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# Ground response to high horizontal stresses during longwall retreat and its implications for longwall headgate support

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## Abstract

Roof falls in longwall headgate can occur when weak roof and high horizontal stress are present. To prevent roof falls in the headgate under high horizontal stress, it is important to understand the ground response to high horizontal stress in the longwall headgate and the requirements for supplemental roof support. In this study, a longwall headgate under high horizontal stress was instrumented to monitor stress change in the pillars, deformations in the roof, and load in the cable bolts. The conditions in the headgate were monitored for about six months as the longwall face passed by the instrumented site. The roof behavior in the headgate near the face was carefully observed during longwall retreat. Numerical modeling was performed to correlate the modeling results with underground observation and instrumentation data and to quantify the effect of high horizontal stress on roof stability in the long-wall headgate. This paper discusses roof support requirements in the longwall headgate under high horizontal stress in regard to the pattern of supplemental cable bolts and the critical locations where additional supplemental support is necessary.

### Keywords

Longwall mining; Longwall headgate; High horizontal stress; Supplemental support

## 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 coal 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 could potentially cause injuries or fatalities. Rehabilitation of failed roof in



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the headgate would also expose miners to the risk of injuries. Roof falls in the headgate, though infrequent, mostly occur in the belt entry near the face. 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 [1–8]. Previous studies have demonstrated that 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 played an important role in the stability of a headgate.

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 horizontal stress. Mark, Mucho, and Dolinar 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 affected, to a large extent, by rock type, entry orientation, and longwall orientation [1]. The effects of horizontal stress can 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, and (3) horizontal stress concentration and relief depends on panel orientation, the direction of retreat, and the sequence of longwall panel extraction.

To prevent roof falls in the longwall headgate during longwall mining, it is important to understand how the ground responds to high horizontal stress and the related roof support requirements in the longwall headgate. This study focuses on the ground response in the headgate of a longwall panel under high horizontal stress in the Pittsburgh seam. The study is based on the observations, instrumentation, and numerical modeling of the headgate during longwall retreat. An instrumented site was chosen in the track entry of the longwall headgate to monitor stress changes in the pillars, deformations in the roof, and loading in the cable bolts during longwall retreat. Numerical modeling was performed to correlate the modeling results with underground observations and instrumentation data and to quantify the effect of high horizontal stress on roof stability in longwall headgate. Roof support requirements in the longwall headgate under high horizontal stress are discussed in regard to the pattern of supplemental cable bolts and the critical locations where additional supplemental support is necessary.

## 2. Description of the study site

This study involved a longwall mine in the Pittsburgh seam in northern West Virginia. The longwall panels in the mine were developed by three-entry systems oriented in approximately an east-west direction. Horizontal stress measurements in the adjacent longwall mines showed that the major horizontal stress orientation is about N70°E, and its magnitude is on average about three times that of the overburden stress. The longwall panel in this study was oriented at 30° to the major horizontal stress, and the headgate area is located in an area of concentrated horizontal stress. After a roof fall occurred in the belt entry, an instrumentation site was selected to monitor the loading in the pillars, deformation in the roof, and performance of the roof support.

Fig. 1 shows the panel layout and the instrumentation site. The longwall panel was 356.7 m wide, developed by 35 m by 42 m and 30.5 m by 83.4 center-to-center chain pillars and 4.9 entries. The immediate roof generally consisted of shale, rider coal, claystone, and sandstone or limestone, and the floor was claystone or shale. The coal seam was about 2 m thick, and a claystone layer of about 0.3 m was present on the top of the coal seam. The claystone was very weak and susceptible to weathering and was removed during development to make a 2.3 m entry height. The roof was primarily supported by three 2.7 m long and 22 mm diameter combination bolts with steel channels on 1.2 m spacing. Cable bolts of 3.7–4.9 m long and 15 mm were used for supplemental support. The belt entry and crosscuts were supported by two 2.7 m combination bolts as side bolts, 3.7 m cable bolts as center bolts with steel channels on 1.2 m spacing for primary support, and eight 3.7 m cable bolts at intersections for supplemental support. The #1 entry and track entry were supported by three 2.7 m combination bolts with steel channels on 1.2 m spacing for primary support and six 3.7 m cable bolts at intersections for supplemental support. The #1 entry and track entry were also supported by a single row of 9-point hardwood cribs on 3.0–3.7 m spacing installed inby the face during longwall retreat.

A roof fall occurred at an intersection in the belt entry after the face advanced about 610 m from the setup entry (Fig. 1). The roof fall was about 3.0–3.7 m high with a domed shape at the top. The fallen roof was claystone and shale with laminations. The intersection was supported by 3.7 m cable bolts for supplemental support. A 6.1 m scope hole at the intersection one block outby the roof fall showed a weak claystone layer above the primary-bolted horizon (Fig. 2). A geotechnical evaluation determined that the existence of a weak claystone layer in the immediate roof, high horizontal stress in the headgate area, and insufficient supplemental support contributed to the roof fall. An instrumentation site was then selected in the track entry to monitor the pillar loading, roof movements, and roof support performance (Fig. 3). The instruments included four cable bolt load cells to measure the load in the cable bolts, six borehole pressure cells to measure the stress change in the pillars, three 6-point roof extensometers to measure roof deformation, four convergence meters to measure crib convergence, and one multipoint borehole extensometer to measure the pillar expansion. Roof geology at the instrumentation site was obtained by a6.1 m scope hole as shown in Fig. 2. The instrumentation results are described in detail by Gearhart, Zhang, and Esterhuizen [9].

Observations of the roof conditions in the belt entry showed that roof cutters occurred within about 30.5 m outby the face with severe cutters mostly within 15.2 m outby the face. To prevent additional roof falls from occurring in the belt entry, two 4.9 m cable bolts with T-3 steel channels on 2.4 m spacing in mid-blocks and 1.2 m spacing at intersections were added in the belt entry outby the face after the first roof fall occurred. With additional roof support, the roof condition in the belt entry was significantly improved, even though roof cutters were still present at the entry corners in the belt entry near the face. When the face advanced about 305 m from the first roof fall, the face advancing rate reduced from about 6–9 to 1.5–3 m/day due to operational issues. With a slow advancing rate, the roof cutters propagated to 15–30 cm deep, and the roof sagged 8–10 cm within 15–30 m outby the face. The roof cutters and sagging later became so severe that a second roof fall occurred in the belt entry

near the face about 15 m inby the intersection corner (Fig. 1). Fig. 4 shows the roof condition outby the second roof fall in the belt entry.

## 3. Numerical model validation

Procedures have been developed by Tulu et al. and Esterhuizen, Mark, and Murphy to model ground response induced by longwall extraction and roof caving [10–12]. The modeling procedures produce realistic results of stress and deformation around the long-wall gateentry and chain pillars. The pillars, roof, floor, and overburden are modeled to achieve a full-scale, three-dimensional longwall model from the underground mining level to the surface. One advantage of the model is that it allows researchers to investigate not only the vertical stress distribution but also the horizontal stress distribution around the longwall panel.

