Evolution of mining-induced stress in fully mechanized top-coal caving under high horizontal stress

Yuming Huo | Xuanmin Song | Zedong Sun | Zhonglun Wang | Haocheng Li

Key Laboratory of In-situ Property-improving Mining of Ministry of Education, Taiyuan University of Technology, Taiyuan, China

Correspondence
Xuanmin Song, Key Laboratory of In-situ Property-improving Mining of Ministry of Education, Taiyuan University of Technology, Taiyuan, China.
Email: xminsong@163.com

Funding information
Independent Research Projects of State Key Laboratory of Coal Resources and Safe Mining, CUMT, Grant/Award Number: SKLCRSM19KF019; National Natural Science Foundation of China, Grant/ Award Number: 51904200; Shanxi Applied Basic Research Programs, Science and Technology Foundation for Youths, Grant/ Award Number: 201901D211032; Scientific and Technological Innovation Programmes of Higher Education Institutions in Shanxi, Grant/Award Number: 2019L0183

Abstract
In fully mechanized top-coal caving (FMTC), the effects of coal caving are closely related to the degree of damage to the top-coal which is determined by the stress state therein. Therefore, research into the evolution of mining-induced stress field is key to understanding failure mechanisms of top-coal. By taking the 12 309 FMTC face in Wangjialing Coal Mine (China) as the engineering background and using field measurement and numerical simulation, we studied the evolution of the principal stress field in FMTC under high horizontal stress. The research results demonstrated that in situ stress in Wangjialing Coal Mine was a high horizontal stress and lateral pressure coefficients in the north-south and east-west directions were 1.52 and 0.45, respectively. Under the influence of mining, principal stresses were concentrated in front of the coal wall, with concentration factors of 2.26, 2.24, and 2.85, respectively. The minimum principal stress in unconstrained sides of the top-coal in the roof-control zone was tensile. The directions of intermediate and minimum principal stresses in the top-coal were more sensitive to the influence of mining compared to the maximum principal stress. During rotation of the principal stress direction in top-coal, the location (19 m in front of the coal wall) where the maximum and intermediate principal stresses were equal and the location of the coal wall are key positions.

KEYWORDS
coal mining, FMTC, high horizontal stress, numerical analysis, principal stress field

1 | INTRODUCTION

Since the technology of fully mechanized top-coal caving (FMTC) was first applied in the 1950s, with full development, it has become one of the landmark achievements in the field of coal mining in China, and been recognized around the world. The studies of basic theories of FMTC mainly focus on the relationship between supports and surrounding rock failure mechanisms of top-coal and top-coal caving. The studies of top-coal caving directly determine operational parameters of FMTC on site, and broken lumpiness of top-coal directly affects recovery of top-coal, while failure of top-coal is a mechanical response under mining-induced stress. Therefore, the evolution of mining-induced stresses is one of the key problems facing those studying basic theories of FMTC.

Relevant research on mining-induced stresses in FMTC is limited by the relative complexity of the mechanical properties of a coal mass, mining disturbance, and failure processes therein. In previous research, by taking Omerler...
Coal Mine in Turkey as background, a three-dimensional (3-d) numerical model was established by using FLAC3D numerical simulation software. Peak location and range of influence of advanced abutment pressure in an FMTC face were studied and compared with measured results. Based on actual measurement and research on advanced abutment pressure, a mechanical model of top-coal failure was established and the top-coal was divided into roof action layer, short beam structure layer, and support action layer. By numerical simulation and physical simulation, the evolution of mining-induced stresses in an FMTC face was analyzed, showing that stress shells (abstract shell-shaped zones) under a high stress were present in rock surrounding the working face. Moreover, the location and function of stress shells and the reason for their formation were analyzed. The coefficient $CN$ in the relationship between yield and caving was proposed. Furthermore, based on in situ stress state, Mohr-Coulomb/Hoek-Brown criteria, and mechanical behavior of strain-softening materials, yield and caving criteria for the top-coal in an FMTC face were established. By taking an FMTC face in Jingyuan Coal Mine, Gansu Province, China, as our engineering background, changes in the maximum principal stress and abundant pressure in top-coal were studied and analyzed through numerical simulation. In Qianqiu Coal Mine, Sanmenxia City, Henan Province, China, advanced abundant pressure in an FMTC face was studied and divided into the following four zones: initial compression and plastic deformation zone, intensive compression and damage zone, roof rotation zone, and shield support action zone. Furthermore, the magnitude and direction of the principal stresses around the stoping roadways caused by the traditional long-wall mining and fully mechanized caving were analyzed by employing numerical simulation with finite difference. By using a numerical simulation, the mining-induced stress field in fully mechanized caving of coal seams with different thicknesses was studied and main characteristics of stress evolution and danger zones were expounded. The range of influence and evolution of vertical stress were obtained through field measurement of vertical stress in the top-coal in Tashan Coal Mine, Shanxi Province. In addition, numerical simulation of the principal stress field in top-coal in fully mechanized caving faces adjacent to the gob was conducted and concentration and rotation of the principal stress axis during stoping were analyzed. Rotational characteristics of the principal stress direction in top-coal around the goaf were also studied.

