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Roof Failure in Longwall Headgates – Causes, Risks, and Prevention

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ABSTRACT: Roof failures in the longwall headgates mostly occur outby the T-junction area within the front abutment pressure zone. The roof in this area could fail in the form of cutters, sagging, or collapse. Although front abutment pressure, high horizontal stress, and adverse roof geology are primary risk factors that cause headgate roof failure, other mining factors such as panel orientation, pillar sizes, roof support and operational parameters also contribute to the instability of a headgate. To prevent headgate failure during longwall mining, it is important to understand the causes of roof falls, risk factors, and effective risk mitigation measures. This study is based on the headgate roof support experience in a longwall mine in the Pittsburgh seam. The occurrence of roof falls in two longwall panels and the geotechnical solutions are described in detail. Numerical modeling was conducted to investigate the effect of the longwall retreat direction on stress concentrations in the headgate. Causes and risks of roof falls in the longwall belt entry, and mitigation measures for roof-fall risks are discussed. Through diligent geologic reconnaissance, proper roof support design, and proactive risk management, roof falls in longwall headgates can be prevented.

1. INTRODUCTION

Longwall mining is the primary underground coal mining method in the United States, and currently accounts for more than 60% of the underground mine production. The longwall headgate, as a passageway for the longwall crew, intake air, material supplies, and coal belt transportation, is critical for both safety and continuous production of the longwall panel. A roof fall in the longwall headgate would not only result in substantial interruption of production but potentially cause injuries or fatalities. Rehabilitation of failed roof in the headgate would also expose miners to the risk of injuries. Due to the importance of the longwall headgate to longwall production, roof support in the headgate has been carefully designed to accommodate both abutment pressure and horizontal stress. However, because the roof stability in the longwall headgate is influenced by many factors associated with both geology and operational parameters, roof falls still occur, though very infrequently, in the headgates of U.S. longwall mines.

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Roof failure in the headgate mostly occurs outby the T-junction area within the front abutment pressure influence zone. Considerable research has been conducted to determine the effects of various factors on headgate roof stability, as well as effective measures to support the roof in longwall mines in the Pittsburgh seam (Mark et al., 1998; Chen et al., 1998; Su et al., 1995, 1999, 2002, 2003; Hasenfus and Su, 2006; Van Dyke et al., 2015). Previous studies have demonstrated that front abutment pressure, high horizontal stress, and transitional roof geology are primary factors that cause headgate roof failure. These studies also showed that panel orientation, retreat direction, pillar sizes, and roof support also play an important role in the stability of a headgate. In some cases, roof failure can also be caused by floor heave, severe rib sloughage, and slow face advancing rate.

In underground coal mines located in the eastern United States, the magnitude of the maximum horizontal stress is typically three times greater than the vertical stress, and about 40% greater than the minimum. Mark et al. (1998) studied seven cases of headgate failures caused by high horizontal stress in different coal seams in the United States, and stated that roof stability is to a large extent affected by rock type, entry orientation, and longwall orientation. The effects of horizontal stress may be summarized in these statements: (1) a laminated roof is very vulnerable to high horizontal stress; (2) entries that are aligned with the maximum horizontal stress will suffer less damage on development than those perpendicular to it; (3) and horizontal stress concentration and relief depends on panel orientation, the direction of retreat, and the sequence of longwall panel extraction.

The impact of anomalous geology on headgate ground control in the Pittsburgh seam has been well studied (Su et al., 1999, 2002; Van Dyke et al., 2015). A study by Van Dyke et al. showed how transitional geology affected longwall ground control in three longwall mines in the Pittsburgh seam. The study identified a list of dominant geologic factors in the transition zone that posed ground control challenges during both development and longwall mining. The factors included weak claystone roof, shale channels, sandstone channels, slickensided zones, laminated roof, soft floor, and regional syncline. Roof cutters, excessive headgate convergence, floor heave, and roof falls were experienced in the transition zones in those mines, and additional roof support and in-mine geotechnical monitoring were required to attack the local ground control challenges.

To prevent headgate failure during longwall mining, it is important to understand the causes and potential scale of roof falls, risk factors, and roof support requirements. This study focuses on headgate roof support based on the experience in a longwall mine in the Pittsburgh seam. The occurrence of roof falls in the belt entry of two longwall panels and geotechnical solutions are described in detail. Numerical modeling was used to investigate the effect of longwall retreat direction on stress concentrations in the headgate. Causes and risks of roof falls in the longwall headgate, and mitigation measures for roof-fall risks are discussed in this paper.

2. OCCURRENCE OF ROOF FALLS IN THE LONGWALL HEADGATE

The longwall headgate is so crucial to longwall production that it is generally well supported in accommodating both development and abutment loading. Roof falls in the longwall headgate are very uncommon. Lessons learned from roof falls in the headgate of a particular longwall mine in the study were not only invaluable for supporting the roof in the same mine but also useful for understanding how to deal with roof-fall risks in the longwall headgate in general. To illustrate causes and risks of roof falls in the longwall headgate, four roof falls in two adjacent panels in a longwall mine in the Pittsburgh seam are presented below in detail.