With advancements in the FLAC3D program and newly developed gob model, a FLAC3D longwall model was set up based on the geological and mining conditions of the study panel [13]. The model included sufficient details to simulate the gateroad development and longwall retreating. The modeled overburden depth was 213 m. The headgate area, with a gob dimension of 183 m 305 m, was modeled to simulate a 357 m wide panel. Fig. 5 shows the 3-D view of the model at the coal seam level. The full-scale model extends 122 m below the coal seam and 213 m above the coal seam to the surface. The overburden strata was modeled by ubiquitous joint material, and the rock lithology in the overburden was obtained from the closest corehole to the instrumentation site. The roof geology in the immediate roof was obtained from the scope hole at the instrumentation site. Bedding planes between different rock types were modeled by interfaces. Table 1 shows the rock properties used in the model. The Mohr-Coulomb failure criterion was used for the coal pillar, immediate roof, and floor. The gob was modeled by strain-hardening material implemented by the FISH scripting language available in FLAC3D. The details about implementation of the gob material in FLAC3D can be found in Tulu et al. [10]. Horizontal stresses were applied to the model by a major and minor horizontal-to-vertical stress ratio of 3 and 2, respectively. The entire model consisted of about 1,000,000 elements and 62 interfaces.

Surface subsidence and measured vertical stress in the pillars were used for numerical model validation. To validate the numerical model for reasonable overburden movement, the surface subsidence predicted by the numerical model was compared to the surface subsidence predicted by an empirical subsidence model CISPM-W [14]. Fig. 6 shows the final surface subsidence profiles predicted by both the numerical and empirical models. By comparison, the surface subsidence predicted by the two models agrees reasonably well. Under a mining height of 2.3 m, both models predicted 1.5 m of maximum subsidence around the center of the panel and 6.1–9.1 cm of subsidence at the edge of the panel.

Fig. 7 shows the vertical stress distribution around the headgate area of the longwall panel under 213 m of overburden depth. The maximum abutment pressure is 13.1 MPa, about 2.5 times the vertical stress. The vertical pressure change in the pillars measured by borehole pressure cells (BPCs) are compared to the vertical stress in the pillars from the model. Fig. 8 shows the vertical stress distribution across the chain pillars when the instrumentation site is at a different position in respect to face location. The BPC readings are plotted in Fig. 8,

which shows that the measured pressure in the pillars fits well with the abutment pressure distributions obtained from the model.

## 4. Ground response to high horizontal stress in longwall headgate during longwall retreat

Longwall mining will induce vertical abutment pressure over the solid ground by the gob. At the same time, horizontal stress in the roof also changes as a result of a vertical stress increase as well as horizontal movement of the strata towards the gob. Both horizontal stress concentration and relaxation can occur in the headgate area near the face. The effect of high horizontal stress on roof stability is manifested by roof sagging around the center and roof cutters at the corners in the belt entry, as well as in the crosscuts near the face. The roof falls in longwall gate entries occur under different depth of cover and are more associated with horizontal stress than vertical stress [1,15]. Generally, the roof sagging around the entry center is related to the horizontal stress perpendicular to the entry, but roof cutters are caused by the shear stress around the entry corners.

The results of the instrumentation in the track entry in the study panel showed stress changes in the pillars, increased deformations in the roof, and increased loading in the cable bolts as the face passed by the site. The details of the instrumentation results can be found in Gearhart, Zhang, and Esterhuizen [9].

Observations of the roof behavior in the belt entry of the study panel showed that roof sagging occurred within about 15 m outby the face, and roof cutters occurred within about 15–30 m outby the face. The roof cutters became more severe when the face was within about 15 m approaching an intersection, but much less significant as soon as the face passed the intersection. Fig. 9 shows the cutters in the belt entry within about 15 m outby the face. Close observation underground saw minor roof sagging close to the face.

The horizontal stress change in the belt entry within 30 m outby the face is investigated in the numerical model. Fig. 10 shows the horizontal stress concentration and relief 3 m above the roofline along the belt entry. Fig. 10 clearly indicates a horizontal stress concentration perpendicular to the entry and relaxation parallel to the entry within 30 m ouby the face. The majority of the horizontal stress changes occur within about 15 m outby the face. Within 9 m outby the face, the horizontal stress increases by 10%–50% perpendicular to the entry but reduces by 20%–80% parallel to the entry. These horizontal stress changes make contributions to the roof instability of the belt entry as evidenced by the roof sagging and cutters that occurred in the study panel. The elevated horizontal stress perpendicular to the entry could result in roof sagging, whereas the relaxation of the horizontal stress along the entry could reduce confining pressure and induce tensile stress in the immediate roof. This unfavorable stress environment is present in the belt entry within 9 m ouby the face, where almost all the roof falls occurred during longwall retreating. Although the vertical stress is also concentrated in the area, roof falls seem more likely to occur where the horizontal stress is concentrated.

The shear stress in the belt entry within 30 m outby the face is also investigated in the numerical model. Mostly, shear failure in the form of roof cutters are observed at the entry corners 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).

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

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

As roof cutters are observed at the entry corner within about 1 m of the roofline in the belt entry, the octahedral shear stress at the same location is examined in the model. Fig. 11 shows the octahedral shear stress 1 m above the roofline in the belt entry corners. Fig. 11 shows that the octahedral shear stresses on both sides of the entry are elevated within 30 m outby the face with the majority of the shear stress increase occurring within 15 m outby the face. The extent of the shear stress increase from the model is strongly correlated with the extent and severity of roof cutters observed in the belt entry outby the face.

Roof cutters are also observed at the crosscut corners adjacent to the belt entry in the study panel. The cutters generally occurred in the crosscuts within 9–15 m of the belt entry when the face was within about 15 m from the intersection. The cutter at the inby corner was more severe than at the outby corner of the crosscut. Fig. 12 shows the cutter developed at the inby corner of the cross-cut. The octahedral shear stresses at the crosscut corners are examined in the model. Fig. 13 shows the octahedral shear stress along the length of the crosscut 1 m above the roofline when the face is 15 m from the intersection. Fig. 13 shows that the octahedral shear stresses on both sides of the crosscut increase within about 15 m from the belt entry, but the shear stress at the inby corner is higher than that at the outby corner of the crosscut. The extent of the shear stress increase from the model is also strongly correlated with the extent and severity of roof cutters observed in the cross-cuts of the study panel.

The horizontal stress change affects the stability of belt entry and its adjacent crosscuts much more than other entries and cross-cuts in the headgate. In the study panel, no roof sagging and cutters were observed in the track entry, #1 entry, and crosscuts outby the face. Although roof sagging was observed in the track entry inby the face, there were no roof problems in the entry with wood cribs set up inby the face.

The horizontal stress concentration and relief in the roof over the chain pillars at different face locations are obtained from the model. Fig. 14 shows horizontal stress concentration and relief 3 m in the roof over the chain pillars. Fig. 14 shows the horizontal stress changes both parallel and perpendicular to the gate entries. There is almost no horizontal stress change in the roof parallel to the panel retreat direction in the track entry and #1 entry. However, the horizontal stress in the roof perpendicular to the panel retreat direction relieves inby the face. The horizontal stress relief in the roof above the track entry is less than 5% at face location, but increases to about 10% 30 m inby the face. This may explain why the roof movements measured by the extensometers in the track entry at the instrumentation site were

greatly reduced when the face was 15 m outby the site. One possible reason is that the horizontal stress across the track entry began to relax 15 m inby the face, thus preventing further roof movements. The horizontal stress relief zone across the chain pillars is within 61 m from the gob edge. The #1 entry, which is 66 m away from the gob, is not influenced by horizontal stress change. It should be noted that the small horizontal stress peaks are caused by the effect of entry excavation.

