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Research Article

Accident Analysis in Relation to Main Roof Structure When Longwall Face Advances toward a Roadway: A Case Study

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Practices show that hydraulic supports crushing accidents or roadway supports failure often take place when a longwall face advances toward an abandoned roadway or a predriven equipment recovery room. Therefore, a 2D similar simulation experiment is conducted to reveal the loading mechanism. The result shows that when the workface advances close to roadways, the main roof breaks ahead of the workface and leads to instability of higher strata. These two changes induce a sharp increase of the load on supports and lead to an accident. Thus, more attention should be paid to the advanced fracture. Therefore, mechanical analysis is used to explain the advanced fracture. Results show that the failure of coal pillar being excavated induces a sharp increase in the main roof's hanging length. Once the hanging length reaches the limit, the advanced fracture takes place. Therefore, the stability of the coal pillar and the hanging length of roof strata are two key factors that may induce an accident. To prevent the a similar supports crushing accident, the partial backfilled technology which partly backfills the abandoned roadway in height and length to maintain the stability of the coal pillar is put forward and put into practice. The field test shows a good effect.

1. Introduction

It is common to see roadways laid ahead of workface in longwall mining field practice [1]. As can be seen, the predriven recovery room for removal of longwall equipment [2–6], roadways abandoned due to the change of geological conditions or the adjustment of panel roadways' layout, [7–12], and roadways abandoned between the room and pillar in residual coal areas [13, 14] are three main parts of this model. The challenge of this model is to sustain the stability of the surrounding rock. As the longwall face advances toward the roadway, the front abutment pressure, previously carried by a panel fender, rapidly transfers to the support system installed in the roadway and onto the outby pillar [15]. Once the supports are insufficient, accident showed up [16]. Besides, as can be seen in Figure 1, these three cases have the same surrounding rock characteristics, and it is necessary to study the strata behavior in this model for safety mining.

A lot of research has been done on situation I and II [2, 4, 6–8, 12, 15] (D Wichlacz et al., [17], Oyler D et al., [18]). As shown in these studies, though some technologies have been proposed to prevent a possible accident, much attention has been paid to roadway control technologies under large abutment loads. However, the weighting-induced failure has rarely been discussed. Therefore, Zhou [11], Wu et al. [10], Gu et al. [5], Wang et al. [17], and Lv [18] conduct a series of studies on the weighting-induced failure when the face advances toward the roadways. However, most of their studies are based on field practice which hardly detects the structural characteristics of the main roof and the corresponding strata behavior. In fact, taking gob-side entry as an example, structure and behavior of the main roof will largely affect its surrounding rock stability [19, 20]. Therefore, although the two types of potential failure have been realized, the structural characteristics of the main roof and the corresponding strata behavior have not been

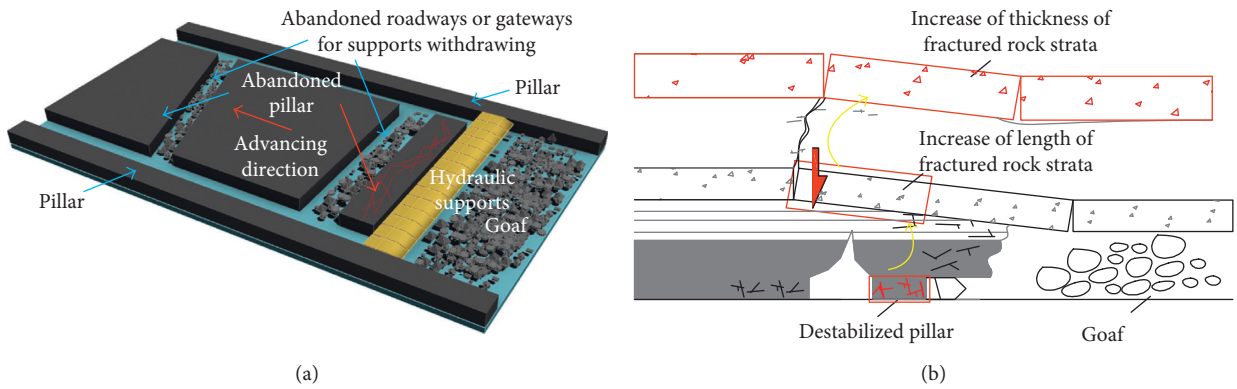

Figure 1: Diagram of abnormal fracture of overlying strata.

clarified. This would lead to a misunderstanding of the loading on the roadway and then the targeted control technologies.