The longwall mine in this case study mined the Pittsburgh seam with an overburden depth of 167.7–228.7 m (550–750 ft). The immediate roof consisted of shale, rider coal, claystone and sandstone, and the floor was claystone, shale, or limestone. The coal seam was about 2.1 m (7.0 ft) thick, and a claystone layer of about 0.3 m (1 foot) was present on the top of the coal seam. The claystone was too weak to support and susceptible to weathering, it was removed during development. A typical geologic column of the mine is shown in Fig.1. Horizontal stress measurements showed that the major horizontal stress orientation is about $N70^0E$, and its magnitude is on average about three times of the overburden stress. Longwall panels, 390.2 m (1,280 ft) wide and oriented at 35^0 to the major horizontal stress, were developed by three-entry systems with 30.5-m (100-t) by 56.1-m (184-ft) center-to-center chain pillars. The entry height was about 2.4 m (8 ft), and the entry width was 4.9 m (16 ft). The face advancing rate was about 15 m (50 ft) per day. The roof was primarily supported by three 2.4–m (8–ft) partially-grouted tension bolts with steel channels on 1.2-m (4-ft) spacing. Cable bolts of 3.7–4.9 m (12–16 ft) were used for supplemental support. Four roof falls occurred in the belt entry (headgate) during longwall mining with three falls in the first panel and one fall in the second panel of the district. All of the roof falls occurred in a new mining district where retreat direction changed from left-handed panels to right-handed panels. The right-hand denotes the retreat direction of the longwall face when approached from the belt entry (Hasenfus and Su, 2006). No roof falls occurred in the left-handed panels in the previous district, even though no supplemental cable bolts were installed.

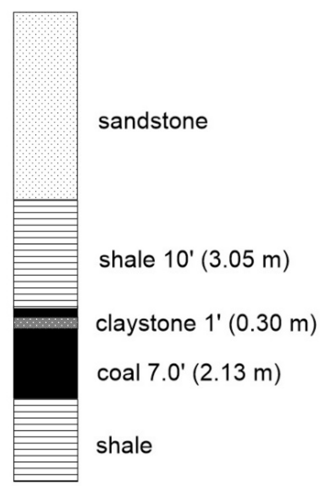

Fig.1. Typical geologic column.

The standard roof support in the belt entry was three 2.4-m (8-ft) partially-grouted tension bolts with steel channels on 1.2-m (4-ft) spacing. When the panels in the new district were developed, a stronger 2.4-m (8-ft) tension cable bolt as the center bolt was used to replace the 2.4-m (8-ft) partially-grouted tension bolt to eliminate coupler breaking at the entry center. No roof sagging and cutters occurred during development. Roof cutters at both sides of the belt entry and roof sagging started within 15.2–30.5 m (50–100 ft) outby the face after the face advanced about 305 m (1,000 ft) from the setup entry. The cutters and sagging became more severe when the face was about 15.2 m (50 ft) from the intersections, but then was very much alleviated as soon as the face passed the intersections. The first roof fall occurred at an intersection in the belt entry after the face advanced about 914.6 m

(3,000 ft) from the setup entry (roof fall I in Fig.2). The fall height was about 3.7–4.6 m (12–15 ft). The immediate roof at the fall location was shale with a 0.3-m (1-ft) rider coal about 3.0–3.7 m (10–12 ft) above the roofline. Five 6.1-m (20-ft) scope holes drilled in the belt entry outby the roof fall showed no separations in the immediate roof. Geotechnical investigation determined that the existence of a rider coal above the bolted horizon, and insufficient supplemental support at the intersections contributed to the roof fall.

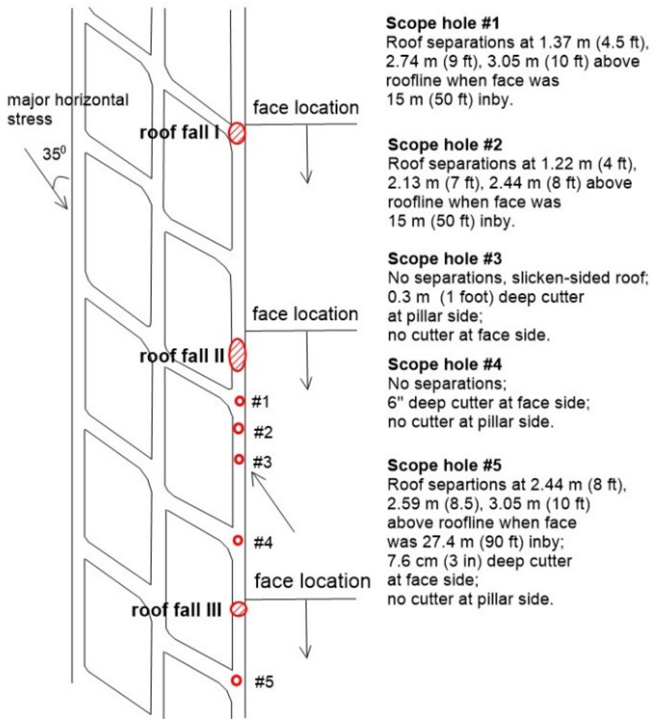

Fig.2. Locations of roof falls in the first panel.