In the research on mining-induced stress fields in FMTC, most scholars took fixed vertical and horizontal coordinate systems as the research space and simplified the mechanics to the case where the maximum principal stress is vertical and the intermediate principal stress equals the minimum principal stress. In that context, the evolution of vertical stress was paid more attention, while in situ stress states and intermediate principal stresses were ignored. The principal stress space can better describe the stress state of elements herein; therefore, by taking the 12 309 FMTC face in Wangjialing Coal Mine as our engineering background, we investigated the evolution of the principal stress field in top-coal in front of the working face under high horizontal stress (the maximum principal stress is nearly horizontal under this in situ stress state). The work involved analysis of the evolution of the magnitude of the principal stress and rotation of the direction thereof. The results of the study may provide a new idea for the study of the mechanism of top-coal failure in fully mechanized top-coal mining. Meanwhile, it provides a basis for the study on the basis of the principal stress field.
ENGINEERING BACKGROUND

2.1 General situation of the working face

In Wangjialing Coal Mine located in the south of Shanxi Province, the panel 12 309 lies in the west wing of the mine and is 260 m and 1320 m long along the working face and advancing direction of the working face, with average burial depth of 360 m. The coal seam has stable occurrence and a simple nearly horizontal structure and has an average thickness of 6.4 m. The location of the panel 12 309 is presented in Figure 1.

The stoping of 12 309 working face was realized using an FMTC process, with a mining height of 3.1 m and height of coal caving of 3.3 m, giving a caving ratio of 1:0.94. ZFY12000/23/34D two-leg top-coal caving hydraulic supports were used, with a rated working resistance of 12 000 kN. The setting load and coefficient of resistance increase separately were 9420 kN and 160 kN/mm. The general situations of overlying rock and floor strata in the working face are shown in Figure 2.

2.2 Measurement of in situ stress field

2.2.1 Test locations

Three stations for measuring in situ stress were selected at locations in the vicinity of the panel 12 309. Measuring stations 1 and 2 were located in tail gateway of the panel 12 305, separately 800 and 500 m from the throat. Moreover, station 3 was located in haulage gateway of the panel 12 306, 600 m from the throat. The locations of measuring stations are displayed in Figure 1.

2.2.2 Test method

By using 3-d hollow inclusion stress measurement, the in situ stress in Wangjialing Coal Mine was measured. Firstly, a drilling machine was used to drill a stress-relief hole with diameter of 130 mm at the measuring stations from the rib to a location unaffected by other disturbances except drilling (ie, to 1.25 times the width of the roadway). After grinding the bottom of the large hole, a concentric hole with a smaller diameter of 36 mm was drilled, thus passing through the point to be measured. An epoxy resin triaxial strain meter was installed in the small measuring hole, and when epoxy resin was fully cured after 24 hours, a coring bit with a diameter of 130 mm was used to relieve the stress in the core with the strain meter. Rock deformation during the stress-relief process could be detected and recorded by the strain gauges in different directions in the strain meter through a data acquisition unit. The method of the in situ stress measurement is displayed in Figure 3.

2.2.3 Test results

σ_x, σ_y, and σ_z represent the components of in situ stress along the south-north, east-west, and plumb-line directions, respectively; λ_x and λ_y indicate the lateral pressure coefficients along the south-north and east-west directions separately. The calculated test results are listed in Table 1.

According to the above results, the horizontal stress σ_X in the south-north direction was vertical to the advancing direction (the X-direction in the numerical model) of the working face and the mean value was 11.52 MPa. The horizontal stress σ_Y in the east-west direction was parallel to the advancing direction (the Y-direction in the numerical model) of the working face, and the mean value was 3.39 MPa. The mean value of vertical stress σ_Z was 7.58 MPa. Therefore, σ_X > σ_Y > σ_Z and lateral pressure coefficients were λ_X = σ_X/σ_Z = 1.52 and λ_Y = σ_Y/σ_Z = 0.45.

NUMERICAL SIMULATION

3.1 Numerical model

In accordance with geological overview of the 12 309 working face in Wangjialing Coal Mine, a FLAC3D numerical model was built with the directions along the working face and advancing direction of the working face as its X- and Y-axes. The total height was 83.24 m, and floor height of the coal seam was 30 m. Moreover, seven layers of overlying strata were established above the coal seam, while three layers of floor strata were built below the coal seam. The model was 400 m long in the X-direction (along the working face) and 300 m long in the Y-direction (advancing direction of the working face). There

![FIGURE 2 Schematic of geological column](image-url)
were 970,703 elements and 1,013,376 nodes used for calculation. The numerical model is illustrated in Figure 4.