## 5. Effect of longwall retreat direction on stress concentrations in longwall headgate

In the Pittsburgh seam, a longwall panel in east-west orientation, sequencing from south to north and retreating from east to west or sequencing from north to south and retreating from west to east, is subjected to high horizontal stress concentration in the headgate. Such a panel is called a right-handed panel. The right-hand denotes the retreat direction of the longwall face when approached from the belt entry.

In the longwall mines of the Pittsburgh seam, ground control challenges were mostly experienced in the right-handed panels [1,2,6–8]. The headgate-stress concentration was first quantified by Su and Hasenfus using three-dimensional finite element modeling [3]. It was found that when the angle $\phi$ is from 0° to 90°, the headgate is in a stress concentration with the worst case occurring at $\phi = 70°$ ($\phi$ is defined by an angle from the headgate outby direction counter-clockwise to the maximum horizontal stress orientation). The headgate is stress-relieved when $\phi$ is from 90° to 180°, with the best condition at $\phi = 160°$.

In this study mine, the longwall retreat direction with respect to major horizontal stress orientation dramatically affects the stability of the headgate. The roof falls occurred in the belt entry in the right-handed panels, but fewer problems were encountered in the left-handed panels under similar geologic conditions, and some left-handed panels were mined without supplemental cable bolts in the belt entry. To compare the difference in ground response between a right-handed panel and a left-handed panel under the geologic condition of the study panel, FLAC3D models were set up to model a right-handed panel with $\phi = 30°$ and a left-handed panel with $\phi = 150°$.

Fig. 15 shows the horizontal stress concentration 3 m above the roofline along the belt entry in the left-handed panel. Fig. 15 indicates that horizontal stress concentration perpendicular to the belt entry is significantly lower than in the right-handed panel.

Fig. 16 shows the octahedral shear stress 1 m above the roofline at the belt entry corner in a left-handed panel. The octahedral shear stress at the belt entry corner is also significantly lower than in the right-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 at the belt entry corners explains why cutters are more likely to occur in the belt entry in the right-handed panel.

## 6. Roof support in longwall headgate under high horizontal stress

The longwall headgate T-junction area is subjected to both abutment pressure and horizontal stress concentration, the influence zone of which is about 15–30 m outby the face. If a roof fall occurs in the longwall headgate, though infrequent, mostly it is in the belt entry. Besides weak roof geology, high horizontal stress concentration is an important factor that contributes to roof failures in longwall headgate.

In longwall headgate in the Pittsburgh coal bed, cutters and roof sagging are commonly observed 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 15–30 m 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, claystone, 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 and laminated immediate roof. Mostly roof sagging develops within about 15 m 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 excessive roof sagging is a sign of roof failure above the primary bolts. Roof sagging may not cause a roof fall if supplemental bolts are anchored in solid roof and provide sufficient support density.

The ground response to high horizontal stress implies that panel orientation and sequence, as well as supplemental support, are important in preventing roof falls in the longwall headgate. To minimize the effect of high horizontal stress, longwall panels should be oriented or sequenced to make major horizontal stress relax at the headgate if possible, and crosscuts should be developed at an optimal angle to the major horizontal stress.

Installation of supplemental roof support is crucial to prevent roof falls in the 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. Cable bolting has long been successfully used in the headgate with weak roof under high horizontal stress [1,2]. In using cable bolting as supplemental support, anchorage horizon and bolting pattern are 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. Roof scoping and monitoring with extensometers can help determine roof separations and good anchorage horizon with minimal roof deformation. Cable bolts should be anchored at least 1.2 m into the solid roof. The observations and numerical modeling has shown that the horizontal stress influence zone is mainly within about 15 m outby the face in the belt entry. To support the

weak roof under high horizontal stress, the priority of supplemental support should first be given to the belt entry 15 m inby and 9 m outby the intersections. Supplementary support should also be considered for the crosscuts within 15 m from the belt entry.

In using cable bolts for supplemental support in the longwall headgate, the bolting pattern should consider potential roof failure height and modes of roof failure under high stresses. For thinly laminated roof and slicken-sided roof, cable bolt pattern should be generally designed with suspension in which the cable bolts should be nearly 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 skin control.

Primary support is also important in resisting shearing of the immediate roof under high horizontal stress. Historically, longwall mines in the Pittsburgh seam used 2.4 m combination bolts as primary bolts, and bolt shearing occurred at the couplers due to roof shearing under high horizontal stress. In recent years, some long-wall mines have been using 1.8 m torque tension bolts as primary bolts to successfully eliminate coupler breaking [8]. Installation of additional bolts at the entry corners in the belt entry also help reduce cutters and maintain a safe walkway towards the face.

## 7. Conclusions

A few conclusions are derived from the observations, monitoring and numerical modeling of ground response to high horizontal stress in the longwall headgate in a Pittsburgh seam longwall mine:

1. Roof in longwall headgate could fail in the form of cutters and sagging under high horizontal stress. Roof falls in long-wall headgate could occur in the belt entry near the face and are mainly associated with weak roof geology and horizontal stress change.
2. A numerical model showed that the horizontal stress in the belt entry increases across the entry but relieves along the entry within about 30 m outby the face. The cutters in the belt entry near the face are associated with shear stress concentration at the entry corners within about 15–30 m outby the face. The model also showed that shear stress and horizontal stress across the entry in the belt entry within 15 m outby the face in a right-handed panel is significantly higher than in a left-handed panel.
3. The ground response to high horizontal stress in the long-wall headgate implies that panel orientation and sequencing are important in minimizing roof problems in the longwall headgate. To minimize the effect of high horizontal stress, longwall panels should be oriented or sequenced to make major horizontal stress relax at the headgate if possible, and crosscuts should be developed at an optimal angle to the major horizontal stress.

4. The impact of high horizontal stress on roof stability is mainly in the belt entry and the adjacent crosscuts. Installation of supplemental roof support is critical to prevent roof falls in the belt entry and adjacent crosscuts with weak roof geology under high horizontal stress concentration.

5. If cable bolts are selected for supplemental support, anchorage horizon and bolting pattern should be carefully designed in such a way that the cable bolts can nearly suspend the immediate roof up to the potential failure height. Horizontal and shear stress concentration in the belt entry implies that the priority of supplemental support should first be given to the roof in the belt entry 15 m inby and 9 m outby the intersections.

