Floor heave mechanism in water-rich soft rock roadways and a DS-IBA control approach

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\textbf{ABSTRACT}
Severe floor heave in underground soft rock roadways heavily affects mine safety and production efficiency. In the present study, the context of the Shanghaimiao mining area is analyzed as the research object. In this regard, the floor heave mechanism and floor control in water-rich soft rock roadways are investigated through laboratory experiments, theoretical analysis, numerical simulation, and field tests. Moreover, a mechanical model of asymmetric floor heave is established. The obtained results reveal that: the main contributors to serious floor deformation in mining roadways are low rock stratum strength, hydrophysical behavior, and mining disturbance. It is found that the roadway floor stability is relevant to the stress concentration coefficient of the roadway side, the burial depth of the roadway, and the cohesion and internal friction angle of the floor rock. Meanwhile, the correlation between the upward resultant stress of the floor and the stress concentration coefficient of the roadway sides is established. Furthermore, the horizontal stress distribution of the roadway floor within 20 m of the advanced working face is simulated and analyzed. Based on the performed analyses and the obtained results, a novel double-seal deep and shallow inverted bottom arch (DS-IBA) floor support strategy is proposed. The proposed strategy is expected to provide a reference for dealing with similar water-rich soft rock roadways.

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\section*{1. Introduction}
The stability control of soft rock roadways is an enormous technical challenge that threatens mine production safety (Wang et al. 2019c; Perry et al. 2016; Xie et al. 2014). Since soft rock strata often contain rich clay minerals with developed fissures, they simply swell when exposed to water, thereby degrading the surrounding rock strength. When there is a mining disturbance, asymmetric heave often arises in the roadway floor (Xu et al. 2021; Wu et al. 2020; Wang et al. 2019d), which severely
affects mine ventilation, haulage, and health of miners. Accordingly, it is of great significance to investigate the instability of roadway floors and establish effective control strategies to improve mining safety and production efficiency (Aghababaei et al. 2016; Michael et al. 2016; Wang et al. 2019b).

Reviewing the literature indicates that the floor heave mechanism and surrounding rock control in soft rock roadways have been widely studied around the world. Kang (1993) and other authors (Jiang et al. 2004; Zhong et al. 2013; Bai et al. 2011; Guo et al. 2021; Mo et al. 2019) showed that the roadway floor heave may be attributed to the low floor strength and instability, which mainly originate from the influence of hydraulic effects and over-mining. Using beam theory, elastoplastic thin plate theory, and rheological theory, Zheng et al. (2014) and other authors (Sun and Wang 2011; Tsang and Tsang 2012; Hou 2017) established a mechanical model for the roadway floor and studied the ultimate bearing capacity, deformation of floor rock strata, and constraints on the floor heave in roadways. It was found that the roadway floor can be controlled by reinforcement, pressure relief, or combined support. He et al. (2013) presented a synergistic surrounding rock-support structure bearing system to control the composite soft rock floor heave. The established system was composed of an active support system coring around a constant resistance, a large deformation bolt-net-anchor coupling support, and grouted bolts. Wang et al. (2019a) successfully reduced roadway deformation and heave with a full-length anchor grouting approach. Furthermore, Ilinets et al. (2019) analyzed the roadway floor heave and found that floor heave can be reduced by cutting a relieve slot from two sides of the roadway. Li et al. (2006) effectively controlled the floor heave in a roadway through stress transfer, driving roadways in the floor of the chamber, and loose blasting in the bottom corner. Chang et al. (2020) effectively controlled the floor heave by combining over-break-backfill with a new support system. Recently, Zhang et al. (2021) presented a combined support system to avoid floor heave originating from the superimposition of static and dynamic loading.