### 3.2 Numerical simulation process

The numerical simulation process included three parts: inversion of the in situ stress field, excavation of the setup room and gateways, and stoping of the working face. Each part was excavated once and the calculation stopped when the maximum imbalance ratio converged to $10^{-5}$. The key parameters and methods for simulation are introduced as follows:

#### 3.2.1 Boundary conditions

**Stress boundary**

The overall height of the numerical model was 83.24 m, and the floor of the coal seam reached an elevation of 30 m of the numerical model; that is, the burial depth of the coal seam in the numerical model was 53.24 m. Owing to the average burial depth of the actual coal seam being 360 m, it was necessary to apply a weight equivalent to strata with a thickness of 306.76 m on the upper boundary of the model. Through the calculation based on average unit weight of the strata of 22 kN/m³, this stress was $\sigma_z' = 6.75$ MPa.

**Displacement boundary**

Displacement constraints in normal direction were applied on the front, rear, left, and right boundary surfaces of the numerical model, while full displacement constraint was applied on the bottom surface of the model.

| Station number | $\sigma_x$/MPa | $\sigma_y$/MPa | $\sigma_z$/MPa | $\lambda_x$ | $\lambda_y$ |
|----------------|----------------|----------------|----------------|------------|------------|
| 1              | 12.30          | 3.59           | 8.15           | 1.51       | 0.44       |
| 2              | 11.23          | 3.58           | 6.64           | 1.69       | 0.54       |
| 3              | 11.03          | 3.00           | 8.11           | 1.36       | 0.37       |
| Average        | 11.52          | 3.39           | 7.58           | 1.52       | 0.45       |

**Figure 3** Schematic diagram of the in situ stress measurement

| **Figure 4** Numerical model | **Table 1** Calculated test results |
|------------------------------|-----------------------------------|
3.2.2 Constitutive model and parameters

The numerical model was made of materials, such as coal and rock, so the FLAC 3D built-in Mohr-Coulomb constitutive model was selected: Parameters of each stratum in the numerical calculation are listed in Table 2.

3.2.3 Inversion of in situ stress

In order to ensure the reliability and accuracy of the numerical calculations, it is believed that to invert the in situ stress field of the numerical model based on the field measurement results is necessary, so that the inversion results and actual test results can correspond to each other. Therefore, the inversion of in situ stress field is an essential basis for testing the reliability of the numerical model. Based on measured in situ stresses, by setting lateral pressure coefficients in the X- and Y-directions in the numerical model to 1.52 and 0.45, the in situ stresses were inverted.

3.2.4 Simulation of the hydraulic support

In the numerical simulation, the hydraulic support was simulated through three stages: setting load, increasing resistance, and constant resistance. To extract the simulation nodes of the hydraulic support, different external forces were separately applied in different stages. The external forces applied in each stage were calculated using the following formulae:

\[ f_H = \begin{cases} f_{ini} + K \times S_H, & S_H < S' \\ f_{max}, & S_H \geq S' \end{cases} \]  \hspace{1cm} (1)

\[ S' = \frac{f_{max} - f_{ini}}{K} \]  \hspace{1cm} (2)

where, \( f_H \), \( f_{ini} \), and \( K \) represent the force (kN) on the simulated hydraulic supports, the setting load (kN) on the hydraulic supports, and the coefficient of resistance (kN/mm) of the hydraulic supports, respectively; \( S_H \), \( f_{max} \), and \( S' \), indicate the subsidence (mm) of the hydraulic supports, the rated working resistance (kN) of the hydraulic supports, and the subsidence (mm) of the hydraulic supports under their rated working resistance, respectively.

By employing the built-in FISH language of FLAC3D, subsidence of the hydraulic support was monitored at a regular interval of 50 time steps and the external forces were applied to the corresponding nodes according to Formulae (1) and (2) and as seen in Figure 5.

4 ANALYSIS OF SIMULATION RESULTS

The numerical simulation was conducted according to the aforementioned method. A horizontal section in the middle of the top-coal was selected and cloud pictures showing the evolution of principal stresses in different simulation stages were extracted, including the in situ stress stage, after excavation of the gateways, and after excavation of the working face.

In accordance with Figure 6, the inversion results of in situ stress show that the maximum principal stress, intermediate principal stress, and minimum principal stress are 11.88 MPa Figure 6A, 7.89 MPa Figure 6D, and 3.52 MPa Figure 6G, respectively. Correspondingly, the inversion results of lateral pressure coefficients are 1.51 and 0.45, respectively, which
are consistent with the measured results. Excavation of the gateways exerted significant influences on the principal stresses in the surrounding rock. By taking a change ratio >5% as the boundary, the range of influence of the maximum principal stress was 29 m Figure 6B. Moreover, the ranges of influence of the intermediate and minimum principal stresses separately were 57 m and 21 m Figure 6E,H). Therefore, it could be considered that the areas where the principal stresses in the top-coal in front of the working face were unaffected by the excavation of the gateways were 231, 203, and 239 m long Figure 6c,F,I). To study the influence of stoping on the evolution of the principal stress field in top-coal, a range covering 203 m and 100 m along the directions of working face and advancing direction of the working face of the top-coal was used as the research area, namely the red dotted area in Figure 6F.