To support the roof at the intersections, two 4.9-m (16-ft) post-tention cable bolts with T-3 steel channels on 1.8-m (6-ft) spacing were added for 15.2 m (50 ft) inby and 9.1 m (30 ft) outby the intersections. When the face advanced for about 91.5 m (300 ft) from the first roof fall, a second roof fall occurred 2.7 m (9 ft) in front of the gate shields and about 13.7 m (50 ft) from the ouby intersection (roof fall II in Fig. 2). The roof first started sagging at the center, and gradually sagged to the stage loader within a shift. The roof fall was about about 9.1 m (30 ft) long, and stopped at the intersection corner inby the intersection. The roof failure propagated 3.0–3.7 m (10–12 ft) in the cable bolted roof, and the roof fell out between the cable bolts, but cable bolts at the roof fall were still anchored in the roof. The immediate roof at the fall location was mainly shale. A scope hole 1.5 m (5 ft) from the fall showed a 15.2-cm (0.6-in) rider coal 1.4-m (4.5-ft) above the roofline and another 0.3-m (1-ft) rider coal 2.7 m (9 ft) above the roofline. The scope holes within 15.2 m (50 ft) outby the fall showed separations up to 3.0 m (10 ft) above the roofline.

With the second roof fall occurring in the mid-block, two 4.9-m (16-ft) post-tension cable bolts with T-3 channels on 1.8-m (6-ft) spacing were also added in the mid-blocks in addition to the intersections. Polyurethane injection was used to further reinforce the roof. The injection holes drilled at the entry corners were 3.0 m (10 ft) deep and 45^0 angled over the pillars. However, the third roof fall still occurred another 91.5 m (300 ft) outby the second fall in the belt entry (roof fall III in Fig. 2). The fall was 3.0–3.7 m (10–12 ft) high, 3.0 m (10 ft) long, and about 27.4 m (90 ft) inby the nearest intersection outby the face. The roof did not completely collapse, but cantilevered over the rib on the pillar side. The roof on the face side was in contact with the stage loader, but the roof on the pillar side was still overhanging (Fig.3). On the face side, the roof broke around the cable bolt plates and fell out between the cable bolts with the 4.9-m (16-ft) cable bolts still firmly anchored in the roof. The scope hole at the intersection outby the fall showed separations at 2.4 m (8 ft), 2.6 m (8.5 ft), and 3.0 m (10 ft) above the roofline. The hole was scoped one week before and no separations were seen. Scoping near the roof fall found three rider coal seams at 2.1–2.4 m (7–8 ft), 1.1–1.4 m (3.5–4.5 ft) and 0–0.15 m (0–0.5 ft) above the roofline. The third roof fall also seemed associated with three layers of rider coal within 2.4 m (8 ft) of the immediate roof. A geologic cross-section along the belt entry also showed that rider coals dipped down near the roof fall locations (Fig.4). The rider coals creates weak planes so that under abutment pressure and high horizontal stress, roof separations develop within 2.4–3.0 m (8–10 ft) above the roofline. As the roof tends to sag, the top coal above the cable bolt plate broke, resulting in more roof sagging and eventually a roof fall. With this understanding, two 4.9-m (16-ft) post-tension cable bolts with steel channels were installed on 1.2-m (4-ft) spacing along the rest of the belt entry in the areas where rider coals were found within 4.9 m (16 ft) above the roofline. The rest of the panel was mined without major roof control issues in the belt entry.

Fig.3. Roof fall by cantilevering over the pillar side in the belt entry.

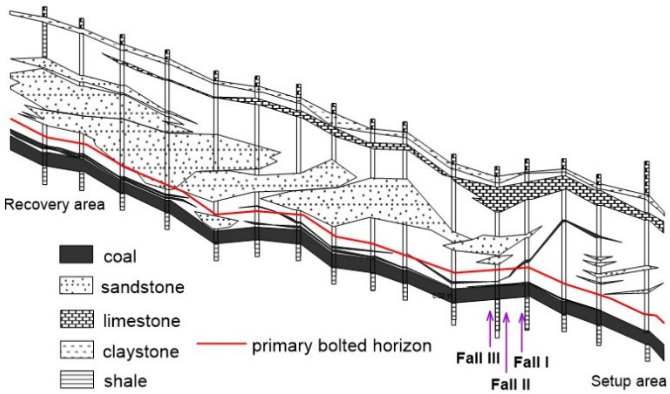

Fig.4. Geologic cross-section along the belt entry.

In the second panel of the same district, two 4.9-m (16-ft) post-tension cable bolts with steel channels were installed on 1.2-m (4-ft) spacing along the entire belt entry. The fourth roof fall occurred about 15.2 m (50 ft) from the intersection near the face in the belt entry when the face advanced about 304.9 m (1,000 ft) from the setup entry (Fig.5). A roof cavity first developed in front of shield #6, and then propagated towards the T-junction in the belt entry. Roof cutter on the face side developed up to about 0.6 m (2 ft) deep, then several 2.4 m (8 ft) primary bolts broke and popped out, and the roof gradually sagged onto the stage loader. The fall was about 7.6 m (25 ft) long in front of the gate shields. The fallen roof was slickensided shale, and no rider coal was observed above the bolted horizon (Fig.6). Two holes at two adjacent intersections outby the fall were scoped, and separations up to 3.0 m (10 ft) above the roofline were observed. The holes has been scoped two weeks before and no separations were seen. The immediate roof in the fall area consisted of shale and sandstone. The coreholes near the belt entry showed that a sandstone channel was present 2.4–3.0 m (8–10 ft) above the roofline. Almost all of the 6.1-m (20-ft) scope holes were wet due to the water coming out of the sandstone main roof. The immediate roof contained slickensided joints when the sandstone dipped down to the coal seam. To reinforce the slickensided roof, a polyurethane injection was used where roof separations were found. No roof falls occurred in the rest of the panel. The third panel was developed with 4.9 m (16 ft) cable bolts as center bolts installed on 2.4-m (8-ft) spacing, and two 4.9-m (16-ft) cable bolts on every row as supplemental support. No roof falls occurred in the rest of the district.