In the Shanghaimiao mining area, the floor strata underlying the coal seams have low strength. When the strata are exposed to hydrophysical behavior or mining disturbance, floor heave with a maximum deformation of 1.2~1.5 m is prone to appear. The floor state does not improve even when bolt-net-anchor support and grouting control measures are used. This phenomenon severely threatens mining safety and production efficiency (Wen et al. 2019). In the present study, the asymmetric heave mechanism of the roadway floor is investigated through theoretical analysis and numerical simulation. Based on laboratory experiments and field tests, a new double seal deep and shallow inverted bottom arch (DS-IBA) floor support strategy is proposed. The performed analyses reveal that the proposed method is an effective scheme to keep the surrounding rock safe and stable.

2. Project background

2.1. Project description

Shanghaimiao mining area, production is primarily focused on coal #5. The coal seam of the 11508 working face is around 350 m deep underground, with an average
thickness of 2.6 m, an average dip angle of 8°. The seam has developed joints. To the east of the 11508 head roadway is the 11508 tail roadway under excavation. To the west is the 11504 goaf which is approximately 26 m away. To the north is the protective pillar of the mining area, the roadway location is shown in Figure 1. On top of coal#5 there is a 0.95 m mudstone pseudo roof. The immediate roof consists of 2.72 m siltstone. The main roof consists of 6.14–9.77 m fine sandstone (aquifer). The immediate floor consists of 0.9–1.2 m mudstone. The main floor consists of 4.3 m siltstone. Figure 2 shows the lithological column of the roof and floor strata of the coal seam.

2.2. Roadway floor failure

During mining operation, failure in the 11505 working face is manifested by compressive deformation at the shoulder, steel strip bending in the roof, and overall inward movement of the sidewall. Roadway floor heave, as the most serious floor heave with a maximum deformation of 1.2–1.5 m, heavily affects the normal advancement of the working face. Field survey and laboratory experiment have attributed roadway floor failure to the following factors:

1) Low support strength. In the original support scheme for the mining roadway of 11505 working face, roof is supported by Φ20 × 2800 mm high strength anchor bolts, while the sidewalls and inverted bottom arches are all supported by Φ20 × 2500 mm full thread anchor bolts, at a row spacing of 800 × 900 mm for both the roof and sidewall bolts and 700 × 900 mm for the floor bolts. Additional roof support is provided by Φ17.8 × 7000 mm mine anchor cables, installed in a group of 3 for odd numbers and 2 for even numbers, at the row spacing of 1600 × 2700 mm. Figure 3 shows the arrangement of the anchor bolts/cables. The roof of the roadway uses anchor cable as reinforcement support, while the side and floor only use anchor bolt support. At the same time, the roadway support is not specifically designed. As the overall support strength is low and no reinforcement is provided at the sidewall corner or other critical portions, the roof and sidewalls were locally deformed during mining operation, especially in the roadway floor, heavily affecting the normal production of the working face. Details are illustrated by Figure 3(a) (b) (e), and (f).
2) Surrounding rock properties. Table 1 gives the mineral composition of the rock sample from the floor stratum of coal 5#, yielded by X-ray diffraction experiment. Minerals in the floor stratum are primarily high expansibility substances like kaolin, illite, and smectite, which collectively contribute 53.3%. The floor rock is soft and easy to muddy. In particular, the soft rock floor composed of mudstone and siltstone contains expansive clay minerals that soften with water,

| Sampling site | Quartz | Kaolin | Illite | Smectite | Chlorite |
|---------------|-------|-------|-------|----------|---------|
| Floor         | 46.8  | 25.6  | 18.7  | 8.9      | —       |

Figure 2. Lithological column of roof and floor strata of the coal seam.

Figure 3. Roadway support diagram showing surrounding rock failure.

Table 1. Quantitative analysis of minerals in the samples.
showing obvious argillization. And disintegration with water, resulting in the loss of strength of the floor and produce strong expansibility (Malkowski et al. 2017).

Note: The table layout displayed in ‘Edit’ view is not how it will appear in the printed/pdf version. This html display is to enable content corrections to the table. To preview the printed/pdf presentation of the table, please view the ‘PDF’ tab.