4.1 Monitoring methods

In the above research area, five measurement lines, each with a length of 100 m, were arranged along the advancing direction of the working face and they were symmetrical relative to the middle line of the working face. The measurement lines were numbered C-1 to C-5 along the X-direction Figure 7.

4.2 Evolution of the magnitude of the principal stresses

By taking measurement line C-3 in the middle of the working face as an example, the evolution of the magnitude of the principal stresses was analyzed. By selecting the area within 30 m of line C-3, principal stresses were extracted every 1 m Figure 8.

The range of 0 to 5 m was roof-control zone for simulating the hydraulic support in the working face. In this zone, the principal stresses firstly increased linearly. In the zone within 1 m from the coal wall, due to the combined effects of the coal wall and the hydraulic support, the principal stresses decreased slightly and then increased. In this zone, σ1, σ2, and σ3 finally increased to 5.07, 3.04, and 1.22 MPa, respectively; σ1 and σ2 reached their peak at 9 m along the measuring line, while the peak value of σ3 was found at 11 m thereon. The peak values of σ1, σ2, and σ3 separately were 26.85, 17.68, and 10.05 MPa. According to the measured in situ stresses (11.88, 7.89, and 3.52 MPa, Figure 5, the concentration factors of the principal stresses in top-coal in the 12 309 working face were 2.26, 2.24, and 2.85, respectively. The peak values and principal stress concentration factors are summarized in Table 3.

At 24 m along the measuring line, the maximum principal stress was equal to the intermediate principal stress, that is, σ1 = σ2. The reason for this is as follows: under high horizontal in situ stress, due to the influence of advanced abundant pressure during stoping, stress on the top-coal in a vertical direction constantly increased, leading to rotation of the direction of the maximum principal stress.

Three principal stresses in elements at 0 m along the measuring line were extracted (where σ1 = 0.59 MPa, σ2 = 0.01 MPa, and σ3 = 0.03 MPa); that is, the maximum and intermediate principal stresses were compressive, while the minimum principal stress was tensile.

4.3 Rotational characteristics of the principal stress directions

4.3.1 Rotation of principal stress direction in top-coal

By extracting the azimuth angle of the principal stresses in the research area Figure 6F. A stereographic projection plot was drawn Figure 9A-C, D-F and G-I separately shows stereographic projection plots of the initial azimuth angles of the maximum, intermediate, and minimum principal stresses, azimuth angle after excavation of the gateways, and azimuth angle after stoping the working face.

Based on the results shown in Figure 8, after excavating the gateways in the model, each azimuth angle of the principal stresses in the research area was unchanged. After excavating the working face, the azimuth angle rotated, that is, excavation of the gateways had no influence on rotation of principal stresses in the research area.

4.3.2 Rotation of principal stress directions along the advancing direction of the working face

The better to express this rotation of principal stress directions in FMTC, principal stresses directions were extracted by taking measuring line C-3 as an example. Based thereon, changes in the angles between each principal stress direction and coordinate planes were drawn Figure 10: Figure 10A-C separately shows the angles of the maximum, intermediate, and minimum principal stresses, azimuth angle after excavation of the gateways, and azimuth angle after stoping the working face.

As displayed in Figure 10A, for measuring line C-3, under the in situ stress state, the direction of the maximum principal stress made an angle of 90° with the Y-Z plane and 0° with the X-Z and X-Y planes, which was consistent with the actual situation. From 25 m along the measuring line, the angles of the direction of the maximum principal stress with the three coordinate planes started to change. To be specific, from 23 to 25 m (σ1 = σ2 at 24 m), the angle of the direction of the maximum principal stress with the X-Y plane increased from
1.1° to 80.6°, while that with the X-Z plane increased from 0.2° to 9.3°, however, the angle with the Y-Z plane decreased from 88.9° to 1.3°. From 11 to 23 m (peak $\sigma_3$ at 11 m), the angle with the X-Y plane first increased slowly from 80.6° to 83.3° (at 16 m) and then decreased to 76.6°. The angle with the X-Z plane first slowly decreased from 9.3° to 6.7° (at 16 m) and then increased to 13.4°, while the angle with the Y-Z plane decreased to, and remained at, 0°. From 9 to 11 m (peak $\sigma_1$ and $\sigma_2$ at 9 m), the angle with the X-Y plane decreased from 76.6° to 64.6°, the angle with the X-Z plane increased from 13.4° to 25.4°, and that with the Y-Z plane remained stable at 0°. Furthermore, from 5 to 9 m (bottom coal wall at 5 m), the angle with the X-Y plane decreased from 64.6° to 60.6° (8 m) and remained stable within 2 m and then decreased to 49.7°. The angle with the X-Z plane first increased from 25.4° to 29.4° (8 m) and remained stable within 2 m and then increased to 40.3°. The angle with the Y-Z plane stabilized at 0°. From 0 to 5 m, namely within the roof-control zone with the hydraulic support, the angle with the X-Y plane first decreased from 49.7° to 37.8° (4 m) and then gradually increased to 77.9°. The angle with the X-Z plane first increased from 29.4° to 52.2° (4 m) and then gradually decreased to 12.1°.