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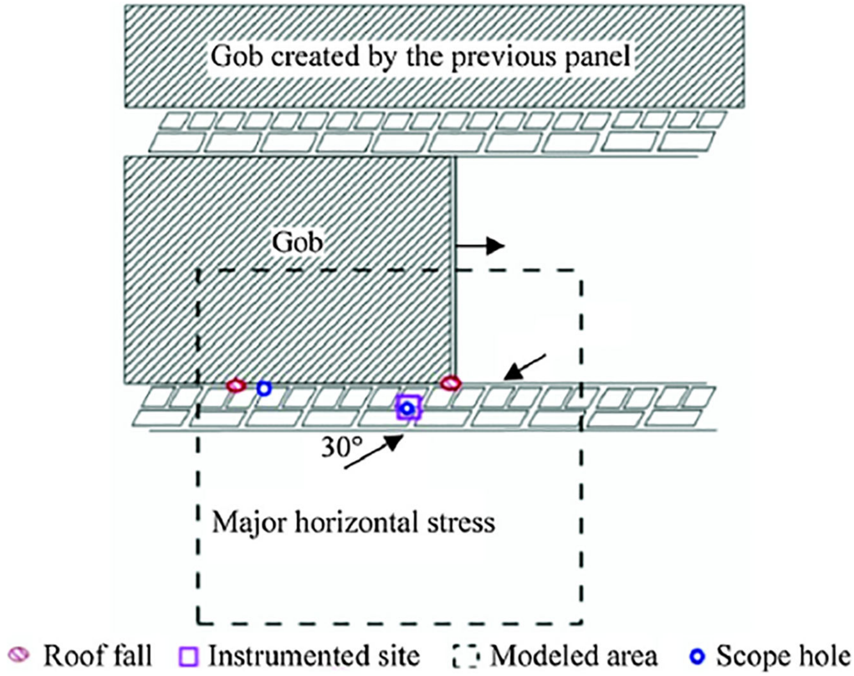