In summary, the roof falls described above showed the following characteristics:

- Roof falls were initiated from either roof cutter at one side of the entry corner or roof sagging at the entry center. The cutters and sagging initiated within about 15.2-30.5 m (50-100 ft) outby the face, and gradually developed into roof falls within about a shift.
- The location of the roof falls was strongly associated with the existence of rider coals and slicken-sides in the immediate roof. However, the exact location of a potential roof fall is difficult to predict by the limited knowledge of variable roof geology and the roof conditions outby the longwall influence zone.
- Though roof falls could occur at both intersections and within mid-blocks, they are more likely to occur within 15.2 m (50 ft) inby the intersections.
- Weak rock at the surface of the immediate roof is likely to break or fracture around the cable bolt plates under heavy loading, resulting in functionality loss of the cable bolts.

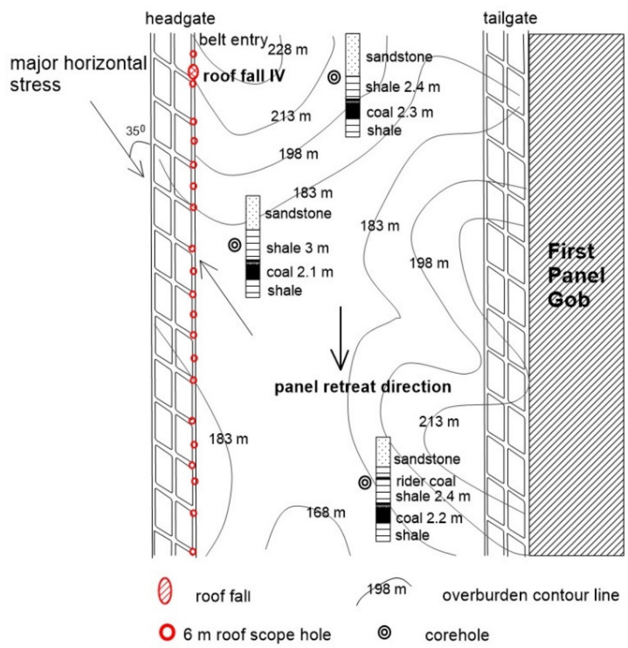

Fig.5. Location of a roof fall in the second panel.

Fig.6. Weak claystone roof fell with slickensides.

3. EFFECT OF LONGWALL RETREAT DIRECTION ON STRESS CONCENTRATIONS IN LONGWALL HEADGATES

In the Pittsburgh seam longwall mines, ground control challenges were mostly experienced in the right-handed panels (Van Dyke et al., 2015; Hasenfus and Su, 2006; Su et al., 2003; Mark et al., 1998; Chen et al., 1998). The headgate-stress concentration was first quantified by Su and Hasenfus (1995) using three-dimensional finite element modeling. It was found that when the angle ϕ is from 0^0 to 90^0, the headgate is in a stress concentration with the worst case occurring at $\phi=70^0$ (ϕ is defined by an angle from the headgate outby direction counter-clockwise to the maximum horizontal stress orientation). The headgate is stress-relieved when ϕ is from 90^0 to 180^0, with the best condition at $\phi=160^0$.

In this case-study mine, the longwall retreat direction with respect to major horizontal stress orientation seems to dramatically affect the stability of the headgate, as demonstrated by the roof falls described above. The roof falls occurred in the panels with $\phi = 35^0$, but no roof falls occurred in the previous panels with $\phi = 145^0$. With new advancements in FLAC3D (ITASCA, 2017) modeling of longwall mining (Tulu et al., 2017; Esterhuizen et al., 2010), the two longwall mining scenarios were modeled based on the geological and mining conditions in the panels where the roof falls occurred. The models were set up for both a right-handed and a left-handed panel to compare the difference in stress concentrations caused by longwall retreat (Fig.7). The models included sufficient details to simulate the gateroad development and associated pillars. The entire overburden from floor strata to the surface was modeled. The overburden strata was represented by a corehole near the roof falls where overburden depth is about 198 m (650 ft). The headgate area with a gob dimension of 195 × 244 m (640 ft × 800 ft) was modeled. Horizontal stresses were applied to the model by a major and minor horizontal-to-vertical stress ratio of 3 and 2, respectively.

As surface subsidence results from overburden movements due to longwall mining, surface subsidence is used to calibrate the numerical model to better simulate the overburden response in the longwall face area. The surface subsidence predicted by the model was compared to the surface subsidence predicted by an empirical subsidence model CISPM-W (West Virginia University, 2009). Fig.8 shows surface subsidence contours predicted by both the numerical model and empirical model. By comparison, the surface subsidence predicted by the two models agrees fairly well. Under a mining height of 2.4 m (8 ft), both models predicted 1.6 m (5.2 ft) of maximum subsidence around the center of the panel and 0.05 m (0.2 ft) of subsidence at the edge of the panel. A 3D view of surface subsidence over the gob around the headgate area is shown in Fig.9.