This paper presents a case study on the strata behavior when the longwall face advances toward an abandoned roadway. The objective of this study is to develop a better understanding of the loading mechanisms when a longwall face advances into a roadway. The arrangement is listed as follows. In Section 2, the geological and mining conditions, as well as the hazard rating, were first presented. In Section 3, a similar simulation experiment was conducted to reproduce the in situ accident and make the loading mechanism clear. In Section 4, mechanical analysis was adopted to detect and analyze the key factor that induces the accident. In Section 5, targeted control technologies were proposed based on the key factor in Section 4, and verification tests were conducted in field. Above all, the control technologies can potentially be applied in other similar projects.

2. Case Study

2.1. Mining and Geological Conditions. LW3101 of the Shenghua coal mine of the Jincheng Coal Group is a workface in coal pillar areas. The mine is located in the southeastern part of the Qinshui coalfield, as shown in Figure 2. A project was conducted to extract the massive valuable coal pillars. The average buried depth of the coal seam is 210 m. The average thickness of the coal seam is 6.5 m. A full-mechanized caving mining technology is adopted in the workface. The cutting height is 2.2 m, and the caving height is 4.3 m. The length of the workface is 84 m. The mining distance is 420 m. Geological conditions in the workface are not complicated except for the long-term abandoned roadways. The density of the coal sample is 1430 kg/m^3. The compressive strength is 19 MPa. The immediate roof is made up of siltstone or mudstone, its thickness is 4.66 m, and its compressive strength is 32.2 MPa. The main roof is made up of siltstone or fine-grained sandstone, its thickness is 3.61 m, its compressive strength is 47.45 MPa, and tensile strength is 5.44 MPa.

2.2. Accident Investigation. The abandoned roadways discovered during the roadways excavation period are shown in Figure 3. As can be seen, the roadways are buried by the falling rock blocks, and its layout is hard to identify. Despite the complicated condition, simple measures were taken to crossing the roadway. Unfortunately, supports crushing accident took place when the workface crossed a 12 m width roadway. As can be seen in Figure 3, the coal pillar lost stability; the caving rocks buried the abandoned roadway and poured into the workface; the overlying strata slid rapidly and lost stability soon. The working resistance of supports increased sharply, and then the chocks had a sudden closure. Some supports were even damaged.

To avoid similar accidents and to put forward targeted measures, various methods were applied to make the abandoned roadways' layout clear. Finally, as can be seen in Figure 3, the result shows that there are about 15 roadways lying ahead of the workface. Based on this, the experiment can be conducted and the mechanical model can be established.

3. Experiment Study of the Accident

In China, similar simulation experiments are widely used for detecting the structural characteristics of key strata and strata behavior of longwall faces [21–24]. Thus, this experiment is convictive to detect the same problem.

3.1. Equipments and Experimental Design. Physical models on a 1 : 30 scale of an overburden system were constructed which is a mixture of sand, plaster, calcium carbonate, mica, and water. As shown in Figure 4, four abandoned roadways were set ahead of the workface. The internal dimensions of the test rig were $3 \times 2 \times 0.2$ m (length × height × width). Monitoring devices to measure the abutment pressure in the "coal" layer and loading exerted on supports were used. The results are shown in Figure 5(e) and have been converted to field's scale dates. The structural characteristic of the main roof and strata behavior is shown in Figures 5(a)–5(d).

3.2. Results of the Experiment. As can be seen in Figure 5, accident shows up when the workface moves close to the 12-meter-wide roadway.