3) Hydrophysical behavior. From the X-ray diffraction experiment of the samples, the floor rock is dominated by high expansibility substances that contribute 53.3%. The rock has low strength and swells, when exposed to water (Malkowski et al. 2022; He et al. 2019). Affected by external factors (e.g. excavation, bolt-net-anchor construction), fissures occurring in the roof run throughout the sandstone aquifer and expose the roof to water, as illustrated by Figure 3(d). They swelled and softened under the action of water, further deteriorating the strength of the floor surrounding rock (Shimamoto et al. 2020).

4) Mining disturbance. Due to the coupling of low overall support strength of the roadway, weak lithological strength of the floor stratum, and hydrophysical behavior, during mining operation, around 1 m thick of the mudstone of the sidewall bottom began to move inward as a whole, as illustrated by Figure 3(c). Compressed by the horizontal stress, the floor also heaved by as much as 1.2m–1.5 m, as illustrated by Figure 3(f).

From the analysis above, the roadway floor has low lithological strength and is dominated by high expansibility substances. When exposed to excavation and mining disturbance, fissures occurring in the roof run through the roof aquifer. Hydrophysical behavior in the roadway floor further deteriorated the surrounding rock strength of the floor, giving rise to roadway floor heave. As this heavily affects the normal production of the working face, it has to be repaired multiple times during mining operation. Hence it is necessary to investigate the deformation and failure mechanism of roadway floor and find a pertinent, effective means to control roadway floor heave.
3. Mechanical model of asymmetric floor heave

Figure 4 shows the along-dip vertical stress distribution within the advance of the working face. Affected by mining disturbance, the stress concentration is remarkably asymmetric—the stress concentration on the working side is remarkably larger than on the other side. A mechanical model of asymmetric floor heave is built, as shown in Figure 5. Here, average vertical stress \((K+1)\gamma H/2\) and \((K’+1)\gamma H/2\) represent the range of the floor stress rise zone induced by the roadway sides. \(K\) and \(K’\) are the horizontal stress concentration coefficient of the roadway sidewalls, \(K<K’\).

Affected by mining disturbance, the vertical stress is asymmetric between the roadway sides. The critical depth of rock movement in the left sidewall floor is \(h_1\), that in the right sidewall floor is \(h_2\). Under the vertical stress, the rock mass in the roadway floor will form an active pressure zone BCG and a passive pressure zone ABC, with BC as the ‘retaining wall’, to compress the ‘retaining wall’ BC, and an active pressure zone ADE and a passive pressure zone ADF, with AD as the ‘retaining wall’, to compress the ‘retaining wall’ AD. In the meantime, the roadway sides are also subjected to horizontal stress \(\sigma_1\) and \(\sigma_2\). This results in an active plastic slip for the rock mass in the active pressure zones BCG and ADE, and a passive plastic slip for the rock mass in the passive pressure zones ADF and ABC. As no movement space is available beneath CDH, the roadway floor is not supported during excavation and is actually ‘open’. When the stress exceeds the strength limit bearable by the rock mass in the roadway floor, the roadway floor will lift up to produce floor heave.

When the floor rock is in Rankine limit equilibrium, taking the rock mass of the left floor side of the roadway as an example, the stress analysis is carried out, the Rankine active slip angle is \(\alpha = 45^\circ - \varphi/2\); the Rankine passive slip angle is \(\beta = 45^\circ + \varphi/2\); \(\varphi\) is the internal angle of friction of the rock. Then the stress acting on point C is written as:

\[
F_a = \left(\gamma h_1 + \frac{K+1}{2} \gamma H\right)\tan^2\alpha - 2c\tan\alpha
\]  
\[
F_b = \gamma h_1 \tan^2\beta - 2c\tan\beta
\]