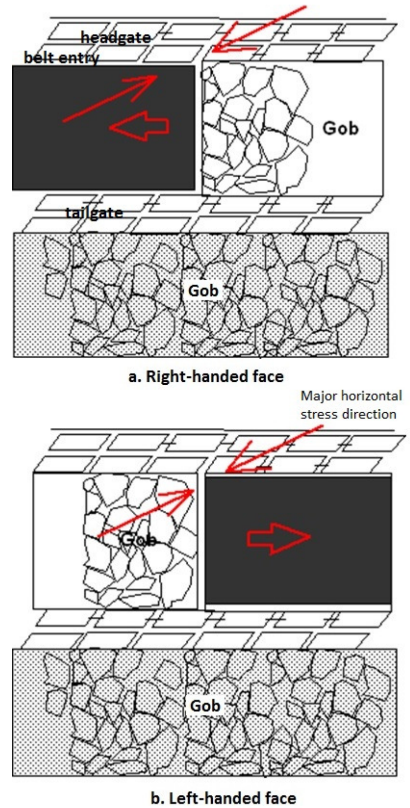

Fig.7. Horizontal stress concentration and relief in right-handed and left-handed panels.

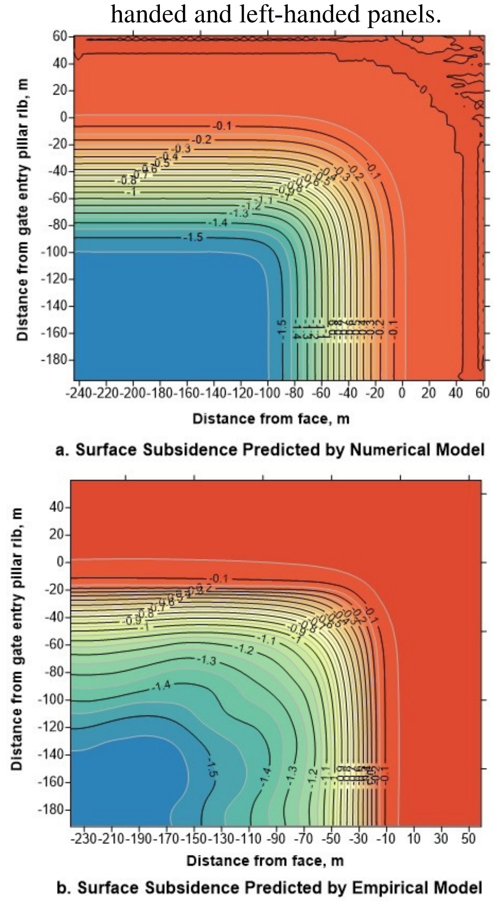

Fig.8. Surface subsidence predicted by numerical model and empirical model.

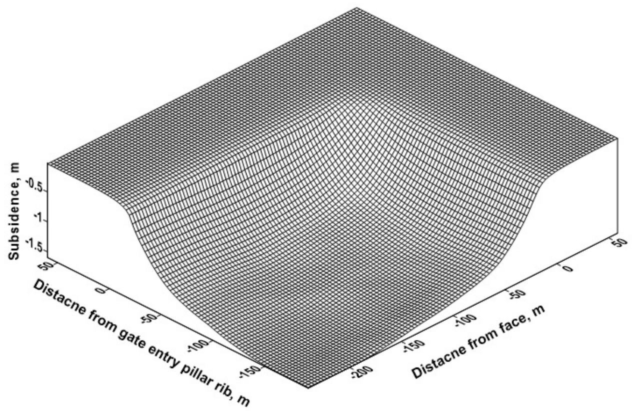

Fig.9. 3D View of surface subsidence predicted by numerical model.

The calibrated model was used to model the distribution of abutment pressure around the longwall face. Fig.10 shows the vertical stress distribution around the headgate area of the longwall panel under 198.2 m (650 ft) of overburden depth. The maximum abutment pressure is 15.97 MPa (2,316 psi), about 3 times the vertical stress. Fig.11 shows the vertical stress distribution across the chain pillars inby and outby the face. This indicates that the vertical stress in the pillars in the belt entry outby the face gradually reduces with distance outby the face, and the abutment pressure influence zone is within about 30 m (100 ft) outby the face.

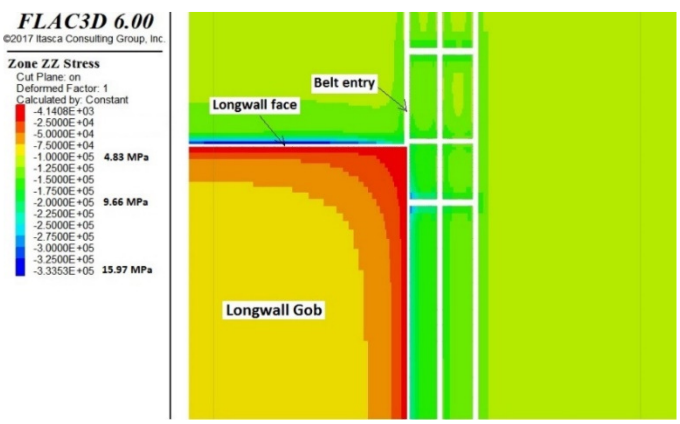

Fig.10. Vertical stress distribution over the headgate area.