**Fig. 1.**
Panel layout and the instrumentation site.

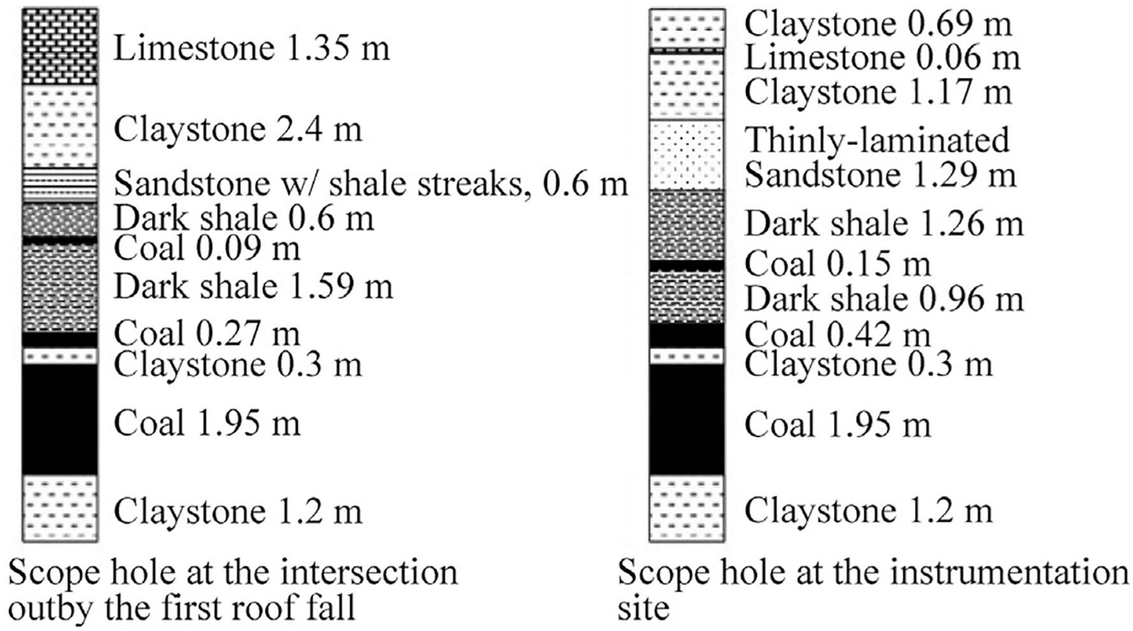


**Fig. 2.**
Geologic columns drawn with the scoping results.

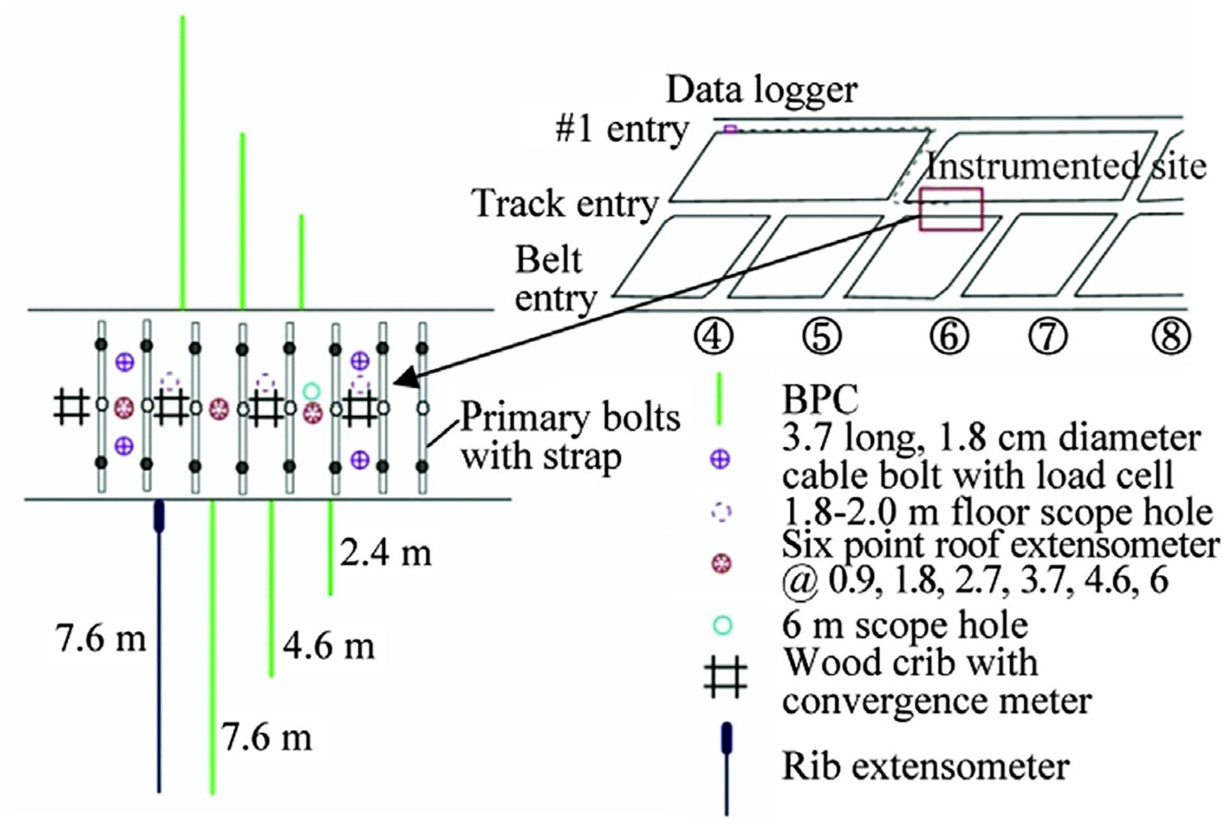


**Fig. 3.**
Instrumentation layout in the track entry.

**Fig. 4.**
Roof condition outby the second roof fall in the belt entry.

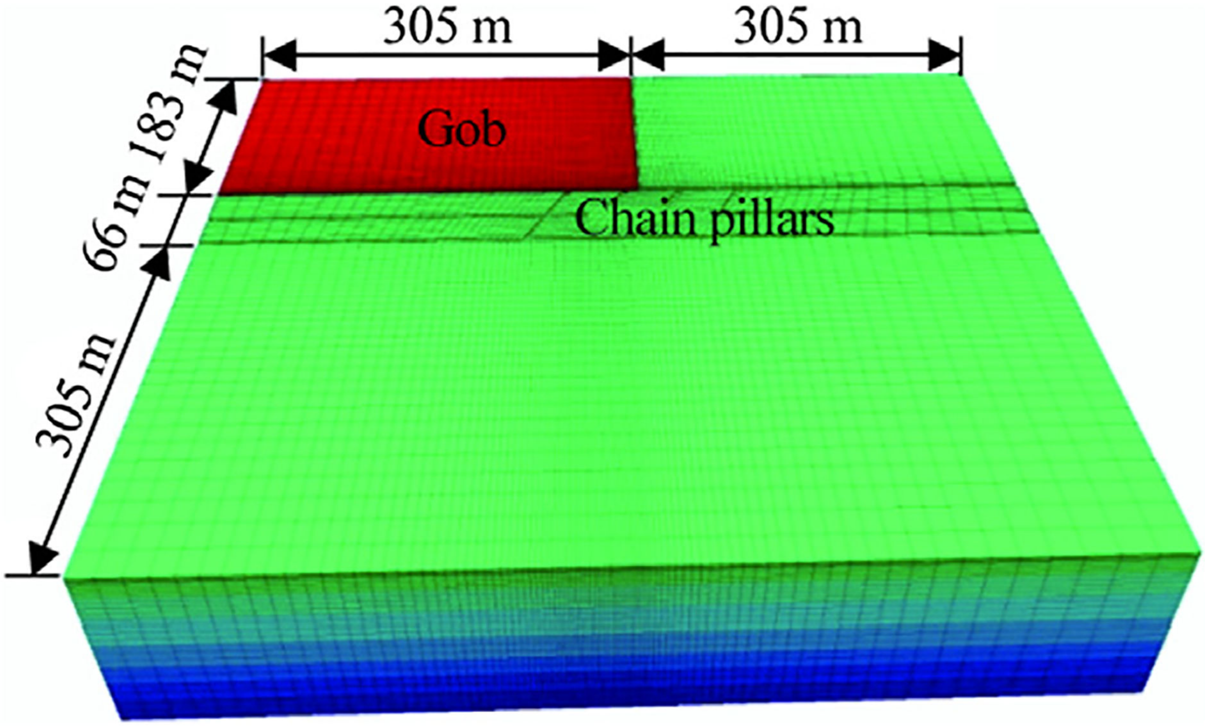


**Fig. 5.**
3D view of the model at the coal seam level.

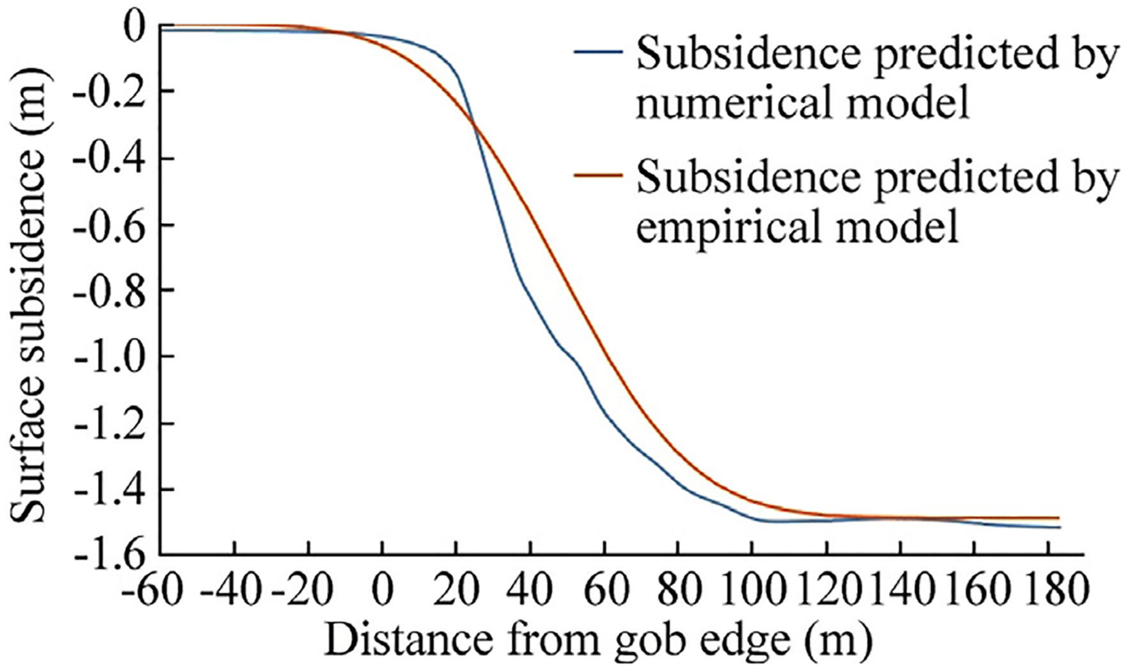


**Fig. 6.**
Surface subsidence predicted by numerical and empirical models.

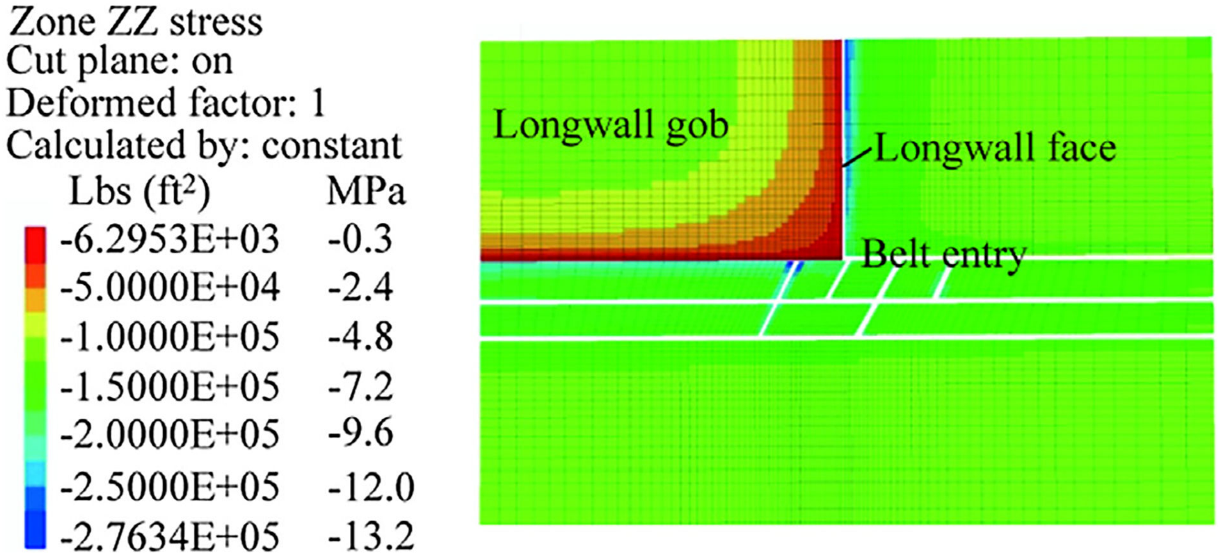


**Fig. 7.**

Vertical stress distribution over the headgate area.

