Mining, Metallurgy & Exploration (2022) 39:1873–1885
https://doi.org/10.1007/s42461-022-00634-9

Roof Stability and Support Strategies Associated with Longwall-induced Horizontal Stress Changes in Belt Entries

Peter Zhang[1] · Gabriel Esterhuizen[1] · Morgan Sears[1] · Jack Trackemas[1] · Todd Minoski[1] · Berk Tulu[2]

Received: 8 February 2022 / Accepted: 1 June 2022 / Published online: 14 June 2022

Abstract
Longwall mining is a highly productive and efficient coal mining method used in the USA. During longwall retreating, the belt entry must be maintained stable, and any roof fall in the belt entry would jeopardize mine safety and substantially interrupt the continuous production of coal in the longwall face. Past experience of longwall mining has shown that belt entry stability was the greatest challenge in longwall ground control, and the occurrence of roof falls in belt entries was largely associated with high horizontal stress. To properly support the roof in the belt entry, it is important to understand how longwall-induced horizontal stress changes affect roof stability in belt entries and to strategically install supplementary support to prevent any potential roof falls. Researchers from the National Institute for Occupational Safety and Health (NIOSH) performed horizontal stress measurements in the immediate roof of the belt entries for two Pittsburgh seam longwall panels oriented unfavorably to high horizontal stress. Hollow inclusion cells (HICells) were installed in the immediate roof at the intersection in each of the belt entries, and stress changes were monitored as the longwall face was approaching and passing the intersection. Numerical models were set up to calculate the longwall-induced horizontal stress changes in the roof at the monitoring sites. With the verified model, investigations were made of how horizontal stress is concentrated and relieved in the belt entry roof near the face under different panel orientations. Both measurements and modeling results showed that high horizontal stress is concentrated in the roof in the belt entry within about 15 m outby the face when a longwall panel is unfavorably oriented to the major horizontal stress. The study demonstrated that longwall-induced differential horizontal stress can be used as an indication of the degree of horizontal stress concentration. Roof support strategies are discussed on how to maintain the stability of belt entry under high horizontal stress concentration.

Keywords Roof stability · Belt entries · Horizontal stress

1 Introduction

Longwall mining is a highly productive and efficient underground coal mining method used in the USA and currently accounts for approximately 60% of the underground coal production. Since the belt entry serves as the passageway for mining crew and supplies going in and out of the face and for coal transporting out of the face, its stability is crucial for longwall safety and continuous production of coal from the longwall face. Any roof fall in the longwall belt entry would not only result in substantial interruption of coal production but potentially cause injuries or fatalities. Even though the roof in the belt entry is carefully supported to accommodate both abutment pressure and horizontal stress, roof falls still occasionally occur in belt entries in US longwall mines, and they are mostly associated with high horizontal stress.

Ground control problems are most likely to occur at longwall gate entries where the roof is subjected to longwall-induced abutment pressure and horizontal stress. Roof control in longwall headgate has been extensively studied by researchers and practitioners especially for Pittsburgh seam longwalls [1, 3, 5, 6, 8–11, 13, 16]. Mark [5] was the first to identify longwall headgate horizontal stress concentrations in the Pittsburgh seam and to propose that horizontal stress measurement, optimal panel orientation, and proper roof support are the essential steps to deal with high horizontal stress. Mark (1998) provided several case histories of

✉ Peter Zhang
nmb2@cdc.gov

1 Office of Mine Safety and Health Research, NIOSH, Washington, DC, USA

2 Department of Mining Engineering, West Virginia University, Morgantown, WV, USA

roof failure from the Pittsburgh seam as well as other coal seams in Central Appalachia, Illinois Basin, Alabama, and Colorado. Previous studies have shown that high horizontal stress and transitional roof geology as well as front abutment pressure are the primary factors to cause roof failure in belt entries. These studies also showed that high horizontal stress with respect to panel orientation and longwall mining direction plays an important role in the stability of a belt entry roof. Ground control concerns caused by high horizontal stress do not seem unique for US longwalls, and international experience with high horizontal stress in longwall gate entries is also shown in the publications by Gale [17] and Nemcik [18].

Horizontal stress measurements have showed that the maximum horizontal stress in Pittsburgh seam longwall mines is typically three times greater than the vertical stress and about 40% greater than the minimum horizontal stress [6, 7]. The ground control challenges in the Pittsburgh seam are mostly likely to be encountered when longwall panels are unfavorably oriented in respect to the maximum horizontal stress [1, 3, 6, 8, 13], Lu and Hasenfus, 2018; [15]. The effect of horizontal stress on belt entry stability was first quantified by Su and Hasenfus [11] using von Mises stress at the T-junction calculated by three-dimensional finite element modeling. It was found that when the angle ϕ is from 0 to 90°, and the belt entry is in a stress concentration with the worst case occurring at $\phi = 70°$ (ϕ is defined by an angle from the headgate outby direction counterclockwise to the maximum horizontal stress orientation). The belt entry is stress-relieved when ϕ is from 90 to 180°, with the best condition at $\phi = 160°$. A software tool has been developed by NIOSH and is available to help mine operators to assess longwall headgate horizontal stress concentrations and to plan accordingly [19].

To prevent roof falls in longwall belt entries, it is important to clearly understand how roof stability is affected by longwall-induced horizontal stress changes in belt entries during longwall retreat and to strategically install supplementary support to cope with high horizontal stress. This study focuses on belt entry roof support based on horizontal stress monitoring, numerical modeling, and roof control experience in Pittsburgh seam longwall mines. The researchers from the National Institute for Occupational Safety and Health (NIOSH) measured horizontal stress changes in the immediate roof in the belt entries for two Pittsburgh seam longwall panels oriented unfavorably to high horizontal stress. Hollow inclusion cells (HICells) were installed in the immediate roof at an intersection in each of the belt entries, and stress changes were monitored as the longwall face was approaching and passing the intersection. Numerical models were set up to analyze how horizontal stress changes affect the roof stability in the belt entries. A horizontal stress concentration factor was introduced to assess the effect of panel orientation in respect to the maximum horizontal stress. Roof support strategies are also discussed on how to maintain belt entry stability under high horizontal stress.

2 Occurrence of Roof Falls in the Longwall Belt Entry

The longwall mine in this study extracts the Pittsburgh coal seam with an overburden depth of 168–366 m. Several roof falls have occurred in longwall belt entries that were oriented unfavorably to the major horizontal stress. Horizontal stress measurements showed that the major horizontal stress orientation in the mine is about N70°E, and its magnitude is on average about three times the overburden stress. Longwall panels were about 457 m wide, developed with three-entry systems. The entry height was about 2.4 m, and the entry width was 4.9 m. All the roof falls occurred in new mining districts where retreat direction changed from left-handed panels to right-handed panels (a right-handed panel is oriented with the belt entry on the right when facing outby from the face). No roof falls occurred in the left-handed panels, even though no supplemental cable bolts were installed. The right-hand denotes that the active longwall face is located to the right when approached from the belt entry. The longwall panels in the Pittsburgh seam are generally laid out along the East–West direction. With major horizontal stress orientation at about N70°E, the headgate area in a right-handed panel is influenced by high horizontal stress concentration.