The horizontal stress concentration and relief over the chain pillars by the gob are also obtained from the model. Fig.12 shows horizontal stress concentration and relief 3 m (10 ft) in the roof over the chain pillars 213 m (700 ft) inby the face. The horizontal stress parallel to the panel retreat direction shows almost no change, while the horizontal stress perpendicular to the panel retreat direction relieves within about 60 m (200 ft) from the gob edge. Significant horizontal stress relief occurs within about 30 m (100 ft) from the gob edge. It should be noted that the small horizontal stress peaks are caused by the effect of entry excavation 3 m (10 ft) below.

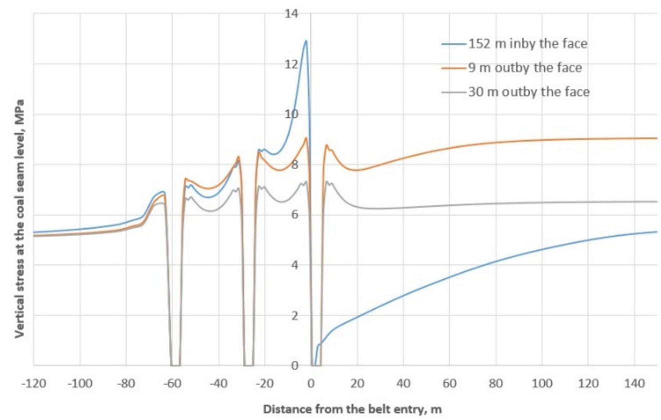

Fig.11. Vertical stress across the gate entries.

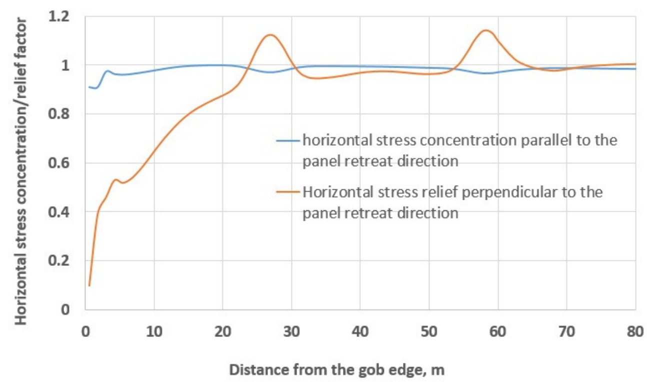

Fig.12. Horizontal stress concentration and relief factors over the chain pillars 213 m (700 ft) inby the face.

Fig.13 shows the horizontal stress concentration 3 m (10 ft) above the roofline along the belt entry. Horizontal stress perpendicular to the entry increases within about 30 m (100 ft) outby the face, while horizontal stress parallel to the entry decrease within about 30 m (100 ft) outby the face. The majority of the horizontal stress changes occur within about 15.2 m (50 ft) outby the face. Maximum horizontal stress concentration perpendicular to the headgate occurs within about 3.0-6.1 m (10-20 ft) outby the face with a horizontal stress concentration factor of about 1.5.

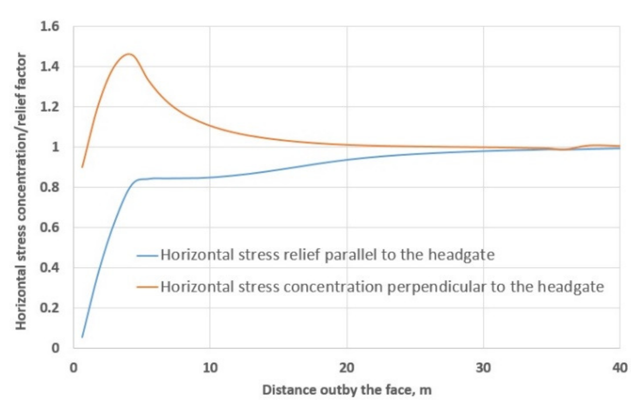

Fig.13. Horizontal stress concentration along the belt entry 3 m (10 ft) above the roofline.

Mostly, shear failure in the form of roof cutters are observed at the entry corner as initial roof failure in the belt entry near the face. Octahedral shear stress can be used as an indicator for potential shear failure. Octahedral shear stress in FLAC3D is defined by Eq. (1).

$$\sigma_{oct} = \sqrt{\frac{2}{3}J_2} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)^2} \qquad (1)$$

where $\sigma_1, \sigma_2, \sigma_3$ are the three principal stresses.

As roof cutters are observed at the entry corner within about 0.9 m (3 ft) of the roofline in the belt entry, the octahedral shear stress at the same location is examined in the model. Fig.14 shows the octahedral shear stress 0.9 m (3 ft) above the roofline in the belt entry corner on the face side. Fig.15 shows the octahedral shear stress 0.9 m (3 ft) above the roofline at the belt entry corner on the pillar side. Both figures indicate that octahedral shear stress at the belt entry corner in the right-handed panel is significantly higher than in the left-handed panel. The difference in octahedral shear stress is caused by the horizontal stress abutment in the right-handed panel and horizontal stress relaxation in the left-handed panel. The higher octahedral shear stress concentration on the belt entry corners explains why cutters are more likely to occur in the belt entry in the right-handed panel.

