The No. 2 Gas Seam small pillars immediately surrounding the remnant barriers had ARMPS version 6 SF over 1.9. Away from the large pillars, where a wide development span exists, the ARMPS SF diminishes to 1.4. SF of these magnitudes normally suggests a relatively stable pillar system. However, it was interpreted that long-term flooding in the No. 2 Gas Seam in a region above the active mining had softened the overlying pillar system and degraded the load bearing capacity of the smaller pillars.

Figure 15. Pillar burst material filling No. 8 entry.

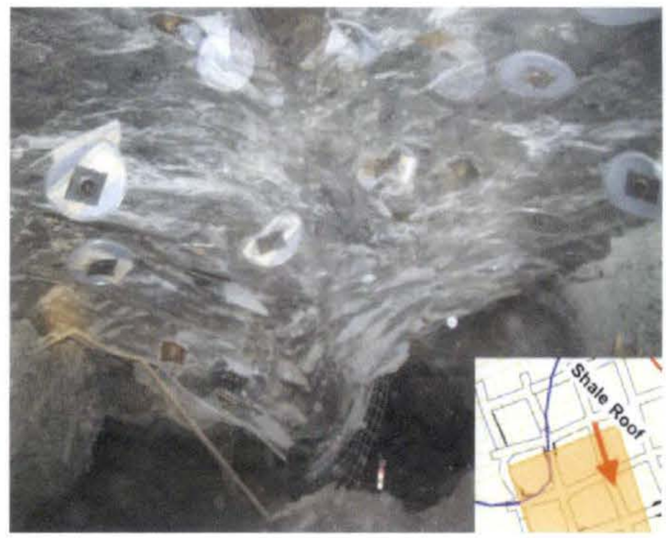

Figure 16. Failed shale roof under No. 2 Gas Seam remnant barrier where roof is being squeezed downward by pressure from Powellton Seam pillar and immediate roof dilation.

The pillars used in the Powellton Seam active mining also maintained an adequate pillar system SF exceeding 2.0. However, the burst apparently resulted from the multiple seam stress concentration combined with conditions including the transition to strong massive sandstone, the burst pillar's position in the bottom of a trough within the coal horizon, and the narrowing of the burst pillar to avoid the sand channel intrusion with the resultant decrease in load bearing capacity. Mitigation for future mining involved redirecting mining away from the sandstone channel region and increasing the pillar size to better cope with unexpected loading should multiple seam stress be encountered again. The determination of appropriate pillar size was conducted with historical back analysis of successful and unsuccessful multiple seam mining configurations across the reserve area. NIOSH ARMPS and pillar load bearing capacities were relied upon in the back analyses. At the time of the evaluation, AMSS had not yet been developed.

SUMMARY

Mining operations including their management, planning staff, and mining personnel must recognize that multiple seam stress can be encountered even where no full extraction has been conducted in the overlying or underlying old workings. Mining crews and management may not realize they have encountered a pseudo gob problem until they encounter deteriorated conditions that can't be explained in terms of a change in geologic condition, increased depth of mining, or inadequate pillar size.

At the onset of unexpected and unexplained rib sloughing, roof scale out, coal seam rolls or dips indicative of subsidence, etc.; mining crews and management should immediately consider that underlying or overlying pillars have yielded and are behaving as pseudo gob. Mining operations must exercise vigilance and immediately react when evidence of such stresses are encountered.

Examples of conditions that could lead to the formation of pseudo gob in overlying or underlying development pillars are low pillar stability factors or high coal recovery coupled with old age of the workings and water weakening the pillar foundation. The impact on the active mining will be more pronounced if the pseudo gob is an underlying feature. For mining to safely and successfully continue, a variety of methods have been applied to mitigate the stresses from pseudo gob situations. The hazard mitigation has required:

- At remnant or gob-solid multiple seam crossings, pillar design should be evaluated and adjusted if necessary to insure adequate global stability in the regions impacted by the elevated stresses.
- Roof and rib support will often need to be increased to maintain adequate ground control at the elevated stress regions in the active seam along the perimeter and over/under the remnant structure of the overlying or underlying seam.
- Acquiring roof support equipment to install appropriate roof rib support to cope with the stresses, and having the machine work stations designed for protection from both roof and rib fall hazards.
- Multiple seam stress interaction can be mitigated by redirecting advance elsewhere away from the high stress region. Applying techniques such as superimposing entries, avoiding mining under or over intact remnant barriers, and striving to establish mining into the destressed zones serve to mitigate the stress interaction when redirecting mining.
- Mitigation can involve no mining in a given region or at a given depth of cover to avoid the impact of multiple seam stress interaction.
- If a credible back analysis can be performed where criteria for safe multiple seam mining can be determined, site specific design has the potential to mitigate stress interaction. The design criteria must be stringent, and the evaluation must focus on relatively small regions to determine the elevated multiple seam stress levels that should be avoided.

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