Three roof falls occurred in the belt entry in one panel in district A during longwall retreating. The panel was oriented at 35° to the major horizontal stress. The first roof fall occurred in front of the gate shields at an intersection in the belt entry after the face advanced about 915 m from the setup entry (roof fall I in Fig. 1). The fall height was about 3.7–4.6 m from roofline. Roof cutters occurred at entry corners on both sides of the belt entry within about 15 m outby the face during longwall retreating. The cutters became more severe when the face was about 15 m from the intersections but then were alleviated as soon as the face passed the intersections. The immediate roof at the roof-fall location was shale with a 0.3-m rider coal about 3.0–3.7 m above the roofline, and the overburden depth was 183–213 m. The roof in the belt entry was supported by three 2.4-m partially grouted tension bolts with steel channels on 1.2-m spacing. No roof sagging or cutters occurred during development. Five 6-m 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 high horizontal stress contributed to the roof fall.

To support the roof at the intersections, two 4.9-m post-tension cable bolts with T-3 steel channels on 1.8-m spacing

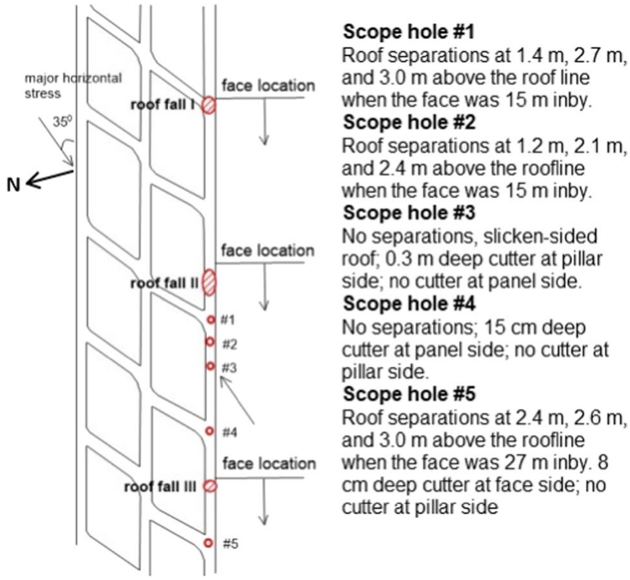

Fig. 1 Roof falls in a longwall belt entry in district A

Fig. 2 Roof fall near the face in the belt entry

were added at the intersections and extended to 15 m inby and 9 m outby the intersections. When the face advanced for about 91 m from the first roof fall, a second roof fall occurred 2.7 m in front of the gate shields and about 15 m from the ouby intersection (roof fall II in Fig. 1). 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 m long and stopped at the intersection corner inby the intersection. The roof failure propagated 3.0–3.7 m 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 laminated shale. A scope hole 1.5 m from the fall showed a 1.5-cm rider coal 1.4 m above the roofline and another 0.3-m rider coal 2.7 m above the roofline. The scope holes within 15 m outby the fall showed separations up to 3 m above the roofline.

With the second roof fall in the mid-block, two 4.9-m post-tension cable bolts with T-3 channels on 1.8-m 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 m deep and angled at 45° over the pillars. However, a third roof fall still occurred another 91 m outby the second fall in the belt entry (roof fall III in Fig. 1). The fall was 3.0–3.7 m high, 3-m long, and about 27 m inby the nearest intersection outby the face. The roof did not completely collapse but cantilevered over the rib on the chain pillar side. The roof on the panel side touched the stage loader, but the roof on the pillar side still overhung (Fig. 2). On the panel side, the roof broke around the cable bolt plates and fell out between the cable bolts with the 4.9-m cable bolts still firmly anchored in the roof. The scope hole at the intersection outby the fall showed separations at 2.4 m, 2.6 m, and 3.0 m 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 0–0.2 m, 1.1–1.4 m, and 2.1–2.4 m above the roofline. The third roof fall appeared to be associated with these three layers of rider coal within 2.4 m of the immediate roof. The rider coals created weak planes so that under abutment pressure and high horizontal stress, roof separations developed within 2.4–3.0 m above the roofline. As the roof began 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 post-tension cable bolts with steel channels were installed on 1.2-m spacing along the rest of the belt entry in the areas where rider coals were found within 4.9 m above the roofline. The rest of the panel was mined without major roof control issues in the belt entry.

Another roof fall occurred in a longwall belt entry in district B. The panel was oriented at 37° to the major horizontal stress. A roof fall of 9.1–12.2 m in length occurred in front of the longwall gate shields about 21 m inby the intersection (Fig. 3). The immediate roof broke out between straps, sagged about 0.3 m around the entry center, and touched the stage loader. Roof cutters were observed at the entry corners on the panel side and chain pillar side (Figs. 4 and 5). The overburden depth in the roof fall area was about 305 m. The immediate roof around the fall location consisted of 15 cm of top coal, dark shale, rider coal, claystone, and limestone above. The roof in the belt entry was supported by two 2.4-m partially grouted tensioned bolts as side bolts and one 3.7-m cable bolt as the center bolt with steel straps every 1.2 m. The ten 3.7-m supplementary cable bolts were installed every 1.2 m at intersections. High horizontal stress was identified as the cause of the roof fall. Two 4.9-m cable bolts every 1.2 m were added to support the roof for the remainder of the belt entry.

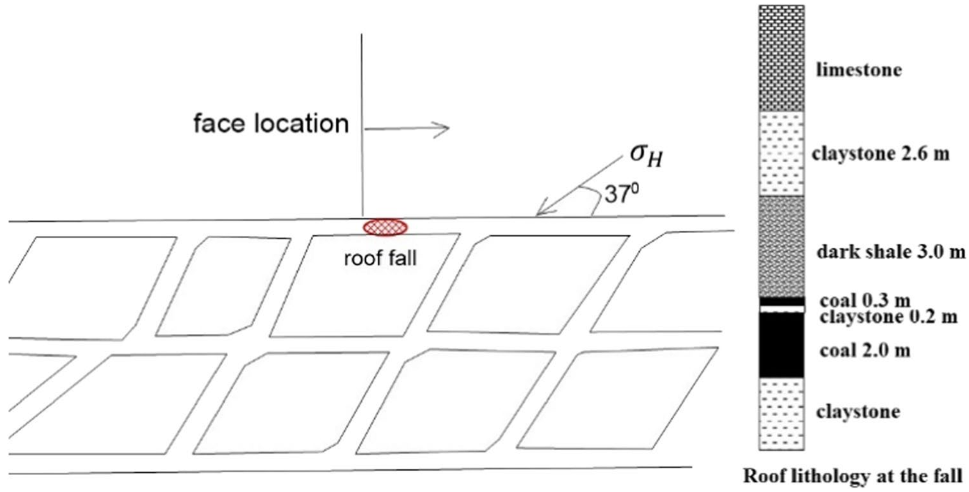

Fig. 3 Roof fall in a longwall belt entry in district B

Fig. 4 Roof cutter developed at the belt entry corner on the panel side

Fig. 5 Roof cutter developed at the belt entry corner on the chain pillar side

In summary, the roof falls in the belt entries showed the following features as described above:

- Roof falls were initiated from either roof cutter at one side of the entry corner or roof sagging at the entry center during longwall retreating. Few roof cutters or sagging occurred during development. The roof cutters, sagging, and separations initiated within about 15 m outby the face and gradually developed into roof falls within about a shift. The roof falls were close to the face, mostly in front of the longwall gate shields.
- The occurrence of the roof falls was strongly associated with weak immediate roof such as claystone, weak shale, thinly laminated shale/sandyshale/sandstone, and transitional roof geology where rider coals, laminated sandstone, and limestone co-exist above the primary-bolted horizon. The roof falls appear irrelevant to overburden depth.
- Roof fall locations could be at intersections or between intersections.
- Supplementary cable bolts were important to support the belt entries under high horizontal stress.