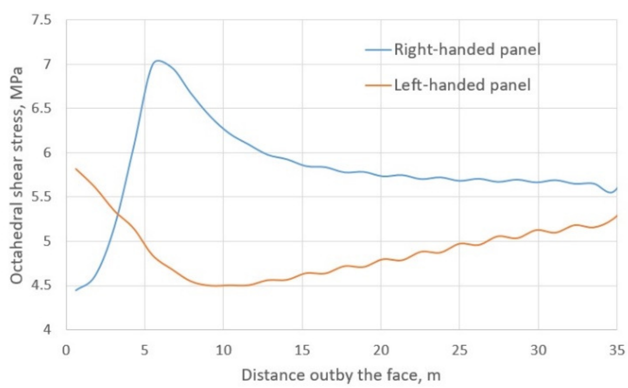

Fig.14. Octahedral shear stress at the belt entry corner on the face side 0.9 m (3 ft) above the roofline.

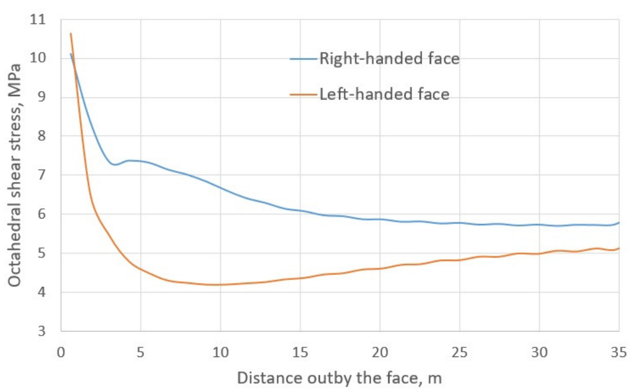

Fig.15. Octahedral shear stress at the belt entry corner on the chain pillar side 0.9 m (3 ft) above the roofline.

4. FACTORS CONTRIBUTING TO ROOF FAILURE IN THE LONGWALL HEADGATE

The longwall headgate T-junction area is subjected to abutment pressure and horizontal stress concentration, the influence zone of which is about 15.2–30.5 m (50–100 ft) outby the face. Mostly, roof falls in the longwall headgates, if they occur, it is in the belt entry. Several factors contribute to roof failures in the belt entry: roof geology, high horizontal stress, and insufficient roof support.

In longwall headgate in the Pittsburgh coal bed, three initial roof failure modes in the form of cutters, roof sagging, and roof breaking between bolts or at the plates, are commonly observed. Roof cutters are seen in weak immediate roof, such as coal, claystone, and laminated shale or sandyshale. Roof cutters are rarely seen during development in the gate entries parallel or subparallel to the major horizontal stress. Mostly, cutters develop at the entry corners at either the face side or pillar side or both within 15.2-30.5 m (50-100 ft) outby the face during longwall retreat. Roof cutters are caused by high shear stress at the upper entry corner and are mainly associated with high horizontal stress. Roof geology and stress orientation control the severity of cutters to be developed. In the Pittsburgh seam, the immediate roof generally consists of rider coal, clayshale and shale, and cutters are often seen in the belt entry outby the face in the right-handed panels. If cutters are minor, overall roof stability is not affected. Deeper cutters at one side of the entry could make the primary bolts fail, and induce a roof fall if supplemental support is not sufficient.

Roof sagging normally develops around the entry center in weak immediate roof. Mostly roof sagging develops within about 50 ft outby the face during longwall retreat. Roof sagging is associated with high horizontal stress across the entry and tensile/compressive fractures around the entry center. Occurrence of roof sagging is a sign of roof failure above the primary bolts. Roof sagging may not cause a roof fall if supplemental support is sufficient. But if the roof sags so much that it is in contact with the stage loader, longwall production is interrupted and the stage loader has to be pulled by a retriever. Time-dependent roof sagging sometimes causes sagged roof to fall to the stage loader if retrieving is unsuccessful.

Roof fracturing could occur between bolts or at the cable bolt plates in the belt entry close to the face. Breaking occurs at weak roof with slickensides, laminations or top coal at the immediate roof. Roof breaking could be caused by roof sagging, heavy load in cable bolt plates, or discontinuities in the immediate roof. Roof breaking between bolts can be minimized by adding steel straps and wire mesh for better surface control.

The three initial modes of roof instability are more likely to occur in the belt entry in the right-handed panel with weak immediate roof under high horizontal stress. Roof instability in longwall headgate is also time-dependent and progressive. A slow longwall retreat rate would allow the roof with cutters or sagging to deteriorate quickly. Any initial roof failure in the headgate could potentially develop into a roof fall if roof surface control and supplemental support are not sufficient.

5. MITIGATIONS OF ROOF-FALL RISKS IN THE LONGWALL HEADGATE

Although roof falls in the longwall headgate are strongly associated with weak roof with geologic anomalies and high horizontal stress, the requirements for roof support is difficult to be reliably determined based on corehole data, considering that roof geology could change within a short distance. A conservative approach can be used to install supplementary support along the whole longwall headgate during development, but longwall development efficiency can be greatly compromised, and can sometimes be economically infeasible. A better approach is to strategically install supplemental support in the high risk areas with roof falls. The following procedure is given to mitigate the roof-fall risks in the longwall headgate.

5.1 Identify geologic risk factors

The primary risk factors in causing roof falls in longwall headgate are roof geology and horizontal stress. Su et al. (1999) has identified the following problematic geologic anomalies that can pose ground control difficulties in the Pittsburgh seam:

- The sudden presence of weaker units, such as claystone, rider coal, and slickensided shale resulting from variations in the coal-depositional environment or from differential compaction.
- Major transitions in roof depositional facies, such as marine or brackish (limestone) to flood plain/river deposits (sandyshale and sandstone).
- The presence of highly laminated strata produced by rapid cyclical variations in depositional environment or differential movement following deposition.
- The presence of sand channel structures near the immediate roof.
- The presence of major shallow-cover stream valleys that may cause horizontal stress concentration and structural weakness under the valley bottom.