where: \(\gamma\) is the gravity density of the rock stratum, kN/m\(^3\); \(H\) is the depth of the coal seam, m; \(K\) is the stress concentration coefficient; \(c\) is the cohesion.
When the active pressure $F_a$ acting on the critical plane BC is larger than the passive pressure $F_b$, the critical interface BC is compressed and is subjected to horizontal stress $r_1$; the resultant stress $F$ of $F_a$, $F_b$ and $r_1$ will be the stress source of the movement of the ABC rock mass. Then the resultant stress $F$ is written as:

$$F = F_a - F_b + \sigma_1 = \gamma h_1 (\tan^2 \alpha - \tan^2 \beta) + \frac{K + 1}{2} \gamma H \tan^2 \alpha - 2c(\tan \alpha - \tan \beta) + \sigma_1$$ \hspace{1cm} (3)

If the resultant stress is decomposed along the AC plane, the component stress along the AC plane is $f_1$; that perpendicular to the AC plane is $f_2$. Then $f_1$ and $f_2$ are written as:

$$f_1 = F \sin \alpha$$ \hspace{1cm} (4)

$$f_2 = F \sin \beta$$ \hspace{1cm} (5)

During rock movement, the action of the pressure $f_2$ perpendicular to the AC plane will produce friction $f_3$ on the AC plane:

$$f_3 = F \sin \beta \tan \varphi$$ \hspace{1cm} (6)

The resultant stress $S$ on the AC plane is written as:

$$S = f_1 - f_3 = F (\sin \alpha - \sin \beta \tan \varphi)$$ \hspace{1cm} (7)

Similarly, we can yield the resultant stress $S'$ along the DF plane on the right roadway side as:

$$S' = F' (\sin \alpha - \sin \beta \tan \varphi)$$ \hspace{1cm} (8)

$$F' = \gamma h_2 (\tan^2 \alpha - \tan^2 \beta) + \frac{K' + 1}{2} \gamma H \tan^2 \alpha - 2c(\tan \alpha - \tan \beta) + \sigma_2$$ \hspace{1cm} (9)

From Eqs. (3) and (9), the thrust on the two roadway sides differs remarkably in amplitude. At a constant angle of friction and where the horizontal stress is the same, the thrust on the roadway sides is primarily relevant to the stress concentration coefficient of the roadway sides and the critical depth of rock movement in the roadway side floor. The stress source of roadway floor heave is the resultant stress $R$ of the stress $S$ of the rock mass in the roadway floor along the AC plane and the stress $S'$ along the DF plane.

$$R = S \cos \alpha + S' \cos \alpha$$ \hspace{1cm} (10)

From the relationship above, roadway floor stability is relevant to the stress concentration of the roadway sidewalls, the burial depth of the roadway, and the cohesion and internal angle of friction of the floor rock.

Given the geological particulars of Shanghaimiao mining area, the 11508 head roadway is 350 m deep underground, with $\gamma = 25 \text{kN/m}^3$, $\varphi = 12^\circ$, $c = 0.9 \text{MPa}$. 

\hspace{1cm}
Assuming that $h_1 = 3.0 \text{ m}$, $h_2 = 2.5 \text{ m}$, supposing a horizontal-to-vertical stress ratio of 1.2, i.e., $\sigma_1 = \sigma_2 = 1.2\gamma H$, we can yield how the upward resultant stress $R$ of the roadway floor changes with the stress concentration coefficient $K$ and $K'$ of the roadway sides:

\[ R = 10.13 + 1.04(K + K') \quad (11) \]

Figure 6 shows the integrated plot of $R$ variation as a function of $K$ and $K'$. When the roadway is outside the coverage of the advance bearing pressure, for example, when $K = K' = 1.2$, $R = 12.72 \text{ MPa}$. When the roadway enters the coverage of the advance bearing pressure, the stress concentration on the two sides differs, $K > K'$, i.e., when $K = 1.6$ and $K' = 1.4$, $R = 13.34 \text{ MPa}$. When the floor is open due to roadway excavation, floor heave will also occur under the action of small vertical upward stress. According to the above analysis, under the condition of weak floor, when the roadway is affected by one-sided mining, the upward stress of the floor reaches 13.34 MPa, which is more prone to serious floor heave. Therefore, in order to effectively reduce the impact of roadway floor heave on safety production, it’s necessary to reinforced the floor.