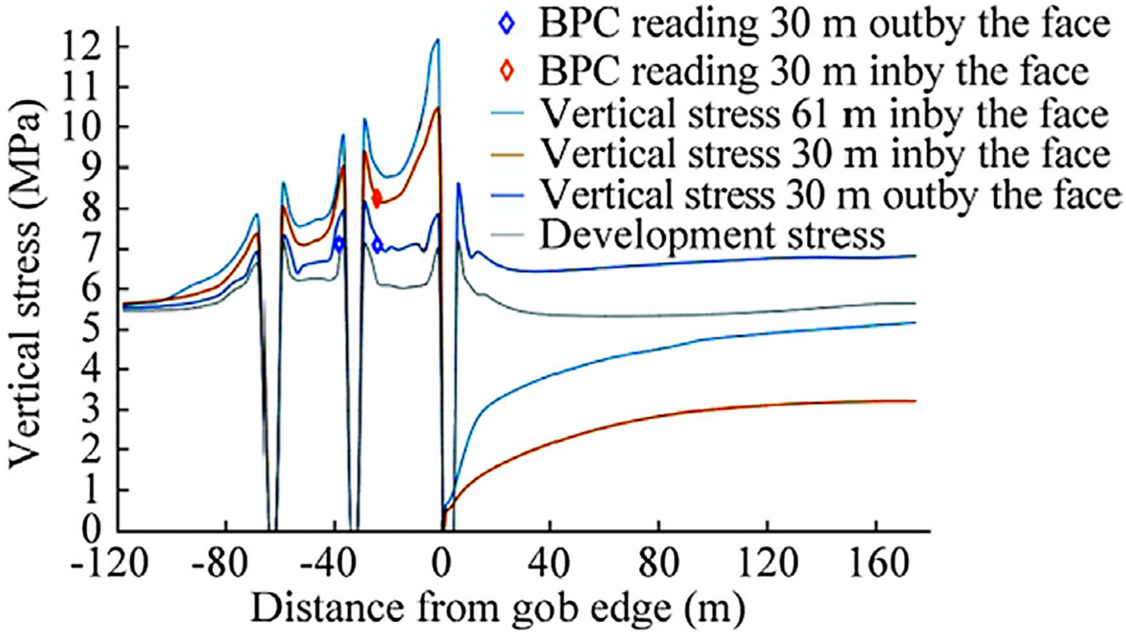


**Fig. 8.**
Vertical stress across the gate entries.

**Fig. 9.**
Cutters developed at entry corners near the face.

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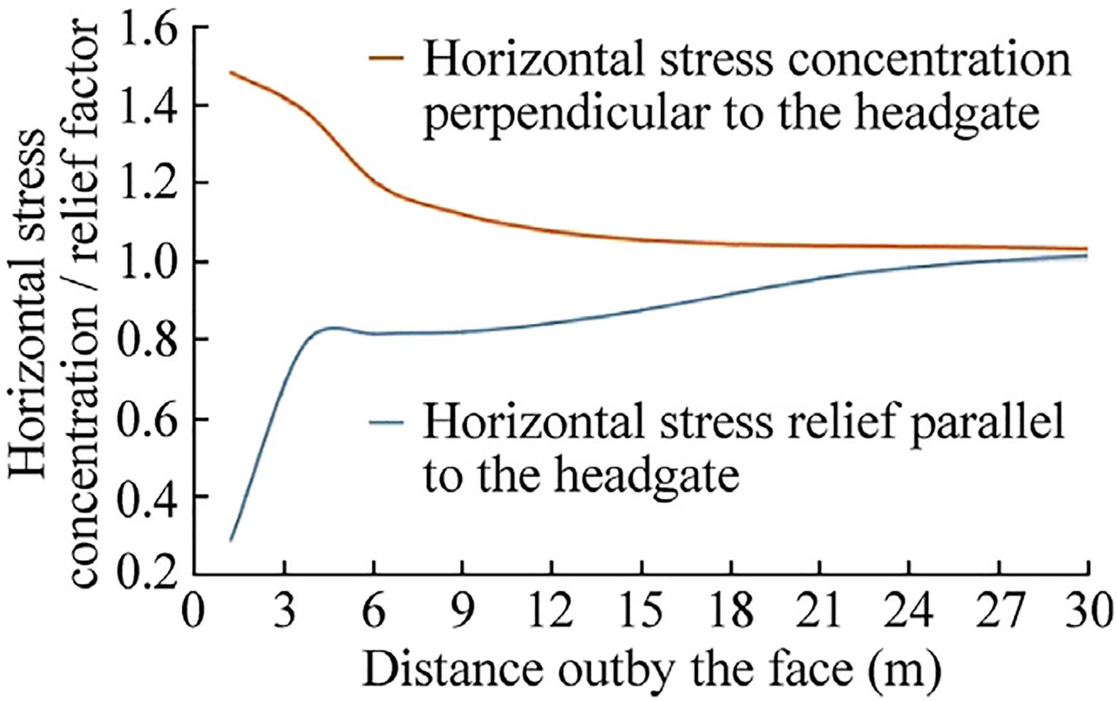


**Fig. 10.**

Horizontal stress concentration and relief along the belt entry 3 m above the roofline.