As shown in Figure 10B, along line C-3, under the in situ stress state, the angle between the direction of the intermediate principal stress and the X-Y plane was 90°, while the angles with the X-Z and Y-Z planes were 0°, which coincided with the actual situation. From 77 m along the measuring line, the angles of the direction of the intermediate principal stress with the X-Y and X-Z planes began to change. From 25
1. The rotation range (25 m) of the direction of the maximum principal stress was smaller than those (77 m) of the directions of the intermediate and minimum principal stresses.

2. The location where the principal stress direction rotated was related to the magnitude of principal stresses, the in situ stress field, the location of the peak principal stresses, and the supporting resistance provided.

3. The support provided by the hydraulic support in the working face affected the rotation of the directions of the maximum and minimum principal stresses, while exerting no significant influence on the rotation of the direction of the intermediate principal stress. For the maximum and minimum principal stresses, similar conclusions were made as follows: the support provided by the hydraulic support in the working face exerted influences on their angles with the X-Y and X-Z planes within 1 m ahead of the coal wall, while it had little effect on the angle with the Y-Z plane.

### 4.3.3 Rotation of principal stress directions along the working face

The rotation of principal stress directions mainly occurred in, and beyond, the range with \( \sigma_1 = \sigma_2 \) (from 0 to 25 m along the measurement line). For the maximum and minimum principal stresses, the angles of their directions with the X-Y and X-Z planes were complementary. In the above analysis based on the simulation data of measuring line C-3, to study rotation of the principal stress directions at different locations in the along the working face, the rotation angles of principal stresses on all measuring lines in Figure 4 were extracted. Based on the analysis of rotation of principal stress directions on measuring line C-3, rotations of different principal stresses showed some interrelationship, therefore, when studying the rotation of principal stress directions at different locations on the working face, only the angles of the maximum principal stress with the X-Y and Z-Y planes along different measuring lines were investigated. As a result, the angles of the maximum principal stress with the X-Y and Y-Z planes from 0 to 23 m along each measuring line were extracted Figure 11A-B.

As shown in Figure 11A, the trends in the angles between the maximum principal stresses on each measuring line and the X-Y plane were similar and the angles recorded on each measuring line rotated from 0° from 23 to 25 m to the level shown in Figure 10A. From 10 to 23 m, the rotation angle of the maximum principal stress direction on line C-3 in the middle of the working face was larger, and rotation angles measured along lines C-2 and C-4 were similar, as were those obtained along C-1 and C-5, however, changes in the angles of the maximum principal stress with the X-Y plane measured along lines C-1 and C-5 evolved symmetrically on both sides of line C-3 with those recorded along lines C-2 and C-4, respectively. Along line C-3, we measured the largest rotation angle between the maximum principal stress and the X-Y plane.
plane, followed by those along lines C-2 and C-4, while lines C-1 and C-5 showed the smallest rotations. From 3 to 10 m, rotation curves of the maximum principal stress obtained from the five measuring lines overlapped. From 0 to 3 m, rotation curves plotted along lines C-2, C-3, and C-4 overlapped as did those along lines C-1 and C-5. Furthermore, rotation angles obtained along lines C-2, C-3, and C-4 were greater than those along lines C-1 and C-5.

As demonstrated in Figure 11B, the angles of the maximum principal stress on each measuring line (except for line C-3) with the \( Y-Z \) plane showed a similar trend, and rotation curves obtained from the lines C-1 and C-5 overlapped, as did those along C-2 and C-4. Differing from the characteristics whereby angles were unchanged on line C-3, the angles between the maximum principal stresses on the other four measurement lines and the \( Y-Z \) plane first decreased, then increased, and finally fluctuated. Owing to the fact that line C-3 was located on the mid-line of the advancing direction of the working face, the angle between the maximum principal stress and the \( Y-Z \) plane was unchanged at 0°, while measurements on the other four lines evolved symmetrically relative to line C-3. Moreover, the angle between the maximum principal stress and the \( Y-Z \) plane rotated to the mid-line on the advancing direction of the working face and the greater the distance from the mid-line, the greater the angle of rotation.
5 | DISCUSSION

5.1 | Research content

In previous research, many scholars have taken the vertical-horizontal coordinate system as the key evaluation criterion and ignored the effects of hydraulic supports and the intermediate principal stress. They focused on vertical stress and regarded the vertical stress as \( \sigma_1 \). Under a high horizontal stress, the direction of the maximum in situ stress in top-coal was nearly horizontal and the direction of the intermediate principal stress was nearly vertical. In the stoping of the working face, due to mining-induced stress, the intermediate principal stress gradually increased within a certain range, while the rate of increase in the vertical stress exceeded that of the horizontal stress. At a certain location, the vertical stress exceeded the horizontal stress, leading to rotation of principal stress directions from nearly horizontal to nearly vertical, thus deflecting the principal stress space in the top-coal. The deflection of the principal stress space has direct effects on the development trajectory of fractures in top-coal, so it is necessary to study the failure mechanisms of top-coal by exploring the evolution of the principal stress field.