3 Monitoring Horizontal Stress Changes in the Belt Entry Roof

The historical roof falls in the longwall belt entries showed that the falls occurred near the face and were strongly associated with horizontal stress changes induced by longwall retreat. To understand how horizontal stress changes in the belt entry roof in response to longwall retreat, the stress changes in the immediate roof in the belt entries were monitored for two longwall panels in a new district in the Pittsburgh seam. Hollow inclusion csells (HICells) were installed in the roof at an intersection in each of the belt entries, and stress changes were monitored as the longwall face was approaching and passing the intersection. Figure 6 shows the panel layout and HICell locations at the monitoring sites. The two longwall panels were 457 m wide developed by three-entry chain pillar systems. The chain pillars were 43 m × 73 m and 24 m × 37 m center-to-center in panel A and 30 m × 56 m and 30 m × 56 m center-to-center in panel B. The panels were oriented at 37° to the major horizontal stress. The overburden depths were 259 m at both sites, and mining height was 2.3 m.

HICells were installed into 6-m roof holes about 3 months before the longwall faces advanced to the monitoring sites. The HICells were located at the center of the intersections about 1.2 m from the pillar line on the chain pillar side. A data logger was placed in the adjacent crosscut at each site to record the data every hour until the face passed the intersection. The immediate roof at each intersection was scoped, and Fig. 7 shows the geologic columns of the roof at each site. The immediate roof at both sites consists of shale, claystone, and limestone. The HICells at both sites were securely epoxied in the limestone roof about 6 m above the roofline. The belt entries in both panels were supported

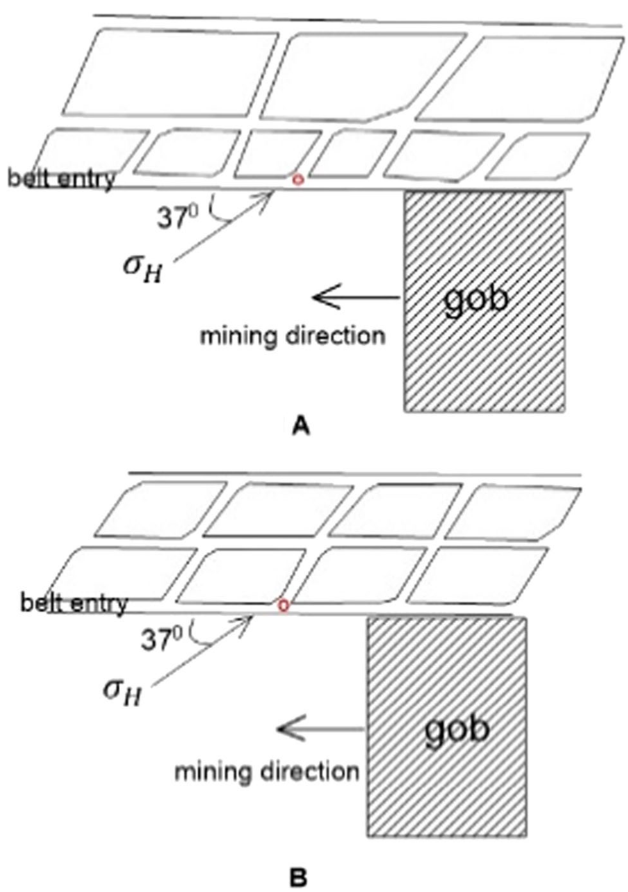

Fig. 6 Panel layout and HICell locations at the monitoring sites

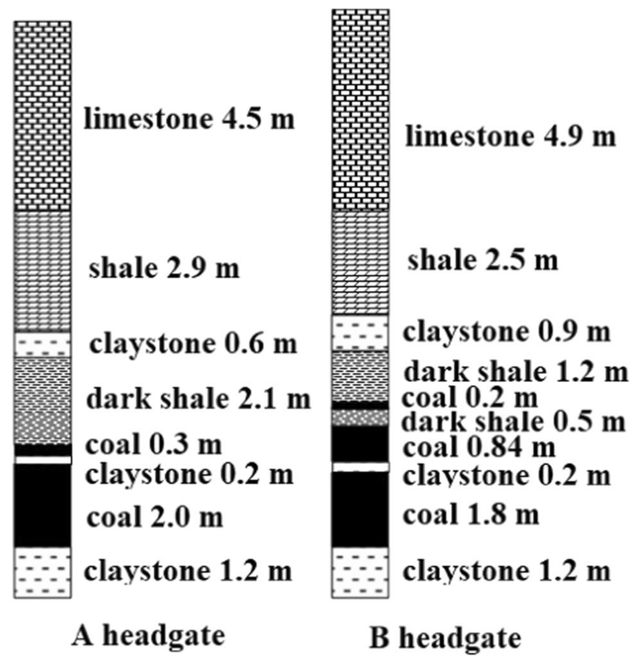

Fig. 7 Geologic columns of the roof at the test sites

with three 1.8-m fully grouted tension bolts with steel straps every 1.2 m except that the center bolt was replaced by one 4.9-m cable bolt at every 2.4 m. Two rows of 4.9-m cable bolts were installed through straps at both intersections and mid-blocks as supplementary support. At the two monitoring sites, cutters of 5–8 cm were observed at the belt entries corners on the panel side within about 15 m outby the longwall face. No cutters on the chain pillar side or roof sagging were observed outby the longwall face.

Figures 8 and 9 show the measured stress changes at the HICell locations in panel A and panel B as each longwall face approached the site from 24 m inby until the face passed the monitoring site. As this study focuses on horizontal stress changes affected by longwall retreat, only three stress components on the horizontal plane were examined, which are horizontal stress changes along and across the belt entry and horizontal shear stress along the belt entry. The horizontal stress changes were calculated for the face locations from 24 m inby to 12 m outby. Both figures show that significant horizontal stress changes began when the face was about 12 m inby the HICell locations. Negative stress indicates stress increase by compression, and positive stress indicates stress relief by tension. The horizontal stress across the belt entry increased as the face approached the HICell location and then relieved after the face passed the intersection in both panel A and panel B. The shear stress in the horizontal plane parallel to the roof increased at both locations as the face approached and passed the intersections. The horizontal stress along the belt entry showed an opposite trend at the two sites as the face approached and passed the intersection: relieving and then