Anomalous and transitional geology often create zones or planes of weakness, the impact of which can be laterally extensive or confined in extent. Often times, it is simply the unknown, unexpected, or erratic nature of these features that creates the greatest challenges to longwall roof support (Van Dyke et al., 2015). Roof geology reconnaissance has been used to identify geologic anomalies by utilizing a combination of roof drilling data, geophysical logs, underground scoping and mapping (Su et al., 1999; Van Dyke et al., 2015). Systematic roof scoping, strategically planned corehole exploration, and detailed in-mine geologic mapping greatly help with identification of risk areas and requirements for roof support (Van Dyke et al., 2015).

5.2 Install supplemental roof support in identified risk areas

Installation of supplemental roof support is crucial to minimize the risk of roof falls in longwall headgate. Supplemental support is designed to support the roof in case roof failure occurs above the top of the primary bolts. Options of supplemental support include cable bolts, cable trusses, and bar trusses. Various types of cable bolts, such as conventional cable bolts, tensioned cable bolts, post-tensioned cable bolts, and fully-grouted injection cable bolts, are available. Cable bolting has long been widely used in the headgate in anomalous geologic influence zones under high horizontal stress (Chen et al., 1998, Mark et al., 1998). In using cable bolting as supplemental support, the selection of anchorage horizon is critical to ensure that cable bolts can hold the roof through beam building and suspension. Strong roof, such as limestone, sandstone, or massive shale and sandyshale, makes good anchorage horizon. Cable bolts should be anchored at least 1.2 m (4 ft) into the solid roof. To support the roof with the worst stress condition, the priority of supplemental support should first be given to the intersections and the belt entry within 15 m (50 ft) inby the intersections. Installation of cable bolts in mid-blocks can be determined by assessment of local roof geology. Roof-fall risks can be minimized if sufficient supplemental support is installed in both intersections and mid-blocks in transition zones and under valley bottoms.

In using cable bolts in the risk areas in longwall headgate, bolting patterns should be generally designed with suspension in which the cable bolts should be sufficient to hold the dead weight of the potentially failed roof under the anchorage horizon. Experience in the Pittsburgh seam has shown that cable bolts installed at the entry center are effective in resisting roof sagging. With weak roof present at the surface of the immediate roof, steel channels should be installed together with cable bolts to improve roof surface control.

5.3 Consider additional measures

In addition to supplemental roof support, other mitigation measures to reduce roof-fall risks in the belt entry should also be considered, which include:

- Longwall panels should be oriented or sequenced to make major horizontal stress relax at the headgate if possible.
- Primary support is also important in reducing the risk of roof falls in the headgate. Historically, 2.4-m (8-ft) two-piece, partially grouted tension bolts were used

as primary bolts, and bolt breaking occurred at the couplers due to roof shearing under horizontal stress. In recent years, many longwall mines have been using 1.8-m (6-ft) one-piece, fully grouted tension bolts as primary bolts to successfully eliminate coupler breaking (Van Dyke et al., 2015).

- Crosscuts can be made more stable if optimally angled with the maximum horizontal stress.
- The roof is more stable if four-way intersections can be replaced with three-way intersections.
- The roof condition can be improved by changing pillar design. Su et al. (2003) has demonstrated that a new pillar design with 18 × 43 m (60 ×140 ft) pillars on the face side significantly improved the roof conditions in the headgate by reducing horizontal stress in the belt entry near the face.

6. CONCLUSIONS

A few conclusions are derived from the headgate roof support experience in a Pittsburgh seam longwall mine, the numerical modeling of stress changes in the longwall headgate, and the analysis of roof fall causes and risks as follows:

- Roof in longwall headgate could fail in the form of cutters, sagging, and breaking between bolts under high horizontal stress. Roof falls could occur both at intersections and in mid-blocks, but they are more likely to occur within 15.2 m (50 ft) inby the intersections in the longwall headgate.
- Roof falls in longwall headgate are mainly associated with geologic anomalies under high horizontal stress.
- A numerical model showed that the horizontal stress perpendicular to the headgate increases and the horizontal stress parallel to the headgate relieves within about 30.5 m (100 ft) outby the face. The cutters in the belt entry near the face are caused by shear stress concentration at the entry corners within about 15.2 m (50 ft) outby the face. The modeling showed that the shear stress concentration in the headgate in a right-handed panel is significantly higher than in a left-handed panel.
- The requirements for roof support in the longwall headgate are difficult to reliably determine based on the limited knowledge of variable roof geology and observed roof conditions. A risk management approach should be used to prevent roof falls in the headgate by strategically adding supplemental support in high risk areas. Systematic roof scoping, strategically planned corehole exploration, and detailed in-mine geologic mapping greatly help with the identification of risk areas and requirements for roof support.
- Installation of supplemental roof support is critical to prevent roof falls in areas with geologic anomalies under horizontal stress concentration. Other mitigation measures that address the roof-fall risks in the longwall headgate include optimal panel orientation and retreat direction, new pillar design to reduce horizontal stress, geologic mapping, and in-mine geotechnical monitoring.

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