5.2 | Magnitude of principal stresses

As presented in Figure 8, the evolution of the magnitude of the principal stresses was similar to previous research results. At the bottom coal wall, the decreasing trend in the principal stresses was caused by the influence resulting from the transition of the stress state of top-coal from being supported by bottom coal to being supported by the hydraulic support. The simulated results of magnitude of principal stress at 0 m along the middle measuring line were \( \sigma_1 = 0.59 \text{ MPa} \), \( \sigma_2 = 0.01 \text{ MPa} \), and \( \sigma_3 = -0.03 \text{ MPa} \), that is, the minimum principal stress at this measuring point was tensile. It is believed that the reason for the development of tensile stress is that the influence of hydraulic supports on the top-coal in the roof-control zone was considered in the present simulation. Owing to the measuring points being located in the elements to the rear of the hydraulic support Figure 12. Along the working face, both sides were constrained. The top-coal to the rear of the support was unconstrained along the advancing direction of the working face, therefore, under such conditions with a vertical stress applied with only one side being constrained, tensile stress was generated in the top-coal in the unconstrained side Figure 12A.
5.3 Rotation of principal stress directions

The simulated rotation of principal stress directions showed that principal stress directions were vertical and mutually orthogonal. By extracting and discussing data at characteristic intervals Figure 11A, the angle between the direction of the maximum principal stress and the X-Y plane changed linearly from 4 to 6 m (bottom coal wall at 5 m) and the rate of change was large. This was caused by the transition of top-coal from being supported by the bottom coal wall to being supported by the hydraulic support. The stoping of bottom coal and shifting of the hydraulic support changed the top-coal from being supported by the coal wall to being cooperatively supported by hydraulic supports and the coal wall. This state is an intermediate state, in which the top-coal changes from a single support state of the coal wall to a single support state of the hydraulic support during the fully mechanized mining process. Moreover, the support of the coal wall to the top-coal is passive, while the support of the hydraulic support to the top-coal is active. Therefore, the intermediate state has both active support and passive support, which leads to a significant change in the principal stress field in the top-coal. In the context, the top-coal was subjected to unloading and then loading: This resulted in the rotation of principal stress directions Figure 12.

6 CONCLUSION

The 12 309 working face of Wangjialing Coal Mine was used as our engineering background. Based on this, the evolution of the principal stress field in FMTC under high horizontal stress was studied through FLAC3D numerical simulation while considering factors, such as in situ stress and working resistance of the hydraulic support in the working face. The main conclusions are as follows:

1. The in situ stress around the working face was measured by 3-d hollow inclusion method. It was concluded that mean values of the stresses in the south-north, east-west, and plumb-line directions in the working face were 11.52, 3.39, and 7.58 MPa, and lateral pressure coefficients in the south-north and east-west directions were 1.52 and 0.45, respectively. Therefore, Wangjialing Coal Mine was under high horizontal stress.

2. Under high horizontal stress, due to influence of mining, the maximum principal stress was equal to the intermediate principal stress in top-coal at 24 m along the measuring line, that is, \( \sigma_1 = \sigma_2 \). Three principal stresses were concentrated in top-coal in front of the working face. The maximum and intermediate principal stresses were concentrated at 9 m along the measuring line, and the peak stresses were 28.65 and 17.68 MPa. The stress concentration factors were 2.26 and 2.24, respectively. The concentration of the minimum principal stress appeared at 11 m along the measuring line, with a peak stress of 10.05 MPa and a stress concentration factor of 2.85. Due to the working resistance of the support and imposed constraints on the working face along the working face, the minimum principal stress was tensile (at 0.03 MPa) in the unconstrained side of the top-coal in this roof-control zone.

3. In FMTC, rotation (77 m along the measuring line) of the directions of the intermediate and minimum principal stresses in top-coal occurred further away than that (25 m along the measuring line) of the maximum principal stress. This indicated that the intermediate and minimum principal stresses showed higher sensitivity to the influence of mining and rotation in the early stage (25 to 77 m) of face advance was reflected by the rotation toward the mid-line of the working face along the working face thereof.

4. The location (24 m along the measuring line) at which the maximum principal stress was equal to the intermediate principal stress and that of the coal wall (5 m along the measuring line) were key locations for rotation of principal stress directions in the top-coal. From 23 to 25 m, the principal stress rotated through 79.5° and its rotation angle reached 22.8° within the interval from 4 to 6 m. The supporting resistance of the hydraulic support had no effect on rotation of the direction of the intermediate principal stress in the top-coal, while the directions of the maximum and minimum principal stresses rotated through 40.1° under the influence of the support resistance provided.