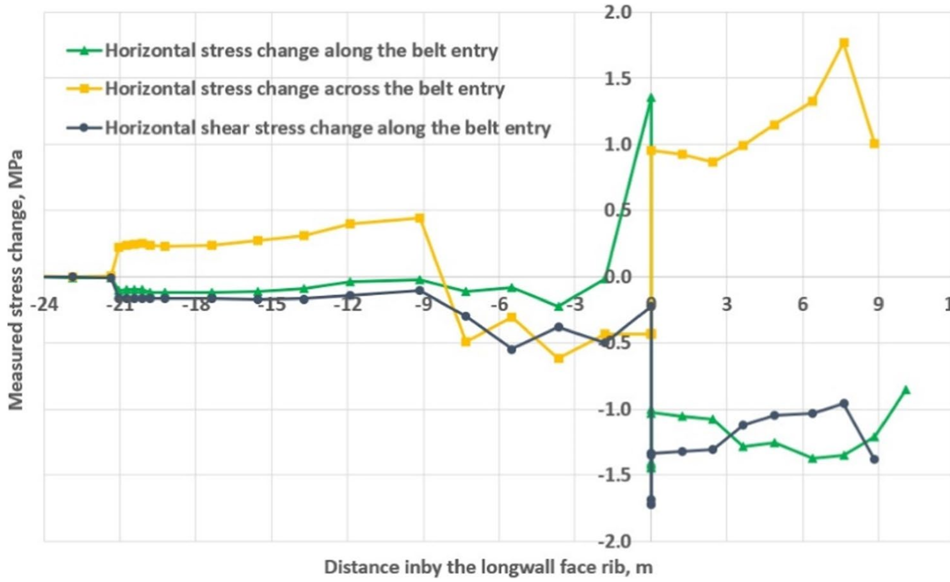

Fig. 8 Measured stress change at the HICell location in panel A

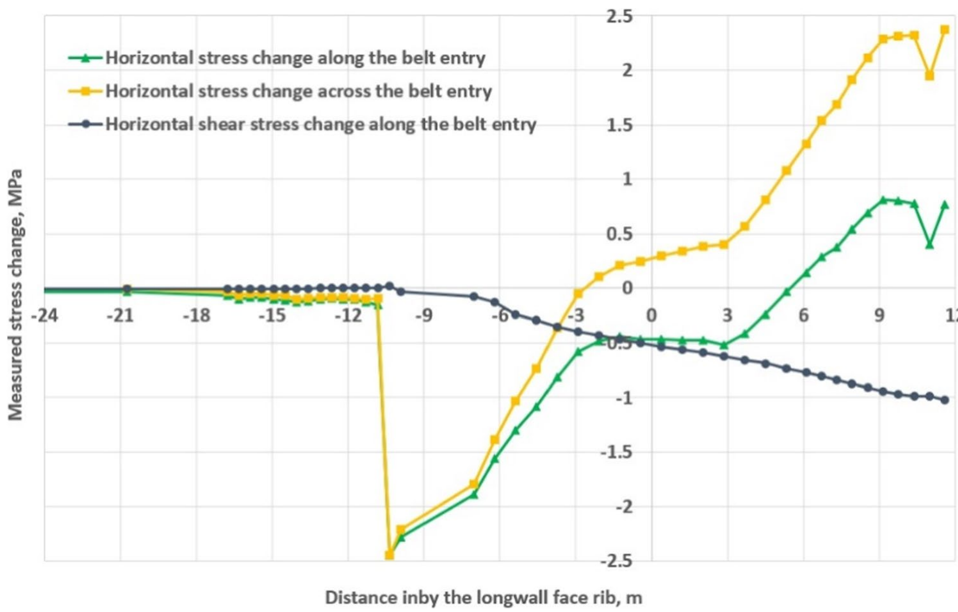

Fig. 9 Measured stress change at the HICell location in panel B

increasing in panel A but increasing and then relieving in panel B. The difference could be caused by the stability of the limestone layer in which the HICells were installed. The horizontal stress monitoring showed that the longwall-induced horizontal stress changes occurred within about 12 m outby the face in the limestone roof 6 m above the roofline at the intersections in the belt entries. The measured horizontal stress reliefs are less than about 2.8 MPa, and no significant difference was seen between panel A and panel B. Compared to the amount of in situ horizontal stress in the roof, the measured horizontal stress reliefs are relatively small. Since the horizontal stress relief over the longwall headgate results from the effect of roof caving and fracturing over the longwall gob, smaller amount stress relief is expected in the roof horizon above the caving zone. Higher horizontal stress changes are anticipated in the lower roof horizons and are investigated using FLAC3D [4] modeling in this study. The measured horizontal stress changes serve as measurement data for model calibration.

4 Numerical Modeling of Stress Changes in Longwall Belt Entry Roof

Numerical modeling techniques have been developed by NIOSH to calculate longwall-induced stresses and deformations [2, 12, 14]. In this study, FLAC3D models were set up based on the longwall mining layouts at the two horizontal stress monitoring sites. Figure 10 shows the plan view of the FLAC3D model for panel A. To simulate longwall-induced stresses and deformations, the entire overburden strata from the floor to the surface were modeled. The overburden strata were modeled with ubiquitous joint material, and the overburden lithology in the model was based on overburden geology from the closest coreholes. The roof geology was modeled with the geologic columns obtained from roof scoping at each site. The bedding planes between different rock types were modeled as interfaces with friction and cohesion. The roof, floor, and coal were modeled with Mohr–Coulomb material. The rock properties used in the model is shown in Table 1. The gob was modeled by hypo-elastic strain-hardening material implemented by the "FISH" scripting language. The headgate area with a symmetrical gob dimension of 229 × 305 m was modeled. Mining sequence was modeled to include gate entry development and longwall retreating. Horizontal stresses were initiated in the model with the major horizontal stress oriented at 37° to the belt entry as shown in Fig. 10. The magnitude of the maximum and minimum horizontal stresses are 3 and 2 times the vertical stress, respectively.

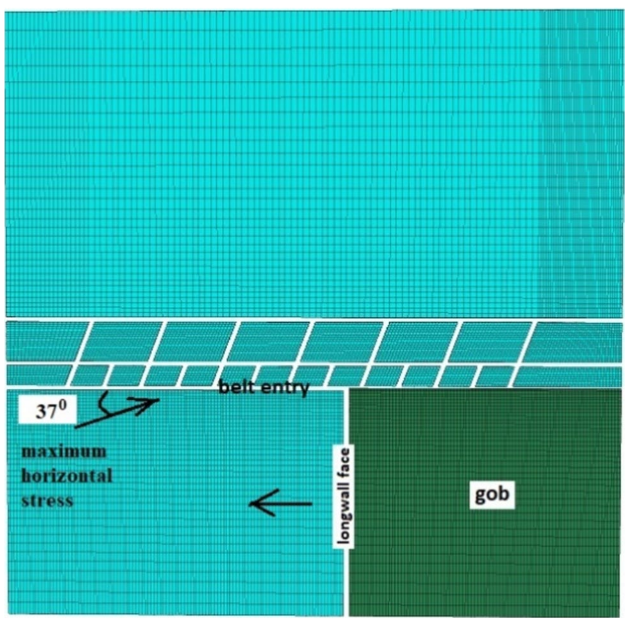

Fig. 10 Plan view of the FLAC3D model for panel A

Models were set up for both panel A and panel B to calculate longwall-induced stresses in the coal pillar and roof. Figure 11 shows the predicted vertical stress distribution at the coal seam horizon over the longwall headgate area for panel A. The predicted peak front and side abutment pressure is 20.1 MPa, about 3 times the overburden pressure. The predicted front abutment pressure influence zone in the belt entry extends to 30–46 m outby the face.

The three stress components in the horizontal plane at each HICell location were examined in the model. As the HICell was located in strong limestone roof 6 m above the roofline, the roof was not yielded at the HICell location. With the limestone horizon above the caving zone, it was anticipated that the longwall-induced horizontal stress changes would be relatively small. Figures 12 and 13 show predicted horizontal stress changes at the HICell locations in panel A and panel B, respectively. The horizontal stress changes are predicted to begin about 12 m outby the face. The predicted horizontal stress change across the entry and shear stress change shows a similar trend and magnitude with the measurements. The predicted horizontal stress change along the entry shows a similar stress increase at the intersections with the measurements. The model predicted stress changes at the HICell locations, which are generally in agreement with the measurements. The calibrated model was used to investigate stress changes at other locations.