4. Numerical simulation

4.1. The model

In order to obtain a clearer picture of the roadway stress variation and failure when exposed to mining disturbance and validate our theoretical calculation, further calculation is carried out on FLAC3D. Figure 7 shows the numerical model built upon available mine geological data. The model is sized 400 m (L) by 200 m (W) by 80 m (H). The Mohr-Coulomb model is used to simulate the failure criterion of the rock stratum. In order to simulate the overburden load, the upper boundary stress of the model is set as 8.75 MPa. The displacement on the left, right, and bottom boundaries is fixed to 0. The mechanical parameters of coal and rock mass in numerical simulation are obtained by conversion on the basis of laboratory test data (Xu et al. 2021). Table 2 gives the mechanical parameters of the coal rock mass.
4.2. Simulation result and analysis

Figure 8 shows the horizontal stress distribution of the roadway floor within 20 m of the working face. From these diagrams:

1) As the roadway floor depth increases, the peak horizontal stress shifts from the working face side toward the middle of the roadway. At 2 m of the roadway floor, the horizontal stress becomes bimodal. Within 3 m of the roadway floor, the peak stress falls on the working face side, where the horizontal stress is obviously larger than on the non-working face side. The horizontal stress is asymmetric. The value in the middle of the roadway is remarkably smaller than the initial rock stress, suggesting that the floor within 2 m has failed. Within 4 m of the roadway floor, the horizontal stress is unimodal in the middle of the roadway, suggesting that the failure of the roadway floor is modest within 4 m. As the roadway floor depth further increases, the horizontal stress gradually decreases and becomes basically symmetric.

2) At 0.5 m of the floor, along the roadway strike, as the roadway is farther away from the working face, the stress at the peak point on the working face side first increases then decreases, with the peak falling at 8 m of the advance working face. As the roadway floor depth further increases, the peak point does not change much.

3) At 4 m of the roadway floor and around 8 m from the working face, the horizontal stress is 19 MPa maximum.

Figure 9 shows the plastic zone variation in the roadway surrounding rock at different distances from the working face. From these diagrams:

| Lithology            | ρ(kg/m³) | E(GPa) | c(MPa) | φ(deg.) | σc(MPa) | σu(MPa) | ν/α |
|----------------------|----------|--------|--------|---------|---------|---------|-----|
| Medium coarse sandstone | 2795     | 7.26   | 5.17   | 27.13   | 45.69   | 1.03    | 0.22|
| Siltstone            | 2632     | 4.52   | 3.25   | 24.16   | 35.76   | 1.22    | 0.19|
| Fine sandstone       | 2586     | 4.36   | 2.94   | 22.37   | 22.53   | 1.55    | 0.15|
| Mudstone             | 1120     | 2.53   | 0.90   | 12.25   | 10.15   | 0.89    | 0.26|
| Coal                 | 1325     | 2.76   | 1.31   | 15.68   | 13.32   | 1.13    | 0.15|
1) After the roadway is excavated, in the absence of mining disturbance, the floor failure depth is around 3.5 m, and the floor heave is about 0.15 m. The initial design should locate the anchor section 3.5 m below the floor.