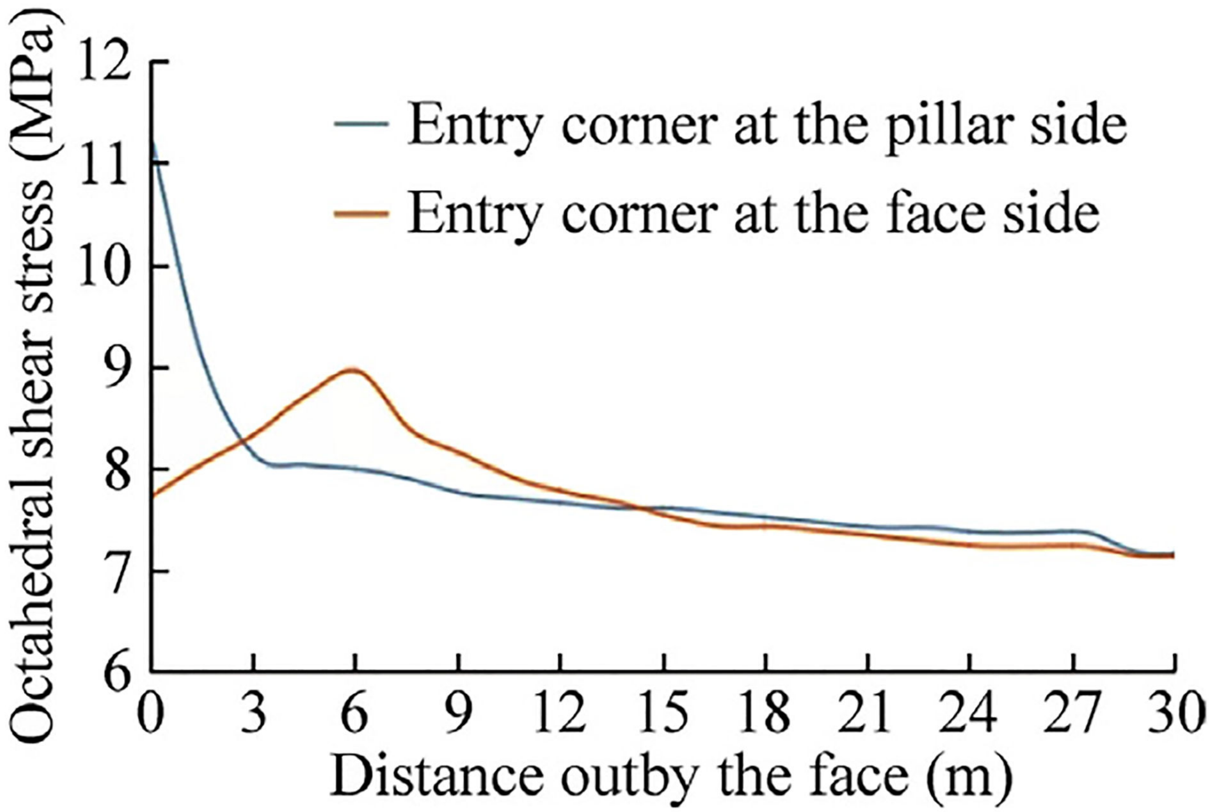


**Fig. 11.**
Octahedral shear stress at the belt entry corner 1 m above the roofline.

**Fig. 12.**
Cutter developed at the inby corner of the intersection.

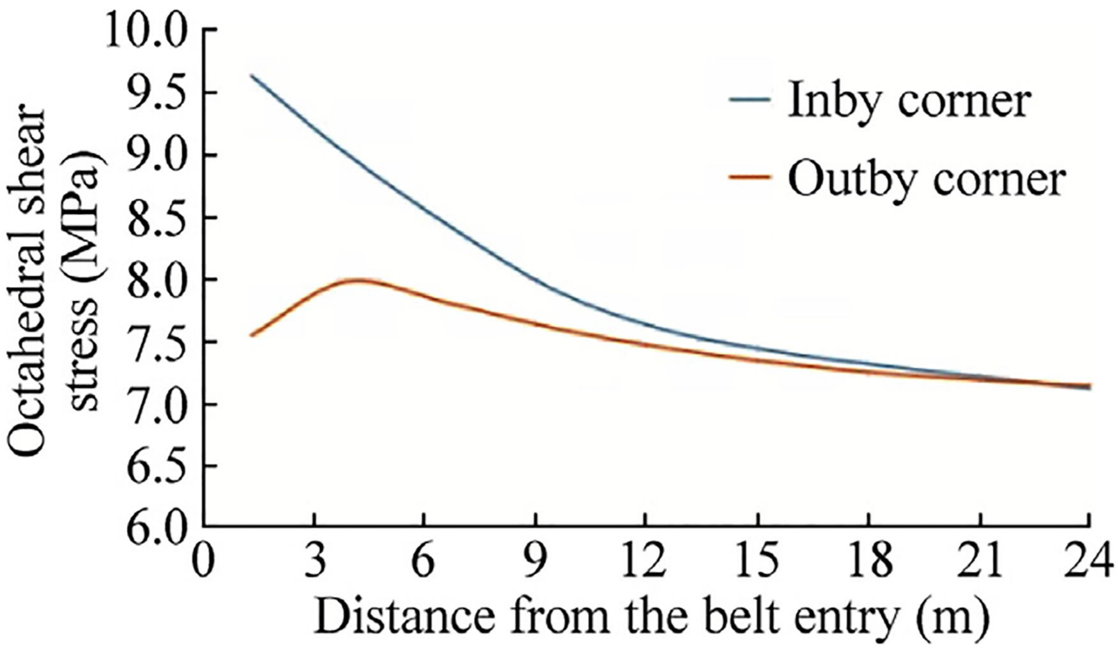


**Fig. 13.**
Octahedral shear stress along the length of the crosscut 1 m above the roofline when the face is 15 m from the intersection.