As roof failure in the belt entry commonly occurs at the T-junction area, significant longwall-induced stress changes would occur in the immediate roof in this area. As shown in Fig. 14, the numerical model predicted horizontal stress concentration and relief factors at the belt entry corner on the panel side 2.4 m above the roofline within 43 m outby the face. The stresses at 2.4 m above the roofline are examined because this

Table 1 Rock properties used in the model

Rock type	Young's modulus, MPa	Poisson's ratio	Cohesion, MPa	Internal friction angle, degrees	Tensional strength, MPa
Coal	2,070	0.30	1.9	28	0.3
Claystone	2,900	0.3	1.9	28	0.3
Shale	11,600	0.25	11.7	35	4.5
Sandyshale	11,600	0.25	11.7	35	4.5
Sandstone	11,600	0.25	17.9	35	6.9
Limestone	17,400	0.22	15.9	35	6.1
Shaley limestone	17,400	0.22	14.5	38	5.9
Shaley sandstone	15,000	0.22	11.7	38	4.8
Siltyshale	11,600	0.25	11.7	32	4.2

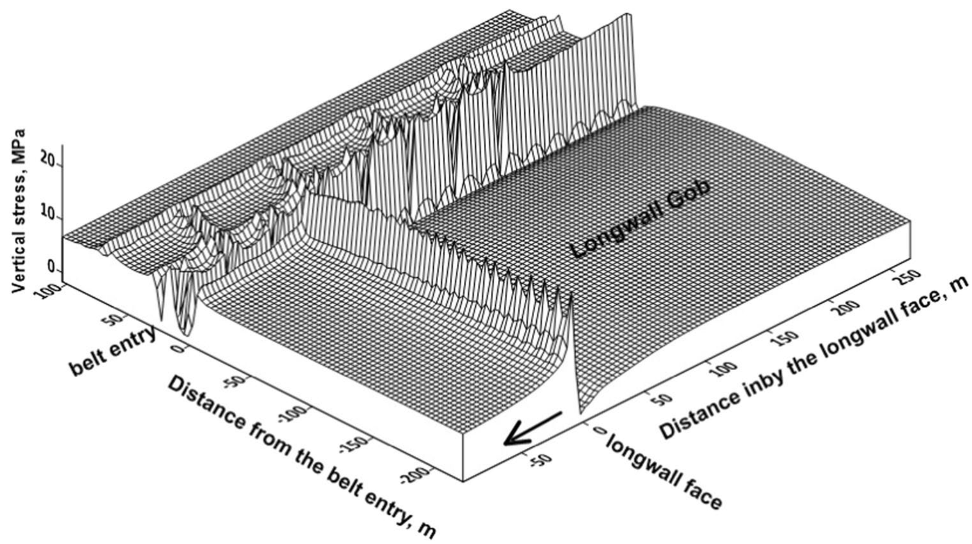

Fig. 11 Predicted vertical stress distribution at the coal seam horizon over the longwall headgate area for panel A

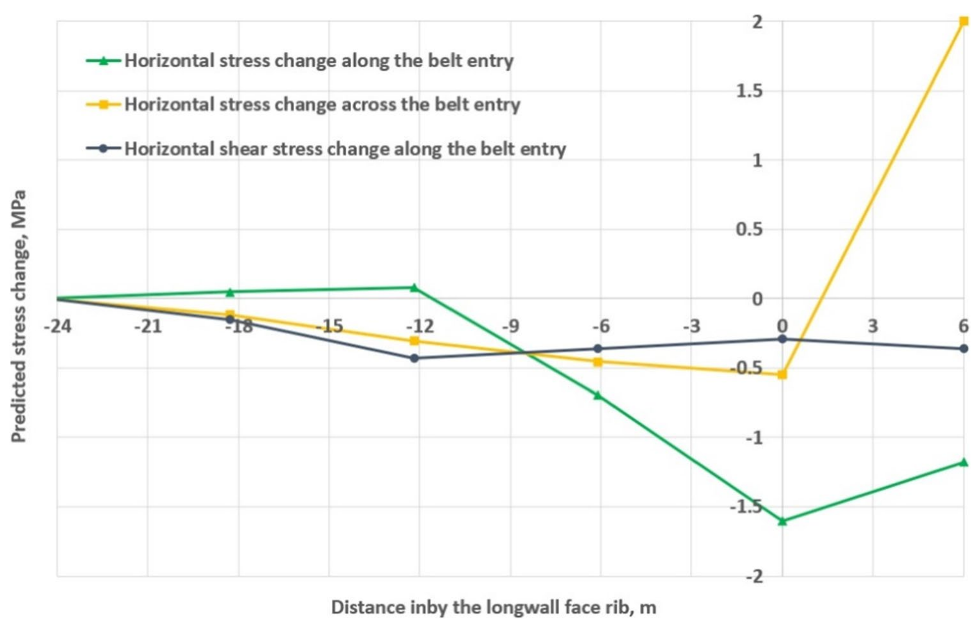

Fig. 12 Predicted stress change at the HICell 6 m above the roofline in panel A

horizon is just above the primary-bolted horizon, and the stability of the roof at this horizon is critical. In the model; the roof at the 2.4-m horizon outby the face is not yielded. Figure 14 shows that horizontal stress across the entry and horizontal shear stress along the entry concentrate within about 15 m outby the face, but horizontal stress along the entry relieves within about 15 m outby the face. At the T-junction area, the maximum shear stress concentration factor is about 2.0, and the maximum horizontal stress relief factor along the entry is about 0.6. The horizontal stress across the entry increases slightly with a concentration factor of about 1.1. Among the three stress components on the horizontal plane, the greatest stress change induced by longwall retreat is the shear stress, which would significantly change and rotate the principal stresses on the horizontal plane. The change of orientation and magnitude of the principal horizontal stresses is a major factor affecting roof stability in the belt entry.

5 Effect of High Horizontal Stress Change on Belt Entry Roof Stability

Experience in longwall mining in the Pittsburgh seam has showed that the roof in the belt entries is likely to fail in the form of cutters and roof sagging [3, 9], Lu et al., 2018; [14]. These failures generally occur in the belt entry in right-handed panels with weak immediate roof under high horizontal stress. Roof cutters are observed during longwall retreating in weak immediate roof, such as coal, claystone, and laminated shale or sandyshale. Although roof cutters can be seen in the crosscuts during development, they