2) At 20 m from the working face, the floor heave is around 0.25 m. Mining began to affect the roadway surrounding rock significantly. As the distance from the working face reduces, the deformation of the roadway floor gradually enlarges. At 4 m from the roadway working face, the maximum deformation of the floor is up to 1.05 m, it is basically consistent with the maximum deformation of the

![Figure 8. Horizontal stress distribution of roadway floor within 20 m of the working face. (a) 0.5 m of roadway floor. (b) 1 m of roadway floor. (c) 2 m of roadway floor. (d) 3 m of roadway floor. (e) 4 m of roadway floor. (f) 5 m of roadway floor.](image-url)
Based on field investigation, theoretical analysis, and numerical studies, when the roadway is within the coverage of the advance bearing pressure, in the presence of mining disturbance, the floor is subjected to horizontal stress. When the stress concentration exceeds the strength limit bearable by the floor, the floor will extend toward the free surface, giving rise to asymmetric floor heave. Hence it is necessary to enhance the support strength of roadway floor, improve the integrity of surrounding rock, and mitigate the effect of roadway floor heave on production safety and efficiency during mining operation.

5. Double seal DS-IBA control

Under the influence of mining, the stress concentration factors on both sides of the roadway are different. An asymmetric heave stress model is established and the resultant force of the bottom plate is calculated. Through numerical simulation, it is further analyzed that due to the influence of mining, the stress concentration factors on both sides of the roadway are different due to different positions away from the working face, and the surrounding rock of the roadway floor is damaged to varying degrees. The damage range of the plastic zone of the floor reflects the stress of the roadway floor to a certain extent, given the roadway floor failure and deformation mechanism in Shanghaimiao mining area, efforts must be employed to enhance the support strength of roadway floor. Now that the roof contains a sandstone aquifer and the floor has to be sealed in time after the roadway is excavated, we propose the use of a double seal deep and shallow inverted bottom arch (DS-IBA) control.
approach. This provides a layer-by-layer control for the roadway floor. In the first layer, anchor bolts are installed to form a ‘shallow arch’ of the floor. In the second layer, anchor cables are installed to form a ‘deep arch’. After each layer has been so supported, they are shotcreted and sealed to form a double seal floor to enhance the overall support strength of the roadway floor surrounding rock.

5.1. Installation of the DS-IBA system

Overbreak the roadway floor to the design section → drill anchor bolt holes and install anchor bolts → first shotcreting (100 mm thick) → install metal nets & steel ladders → apply pretension to anchor bolts → second shotcreting (50 mm thick) → drill anchor cable holes and install anchor cables → install metal nets & W-strips → apply pretension to anchor cables → shotcreting (100 mm thick) → complete floor support → maintain floor shotcreted layers on a regular basis. Figure 10 shows the construction workflow of the double seal DS-IBA system.

5.2. Technical parameters of support

1) Roof support parameters. The anchor cables are $\Phi17.8 \text{ mm} \times 7000 \text{ mm}$ mine cage cables installed in a group of 3 in each row, at the row spacing of $1600 \times 1600$. These cables are assisted by $400 \text{ mm} \times 400 \text{ mm} \times 12 \text{ mm}$ high strength trays. The anchor bolts are $\Phi28 \text{ mm} \times 2800 \text{ m}$ high strength bolts installed at the row spacing of $800 \times 800$. These bolts are assisted by $450 \text{ mm} \times 280 \text{ mm} \times 3.75 \text{ mm}$ W-guards and $150 \text{ mm} \times 150 \text{ mm} \times 10 \text{ mm}$ bolt plates.

2) Sidewall support parameters. The anchor cables are $\Phi17.8 \text{ mm} \times 5000 \text{ mm}$ mine cage cables installed in a group of 2 in each row, with the cables at the two bottom corners pitching $15^\circ$ downward, at the row spacing of $1600 \times 1600$. These cables are assisted by W-strips ($2000 \text{ mm} \times 295 \text{ mm} \times 3.75 \text{ mm}$) and high...
strength trays (250 mm × 150 mm × 10 mm). At the bottom corners, Φ28 mm × 2800 mm shear bolts are used to increase the bolts’ shear resistance. At the other points, Φ28 mm × 2800 mm common high strength anchor bolts are used. These bolts are assisted by 450 mm × 280 mm × 3.75 mm W-guards and 150 mm × 150 mm × 10 mm bolt trays.