ACKNOWLEDGMENT

This work is supported by Independent Research Projects of State Key Laboratory of Coal Resources and Safe Mining, CUMT (SKLCRSM19KF019), the National Natural Science Foundation of China (No. 51904200), Shanxi Applied Basic Research Programs, Science and Technology Foundation for Youths (No. 201901D211032), and Scientific and
Technological Innovation Programmes of Higher Education Institutions in Shanxi (No. 2019L0183).

NOMENCLATURE

- $\sigma_X$: Components of in situ stress along the south-north direction (MPa)
- $\sigma_Y$: Components of in situ stress along the east-west direction (MPa)
- $\sigma_X$: Components of in situ stress along the plumb-line (MPa)
- $\lambda_x$: Lateral pressure coefficients along the south-north direction
- $\lambda_y$: Lateral pressure coefficients along the east-west direction
- $\sigma'_Z$: Applied stress on the numerical model (MPa)
- $\rho$: Density of the stratum in the numerical calculation ($\text{t/m}^3$)
- $E$: Young's modulus of the stratum in the numerical calculation (GPa)
- $\mu$: Poisson’s ratio of the stratum in the numerical calculation
- $c$: Cohesion of the stratum in the numerical calculation (MPa)
- $\varphi$: Angle of internal friction of the stratum in the numerical calculation (°)
- $f_{H}$: Force on simulated hydraulic supports (kN)
- $f_{ini}$: Setting load on the hydraulic supports (kN)
- $K$: Coefficient of resistance of the hydraulic supports (kN/mm)
- $S_{H}$: Subsidence of the hydraulic supports (mm)
- $f_{\text{max}}$: Rated working resistance of the hydraulic supports (kN)
- $S'$: Subsidence of the hydraulic supports under their rated working resistance (mm)
- $\sigma_1$: Maximum principal stress (MPa)
- $\sigma_2$: Intermediate principal stress (MPa)
- $\sigma_3$: Minimum principal stress (MPa)
- $\sigma_{1\text{max}}$: Peak of maximum principal stress (MPa)
- $\sigma_{2\text{max}}$: Peak of intermediate principal stress (MPa)
- $\sigma_{3\text{max}}$: Peak of minimum principal stress (MPa)
- $f_C$: Supporting force from bottom coal to top-coal (kN)

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

ORCID

Yuming Huo [1] https://orcid.org/0000-0001-6130-2190
Zedong Sun [2] https://orcid.org/0000-0003-4952-8810

REFERENCES

1. Wang JC. Engineering practice and theoretical progress of top-coal caving mining technology in China. J Chin Coal Soc. 2018;43(01):43-51. https://doi.org/10.13225/j.cnki.jccs.2017.4101
2. Khanal M, Adhikary D, Balusu R. Prefeasibility study-Geotechnical studies for introducing longwall top coal caving in Indian mines. J Min Sci. 2014;50(4):719-732. https://doi.org/10.11144/ S1062739114040139
3. Onica I, Cozma E, Mihaiescu V (2013). Technical and economic optimization of the parameters of the top coal caving mining method in the Jiu Valley Basin, Geoconference on Science and Technologies in Geology, Exploration and Mining, Sgem 2013, Vol I, 749-756.
4. Vakili A, Heblewhite BK. A new cavability assessment criterion for LongwallTopCoalCaving. Int J Rock Mech Min Sci. 2010;47(8):1317-1329. https://doi.org/10.1016/j.ijrmms.2010.08.010
5. Klishin SV, Klishin VI, Opruk GY. Discrete element modeling of gravity flow of broken rocks in the technology of longwall top coal caving. International Scientific Conference Knowledge-Based Technologies in Development and Utilization of Mineral Resources; 2018:206. https://doi.org/10.1088/1755-1315/206/1/012007
6. Zhang S, Li DP, Ding EJ. Fuzzy signal processing of support pressure in sub-level caving face and controlling of breakage of top coal. Min Sci Technol. 2004;1:881-884. https://doi.org/10.1201/9780203022528.ch167
7. Zhang R, Ai T, Zhou HW, Ju Y, Zhang ZT. Fractal and volume characteristics of 3D mining-induced fractures under typical mining layouts. Environ Earth Sci. 2015;73(10):6069-6080. https://doi.org/10.1007/s12665-015-4376-9
8. Bai QS, Tu SH. A general review on longwall mining-induced fractures in near-face regions. Geofluids. 2019;2019:1–22. https://doi.org/10.1155/2019/3089292
9. Zhu DF, Tu SH, Ma HS, Zhang XW. A 3D Voronoi and subdivision model for calibration of rock properties. Modell Simul Mater Sci Eng. 2017;25(8):25. https://doi.org/10.1088/1361-651X/aa8f19
10. Bai QS, Tu SH, Wang FT. Characterizing the top coal cavability with hard stone band(s): insights from laboratory physical modeling. Rock Mech Rock Eng. 2019;52(5):1505-1521. https://doi.org/10.1007/s00603-018-1578-y
11. Yasitli NE, Unver B. 3D numerical modeling of longwall mining with top-coal caving. Int J Rock Mech Min Sci. 2005;42(2):219-235. https://doi.org/10.1016/j.ijrmms.2004.08.007
12. Hua N, Ying Z, Tao X. Research on sublevel coal's failure and displacement of extremely thick seam’s mining face. 3rd International Symposium on Modern Mining & Safety Technology Proceedings, 2008:79-82.
13. Xie GX, Chang JC, Yang K. Investigations into stress shell characteristics of surrounding rock in fully mechanized top-coal caving face. Int J Rock Mech Min Sci. 2009;46(1):172-181. https://doi.org/10.1016/j.ijrmms.2008.09.006
14. Xie GX, Yang K. Study on characteristics and control technology of mining induced stress shell in thick coal seam. In: Zegong L, Xinzhu H, Shujie Y, Guanglong D, Kicki J, Sobczyk EJ, eds. Mine Safety and Efficient Exploitation Facing Challenges of the 21st Century. Huainan, China: CRC Press-Taylor & Francis Group; 2010:7-14.
15. Yang K, Xie GX, Chang JC. Comparative analysis on mining-induced stress between in-situ observation and numerical simulation in deep mining. Rock Stress and Earthquakes. 2010:549-554.
16. Alehossein H, Poulsen BA. Stress analysis of longwall top coal caving. *Int J Rock Mech Min Sci*. 2010;47(1):30-41. https://doi.org/10.1016/j.ijrmms.2009.07.004