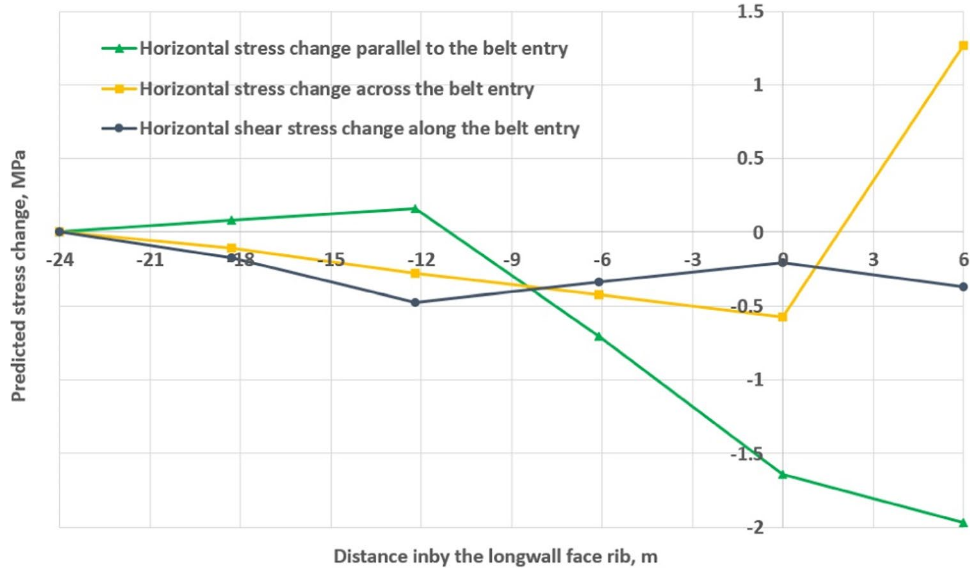

Fig. 13 Predicted stress change at the HICell 6 m above the roofline in panel B

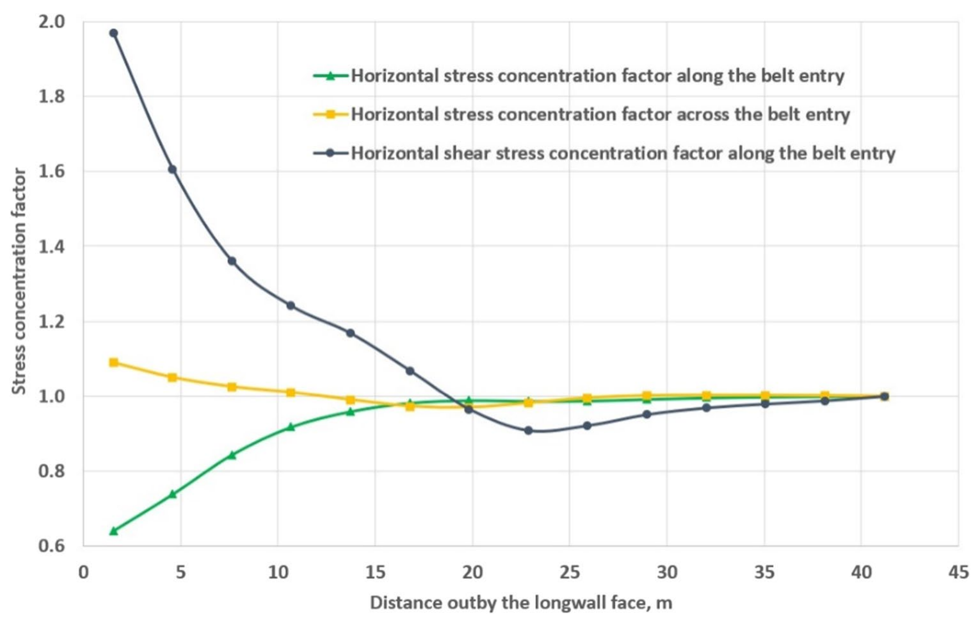

Fig. 14 Horizontal stress concentration and relief factors at the belt entry corner on the panel side 3 m outby the face rib

are rarely seen in the gate entries during development. During longwall retreating, cutters mostly develop at the entry corners at either the panel side or chain pillar side within about 15 m outby the face. Roof sagging normally develops around the entry center in weak immediate roof, and significant roof sag is an indication of roof failure above the primary bolts. Roof sagging may not lead to a roof fall if sufficient supplemental support is installed. But, if the sagging roof touches the stage loader, longwall mining has to be slowed down while the stage loader is pulled by a retriever. Time-dependent roof sagging sometimes causes the sagged roof to fall to the stage loader if retrieving is slow or unsuccessful. When roof cutters or sagging occur in a belt entry, unfavorable panel orientation in respect to maximum horizontal stress is always considered as a primary cause. This study focuses on the effect of longwall-induced horizontal stress changes on belt entry stability.

As derived from Fig. 14, longwall mining would induce principal horizontal stress changes in the belt entry roof outby the face. The difference between the two horizontal principal stresses, referred to as differential horizontal principal stress, can be used as an indicator for the degree of horizontal stress concentration. The differential horizontal stress is defined by Eq. (1):

$$\sigma_{diff} = \frac{1}{2}(\sigma_1 - \sigma_2) \tag{1}$$

where σ_1 and σ_2 are the major and minor horizontal principal stresses in the belt entry roof.

Clearly, the differential horizontal principal stress represents the maximum shear stress along a horizontal direction. In in situ conditions before mining, it is equal to half the difference between the major and minor horizontal stresses. Entry development would make it change slightly, but significant change occurs near the face as a result of longwall mining. As roof rock failure is generally caused by shear, the differential horizontal stress is a major stress component that affects roof stability.

Figure 15 shows differential horizontal principal stress 2.4 m above the roofline along the belt entry corner outby the face. This figure shows that the influence zone by the differential horizontal stress is within about 15 m outby the face, and the stress concentration factor is about 2 at the T-junction near the face. The figure also shows that the differential horizontal stress is higher on the panel side than on the chain pillar side. This approach to investigate the effect of horizontal stress on roof stability excludes the effect of abutment pressure. In fact, the stability of roof in the belt entry is affected by a combination of abutment pressure and horizontal stress, especially at intersections and under deep cover. However, considering that overburden depth does not appear to be an important factor when roof control problems are caused by high horizontal stress, this approach helps to isolate the effects of longwall-induced horizontal stress concentration near the face.

In this study, the longwall retreat direction with respect to major horizontal stress orientation dramatically affects the stability of the belt entry, as demonstrated by the roof falls described above. The roof falls occurred in the panels with $\phi = 35°$ and 37°, but no roof falls occurred in other panels with $\phi = 145°$ and 143°. With the established model for a right-handed panel with $\phi = 37°$, the model was also set up for a left-handed panel with $\phi = 143°$ to compare the difference in stress concentrations caused by longwall retreat. When the longwall panel is oriented to the opposite direction ($\phi = 143°$), the longwall-induced differential horizontal stress drops considerably. Figure 16 shows differential horizontal principal stress 2.4 m above the roofline along the belt entry corner outby the longwall face. The influence zone is still about 18 m outby the face, but the amount of differential horizontal stress reduces greatly, and the stress is mostly relieved. From the roof conditions observed in belt entries between right-handed panels and left-handed panels, the difference in the differential horizontal stress is the major reason why left-hand panels experience good roof conditions without roof cutters and sags.

To understand how panel orientation affects roof stability, the models for panel A were run for different panel orientations. The differential horizontal stress concentration factors were calculated at the T-junction corner on the panel side 2.4 m above the roofline and 3.0 m outby the face. Figure 19 shows differential horizontal stress concentration factors with different panel orientations. The horizontal stress concentration factors change with panel orientation with high stress concentrations at 20–110° and low stress concentrations at 130–180°. This trend is similar to the results obtained by Su and Hasenfus [11] by examining von Mises stress at the T-junction. But, when only the horizontal stress components are investigated, the effect of panel orientation on longwall-induced horizontal stress concentration becomes more apparent. The figure shows that the panel orientation represented by a right-handed or left-handed panel is not an exact indication of horizontal stress concentration or relief in the belt entry. As shown in Fig. 17, not all right-handed panels have high horizontal stress concentration, and not all left-handed panels show low horizontal stress concentration. Figure 19 also suggests that a longwall panel laid out along the major horizontal stress is not the optimal orientation because the orientation does not minimize the differential horizontal stress. The trend