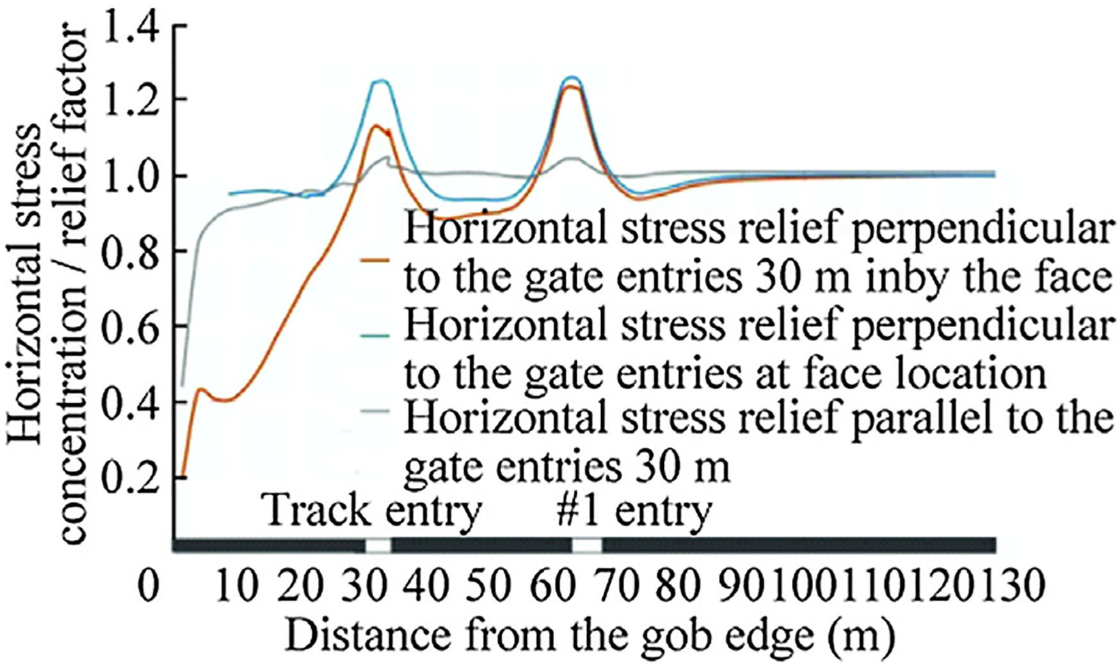


**Fig. 14.**
Horizontal stress concentration and relief factors over the chain pillars.

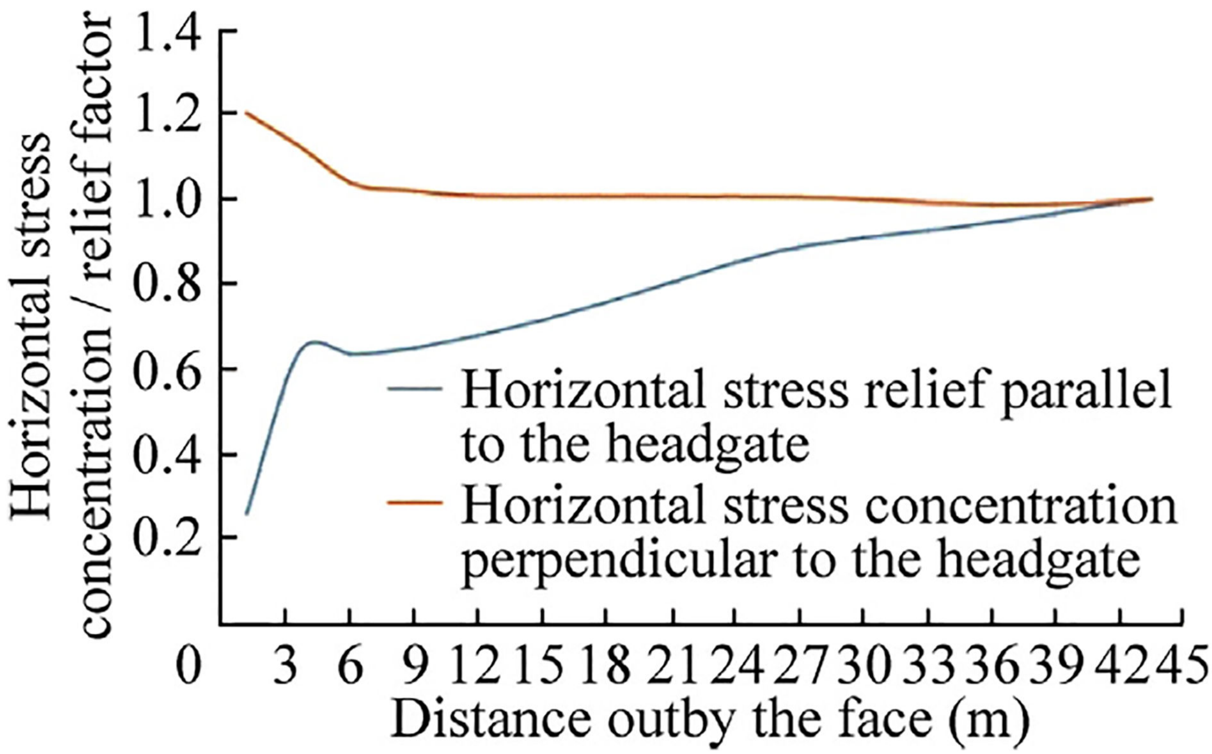


**Fig. 15.**
Horizontal stress concentration along the belt entry 3 m above the roofline in a left-handed panel.

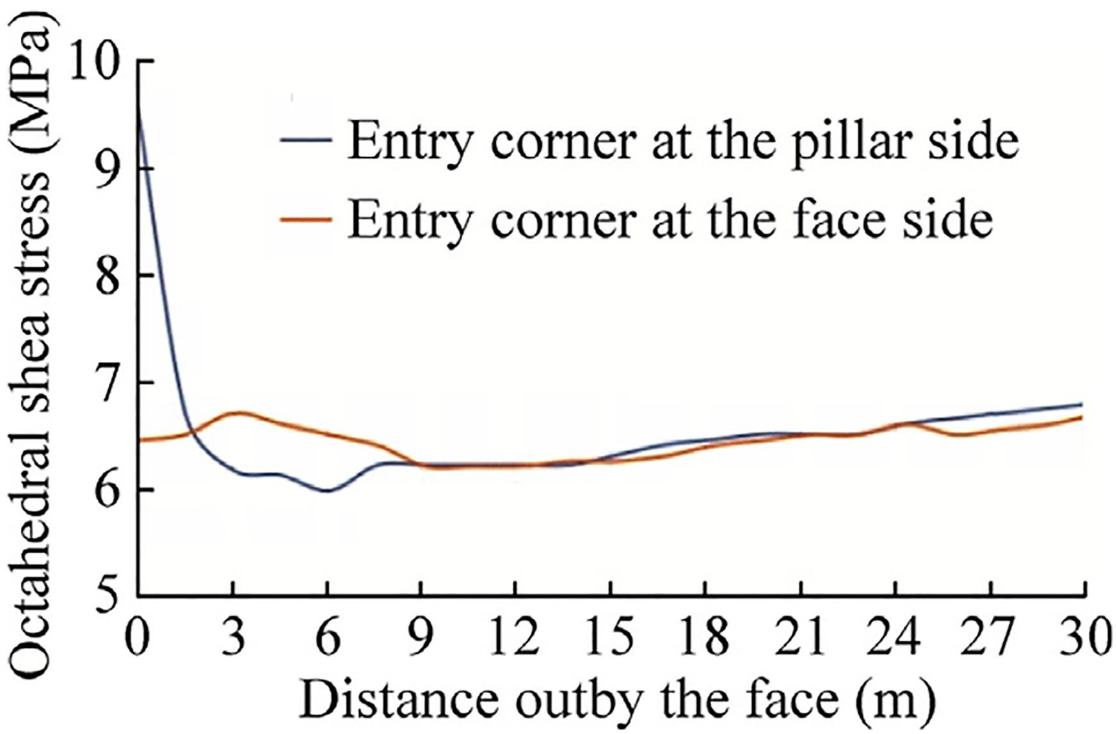


**Fig. 16.**
Octahedral shear stress at the belt entry corner 1 m above the roofline in a left-handed panel.

**Table 1**

Rock properties used in the model.

| Rock type | Young's modulus (MPa) | Poisson's ratio | Cohesion (MPa) | Internal friction angle (°) | Tensional strength (MPa) |
|---|---|---|---|---|---|
| Coal | 2483 | 0.35 | 1.86 | 28 | 0.28 |
| Claystone | 8690 | 0.3 | 5.17 | 30 | 1.79 |
| Shale | 11,586 | 0.25 | 11.72 | 35 | 4.50 |
| Sandyshale | 11,586 | 0.25 | 11.72 | 35 | 4.50 |
| Sandstone | 11,586 | 0.25 | 17.93 | 35 | 6.89 |
| Limestone | 17,379 | 0.22 | 15.93 | 35 | 6.12 |
| Shaley limestone | 17,379 | 0.22 | 14.48 | 38 | 5.94 |
| Shaley sandstone | 14,483 | 0.22 | 11.72 | 38 | 4.81 |
| Siltyshale | 11,586 | 0.25 | 11.72 | 32 | 4.23 |