17. Miao SJ, Long C, Li Y, Wang SR. Numerical research on top coal movement, failure mechanism and supports’ stresses characters of fully mechanized top-coal caving in steep thick seam. In: Cai M, ed. *Rock Mechanics: Achievements and Ambitions*. Huainan, China: CRC Press-Taylor & Francis Group; 2012:973-976.

18. Nan H. The abutment pressure distribution of extremely thick seam top coal caving longwall panel: A case study. In: He X, Mitri H, Nie B, Wang Y, Ren TX, Chen W, Li X, eds. *Progress in Mine Safety Science and Engineering II*. Huainan, China: CRC Press-Taylor & Francis Group; 2014:827-829.

19. Basarir H, Oğe IF, Aydin O. Prediction of the stresses around main and tail gates during top coal caving by 3D numerical analysis. *Int J Rock Mech Min Sci*. 2015;76:88-97. https://doi.org/10.1016/j.ijrmms.2015.03.001

20. Yu B, Zhang R, Gao MZ, Li G, Zhang ZT, Liu QY. Numerical approach to the top coal caving process under different coal seam thicknesses. *Thermal Sci*. 2015;19(4):1423-1428. https://doi.org/10.2298/Tsci1504423y

21. Zhu DF, Song XM, Li HC, Liu ZH, Huo YM. Cooperative load-bearing characteristics of a pillar group and a gob pile in partially caved areas at shallow depth. *Energ Sci Eng*. 2019a;00:1-15. https://doi.org/10.1002/ese3.511

22. Xie J, Gao MZ, Zhang R, Li SW, Tan Q, Qiu ZQ. Lessons learnt from measurements of vertical pressure at a top coal mining face at Datong Tashan mines, China. *Rock Mech Rock Eng*. 2016;49(7):2977-2983. https://doi.org/10.1007/s00603-015-0856-1

23. Wang JC, Wang ZH, Yang SL. Stress analysis of longwall top-coal caving face adjacent to the gob. *Int J Min Reclam Environ*. 2019;2019:1-22. https://doi.org/10.1080/17480930.2019.1639007

24. Jiang LS, Kong P, Zhang PP, et al. Dynamic analysis of the rock burst potential of a longwall panel intersecting with a fault. *Rock Mech Rock Eng*. 2019. https://doi.org/10.1007/s00603-019-02004-2

25. Zhu DF, Tu SH. Mechanisms of support failure induced by repeated mining under gobs created by two-seam room mining and prevention measures. *Eng Fail Anal*. 2017;82:161-178. https://doi.org/10.1016/j.engfailanal.2017.08.029

26. Jiang LS, Kong P, Shu JM, Fan KG. Numerical analysis of support designs based on a case study of a longwall entry. *Rock Mech Rock Eng*. 2019;52(9):3373-3384. https://doi.org/10.1007/s00603-018-1728-2

27. Zhu DF, Tu SH, Ma HS, Wei HM, Li HC, Wang C. Modeling and calculating for the compaction characteristics of waste rock masses. *Int J Numer Anal Meth Geomech*. 2019b;43(1):257-271. https://doi.org/10.1002/nag.2862

28. Bai QS, Tu SH, Yuan Y, Wang FT. Back analysis of mining induced responses on the basis of goaf compaction theory. *Journal of China University of Mining & Technology*. 2013;42(03):355-361+369. https://doi.org/10.13247/j.cnki.jcumt.2013.03.005

How to cite this article: Huo Y, Song X, Sun Z, Wang Z, Li H. Evolution of mining-induced stress in fully mechanized top-coal caving under high horizontal stress. *Energy Sci Eng*. 2020;8:2203–2215. https://doi.org/10.1002/ese3.658