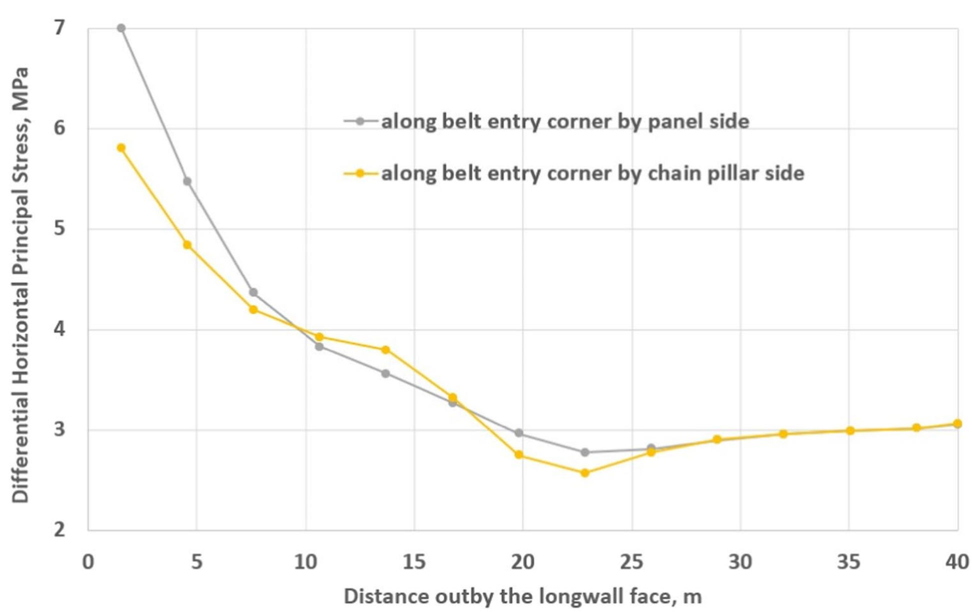

Fig. 15 Differential horizontal principal stress 2.4 m above the roofline along the belt entry corner

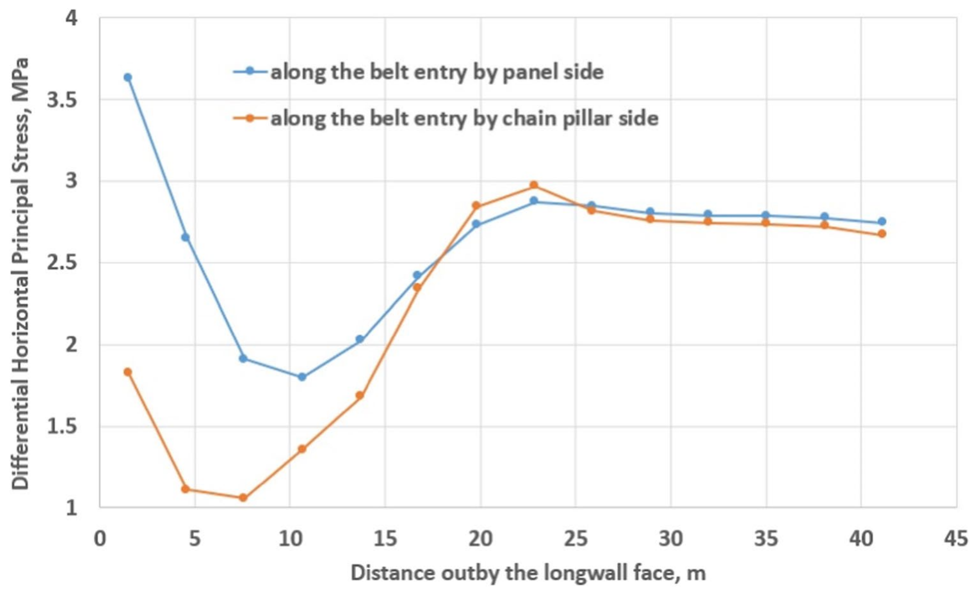

Fig. 16 Differential horizontal principal stress 2.4 m above the roofline along the belt entry corner outby the longwall face if the panel is oriented to the opposite direction

of horizontal stress influence at different panel orientations shown in the figure would apply to all the mining conditions in the Pittsburgh seam, except that the stress concentration factors would change with the magnitudes of in situ major and minor horizontal stresses. When the cases with roof falls and good roof conditions in the belt entry in the Pittsburgh seam are plotted in the figure, it shows roof falls occur at the high differential horizontal stress concentration factor of 1.9–2.4, and good roof conditions are experienced with the low stress concentration factor of 1.0–1.4.

6 Roof Support Strategies Associated with High Horizontal Stress in Belt Entries

In dealing with high horizontal stress, panel orientation and roof support are the keys to preventing roof falls in belt entries. Longwall panels should be oriented or sequenced, if possible, to direct major horizontal stress towards gob at an optimal angle with low horizontal stress concentration as shown in Fig. 17. As horizontal stress monitoring and numerical modeling results

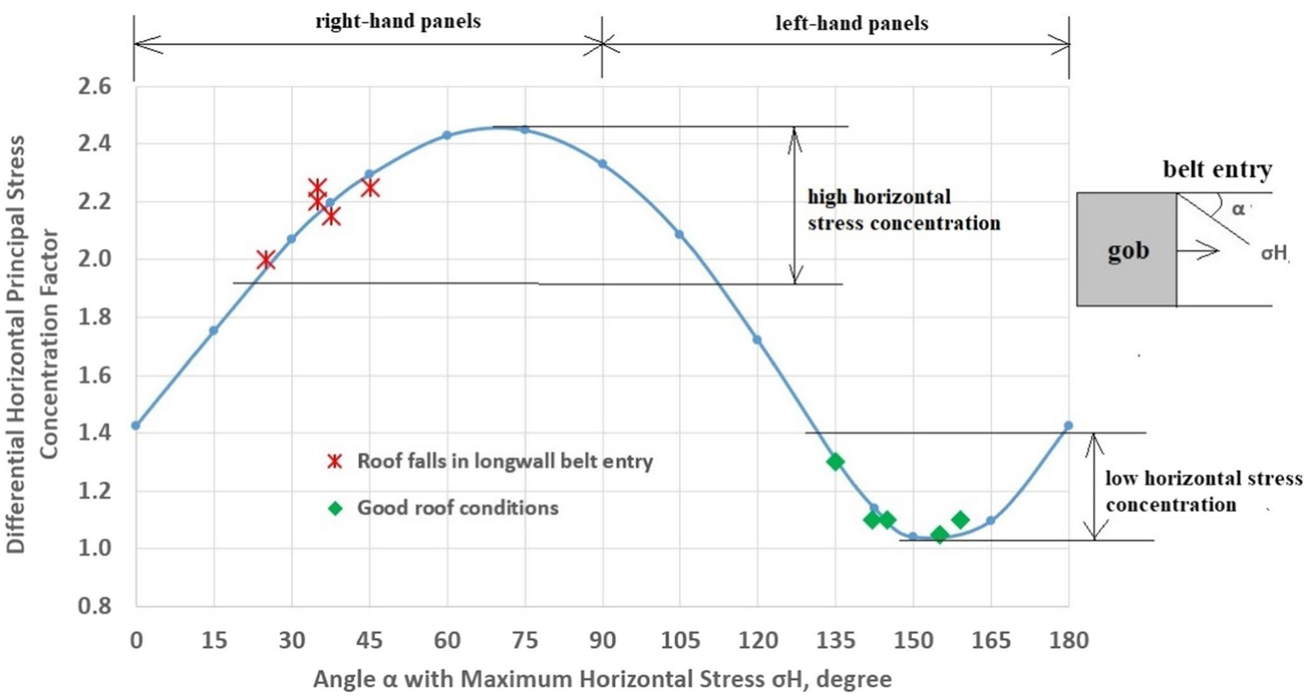

Fig. 17 Differential horizontal stress concentration factors with different panel orientations

show, the horizontal stress influence zone in the belt entry is within about 15 m outby the face. Even for weak roof that is susceptible to horizontal stress, poor roof conditions may not be experienced during development. The narrow space as well as hazardous conditions near the longwall face makes it difficult to install supplementary support when severe roof cutters or sagging occur. Therefore, for right-handed longwall panels, supplementary support should be installed during development in the weak roof. As the roof in intersections and mid-blocks are subjected to about the same level of horizontal stress, supplementary support should be considered in both intersections and mid-blocks under weak roof conditions.