3) Floor support parameters. The anchor cables are Φ17.8 mm × 5000 mm mine cage cables installed in a group of 3 in each row in a nonsymmetric array, one anchor cable is arranged on the left side of the center line of the bottom plate, and two anchor cables are arranged on the right side. The spacing between the left anchor cable and the middle anchor cable is 2400 mm, and the spacing between the right anchor cable and the middle anchor cable is 800 mm. W-shaped steel belt (2000 mm × 295 mm × 3.75 mm) and high strength trays

Figure 11. Support scheme. (a) Front view. (b) Top view.
(250 mm × 150 mm × 10 mm) are used, the spacing between w-steel belt holes is 1600mm, and the construction row spacing is 800mm. The anchor bolts are Φ28 mm × 2800 mm high strength bolts installed at the row spacing of 800mm × 800mm. These bolts are assisted by steel ladders (fabricated from Q235 Φ12 mm round steel) and 150 mm × 150 mm × 10 mm bolt plates.

The pretension of the anchor bolts should be a minimum of 80 kN. That of the anchor cables should be a minimum of 150 kN. Figure 11 shows the arrangement of the anchor bolts/cables. When selecting the support parameters for this scheme, the floor support parameters should be given the same importance as the roof and sidewall support parameters. That is, equal support should be provided across the whole section to increase the overall support strength of the floor. Additional support should also be provided at key points to eliminate weakly supported sites of the roadway.
6. Ground pressure observation and analysis

The new control scheme is field tested on the 11508 head roadway. Figure 12 shows the roadway surrounding rock deformation during mining operation. From the plot, roadway deformation is predominately floor deformation (Malkowski et al. 2021). During the observation, the maximum floor heave is 137 mm, which is around 1000 mm smaller than that under the original support scheme. At around 60 m from the working face, the measuring point enters the coverage of advance influence. At 20 m from the mining roadway, the measuring point enters the area heavily affected by advance. The roadway is not deformed much on the whole, but floor heave still prevails. The maximum deformation is only 137 mm, which does not affect the normal mining of the working face significantly. Obviously, our double seal DS-IBA support strategy effectively controls the floor heave in a water-rich soft rock roadway. Figure 13 shows the as-supported condition of the roadway.

7. Conclusions

1) In the Shanghaimiao mining area, the floor stratum of coal 5# consists of high expansibility minerals like kaolin, illite, and smectite, which collectively contribute 53.3% of the total production. Based on the performed analysis, the roadway floor failure is mainly attributed to the exposure of the mudstone floor and water flow from the roof, low roadway support strength, and mining disturbance.

2) The analysis of the mechanical model of asymmetric floor heave demonstrates that the roadway floor stability is relevant to the stress concentration coefficient of the roadway sidewalls, the burial depth of the roadway, and the cohesion and internal friction angle of the floor rock. Meanwhile, the correlation between the upward resultant stress \( R \) of the floor and the stress concentration coefficient \( K \) and \( K’ \) of the roadway sides is established.

3) The performed simulation indicates that as the roadway floor depth increases, the corresponding peak horizontal stress gradually shifts from the working face side to the middle of the roadway. At the depth of 2 m, the horizontal stress is bimodal and asymmetric. It is found that the stress value on the working face is remarkably larger than that on the non-working face. At the depth of 3 ~ 5 m, the horizontal stress becomes unimodal. As the roadway floor depth further increases, the horizontal stress gradually decreases and becomes symmetric.

4) To enhance the overall support strength of the roadway floor and mitigate the effect of the roof sandstone water on the floor, the floor support parameters should be given the same importance as the roof and sidewall support parameters. In other words, equal support should be provided across the whole section. A new double seal deep and shallow inverted bottom arch support strategy is proposed and verified. field tested. It is found that the maximum floor deformation is only 137 mm, indicating that the proposed strategy has reasonable supporting performance.

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Data availability

The data used to support the findings of this research are included within the paper.

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