Identifying weak roof is important for installing sufficient roof support. The following weak roof geology has been found to be problematic in causing ground control difficulties in the Pittsburgh seam (Su et al., 1995; [6, 7, 13], Lu et al., 2018, [14, 15]: (1) the presence of weaker units, such as claystone, rider coal, and slickensided shale in the immediate roof; (2) the presence of thinly laminated shale, sandyshale, or sandstone; (3) the presence of sand channel structures near the immediate roof; and (4) the presence of major shallow-cover stream valleys that may cause horizontal stress concentration and structural weakness under the valley bottom. Roof geology reconnaissance can be used to identify geologic anomalies by utilizing a combination of roof drilling data, geophysical logs, underground scoping, and mapping [10, 13]. Systematic roof scoping, strategically planned corehole exploration, and detailed in-mine geologic mapping greatly help with identifying risk areas and requirements for roof support [13].

Installation of supplemental roof support is critical to prevent potential roof falls in longwall belt entries. In using cable bolts as supplemental support, a proper anchorage horizon needs to be selected such that the cable bolts are firmly anchored in a stable roof. Strong roof like limestone, sandstone, or massive shale and sandyshale makes a good anchorage horizon. Cable bolts should be anchored at least 1.2 m into a solid roof. For weak roof, bolting patterns should be generally designed in suspension mode in which the cable bolts are assumed to take the dead weight load of the potentially failed roof under the anchorage horizon. Experience in the Pittsburgh seam has shown that cable bolts installed around the entry center are effective in resisting roof sagging and that cable bolts or fully grouted resin bolts installed near entry corners are effective in preventing roof cutters. If weak roof is broken or fractured at the surface, steel channels and meshes are effective measures for surface control.

7 Conclusions

The following conclusions are made based on horizontal stress monitoring in the belt entry in a longwall mine in the Pittsburgh seam, numerical modeling of stress changes in the longwall belt entry, and the experience of roof control in Pittsburgh seam longwall mines:

- Under the influence of high horizontal stress, the roof in the belt entry could fail in the form of cutters and sagging. Roof falls could occur at intersections and in mid-blocks and are mainly associated with weak roof and geologic anomalies.
- Horizontal stress monitoring in longwall belt entries has shown that longwall-induced stress changes mainly occur within about 12 m outby the face. Numerical modeling has shown a similar longwall-induced horizontal stress influence zone within about 15 m outby the face.
- Differential horizontal principal stress can be used as an indicator of horizontal stress concentration in belt entries. The horizontal stress concentration factors change with panel orientation with high stress concentration at 20–110° and low stress concentration at 130–180°. Roof falls occur at the high differential horizontal stress concentration factor of 1.9–2.4, and good roof conditions are experienced with the low stress concentration factor of 1.0–1.4.
- Optimal panel orientation is the first step to prevent roof falls in belt entries. For unfavorably oriented panels, supplementary support should be installed during development in the weak roof in both intersections and mid-blocks. In using cable bolts as supplementary support, the cables should be anchored into a stable roof horizon. For weak roof, the bolting pattern should be designed to cover both entry corners and entry center to prevent potential roof cutters and sagging.

Acknowledgements Data from this manuscript have been presented at the 41st International Conference on Ground Control in Mining, July 27–28, 2021.

Declarations

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

References

1. Chen J, Mishra M, Dubois G, DeMichiei J (1998) Effects of panel mining sequence and retreat direction on the roof stability of longwall headgate entries. In the Proceedings of the 17th International Conference on Ground Control in Mining, p 95–101
2. Esterhuizen GS, Mark C, Murphy MM (2010). Numerical model calibration for simulating coal pillars, gob and overburden

response. In the Proceedings of the 29th International Conference on Ground Control in Mining, p 1–12
3. Hasenfus GJ, Su DWH (2006) Horizontal stress and coal mines: twenty-five years of experience and perspective. In the Proceedings of the 25th International Conference on Ground Control in Mining, p 256–267
4. ITASCA. 2017. FLAC-3D, Version 6.0, User's Guide.
5. Mark C (1991) Horizontal stress and its effects on ground control. Min Eng 1991:1356–1360
6. Mark C, Mucho TP, Dolinar D (1998) Horizontal stress and longwall headgate ground control. Min Eng 1998:61–68
7. Mark C, Gale W, Oyler D, Chen J (2007) Case history of the response of a longwall entry subjected to concentrated horizontal stress. Int J Rock Mech Min Sci 44(2):210–221
8. Su DWH, Draskovich DJ, Thomas EP (2003). Pillar design and roof support for controlling longwall headgate subject to high horizontal stresses. In the Proceedings of the 22nd International Conference on Ground Control in Mining, p 1–10
9. Su DWH, Morris TJ, McCaffrey J (2002) Influence of structural stress concentration and structural irregularity on longwall gateroad roof control. In the Proceedings of the 21st International Conference on Ground Control in Mining, p 18–26
10. Su DWH, Thomas EP, Hasenfus GJ (1999) Roof geology mapping in underground coal mines. In the Proceedings of the 18th International Conference on Ground Control in Mining, p 1–10
11. Su DWH, Hasenfus GJ (1995) Regional horizontal stress and its effect on longwall mining in the Northern Appalachian coal field. In the Proceedings of the 14th International Conference on Ground Control in Mining, p 39–45
12. Tulu IB, Esterhuizen GS, Mohamed KM, Klemetti TM (2017). Verification of a calibrated longwall model with field measurements. In Proceedings of the 51st US Rock Mechanics/ Geomechanics Symposium, 25–28 June 2017. San Francisco
13. Van Dyke M, Lu J, Su DWH, Hasenfus G (2015) Transitional geology and its effects on development and longwall mining in the Pittsburgh Seam. In the Proceedings of the 34th International Conference on Ground Control in Mining, p 309–317
14. Zhang P, Gearhart D, Van Dyke M, Su D, Esterhuizen GS, Tulu B (2019) Ground response to high horizontal stresses during longwall retreat and its implications for longwall headgate support. Int J Min Sci Technol 29(1):27–33
15. Zhang P, Van Dyke M, Su D, Esterhuizen GS, Trackemas J (2018) Roof failure in longwall headgate – causes, risks, and prevention. In Proceedings of the 52nd US Rock Mechanics/Geomechanics Symposium, Seattle, Washington, June 17–20, 2018
16. Lu J, Hasenfus G (2019) Challenges of mining the first right-handed longwall panel in a new reserve block in Pittsburgh Seam. Int J Min Sci Technol 29(1):145–149
17. Gale W (2013) Update of stress concentration effects about longwall panels for improved mine planning. SCT operations, ACARP project C20031:103
18. Nemcik J, Gale W, Mills K (2005) Statistical analysis of underground stress measurements in Australian coal mines. Proc Bowen Basin Symp 117–122
19. NIOSH (2013) AHSM-analysis of horizontal stress effects in mining, version 2.4.04