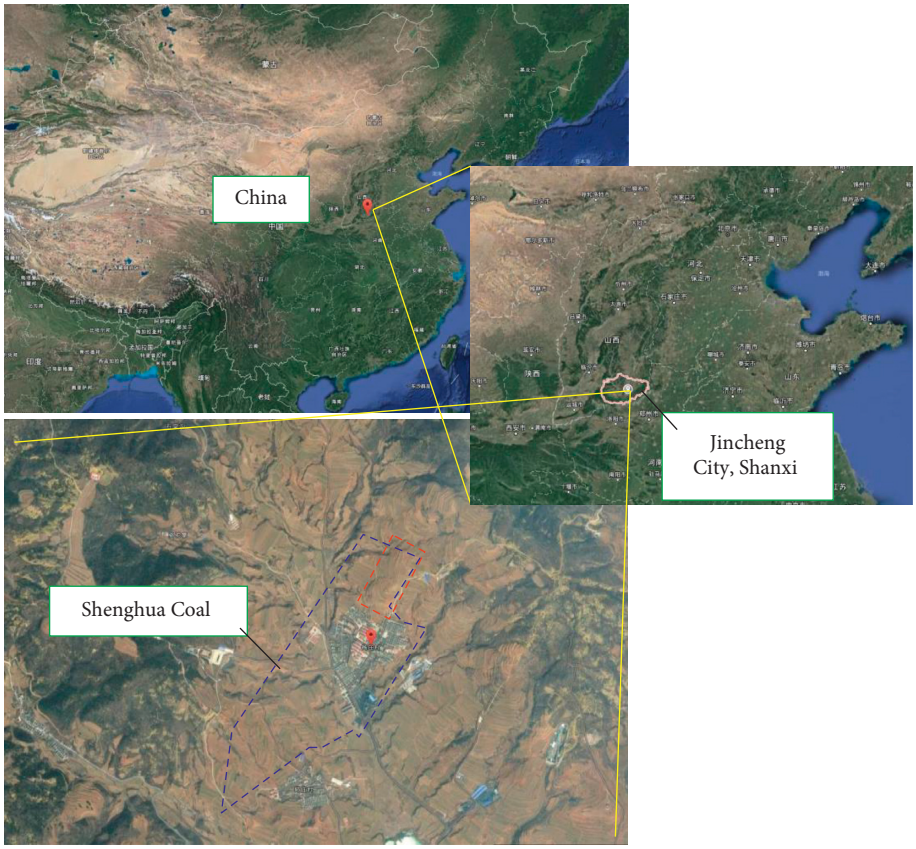

Figure 2: Location of the test site.

In Figure 5(a), when the workface crosses the narrow roadways (6 m or 2.5 m wide), the roof strata fractures behind the workface, and the workface is under the protection of the cantilever made up of the roof strata. In this situation, the abutment pressure is the blue line, and the load on support is the blue point in Figure 5(e). The loading on the support changes little with the workface moving forward.

In Figures 5(b) and 5(c), when the workface crosses the 12 m-wide roadway, the coal pillar breaks down, and the roof strata fractures ahead of the workface, and the length and the thickness of the fractured roof strata increase sharply. The supports are no longer under protection of the cantilever, the loading on support soars to 12500 kN as shown in Figure 5(e).

In Figure 5(d), the main roof slides down to the supports. As a result, in Figure 5(e), the load soars to 16200 kN (the green point), and the abutment pressure in the coal pillar increases (the III curve).

It can be concluded from the evolution of the three curves (I, II, and III in Figure 5(e)) that the abutment pressure transfers forward with the face advancing and increases sharply when there is an abandoned roadway. This evolution will largely impact the stability of the rib and the roadway and then induces a support failure of the roadway.

3.3. Evolution of Support Crushing Accident. Figure 6 is the simplified model of the evolution. As can be seen in Figure 6(a), in most situations, the supports are under the protection of a cantilever or an arch structure made up of main roof. The inferior key strata over the main roof always fracture far behind the workface and therefore have little effects on the workface. The main roof only needs to bear the loading strata.

However, the aforementioned case shows a different structural characteristic. As shown in Figure 6(b), the main roof breaks ahead of the workface and then induces the inferior key strata' fracture. As a result, the inferior key strata act as a loading being exerted on the arch structure which can easily destroy the stability of the main roof and slides on the supports as shown in Figure 6(c). Once the sliding instability takes place, the loading on the supports increases sharply, and the supports crushing accident takes place.

In contrast to Figures 6(a) and 6(b), the different structural characteristics between a normal workface and an abnormal workface can be concluded. Firstly, the length of the fracture interval increases, and the fracture position moves forward. Secondly, the thickness of the fractured roof strata increase and then lead to a sharp increase of the loading on the support.

4. Mechanical Analysis of the Abnormal Fracture and the Preventing Strategy

4.1. Factor Discussion on Advanced Fracture. It has been widely known that the bending moment induces a fracture in the main roof. Thus, more attention should be paid to the factors that affect the position of the maximum moment.

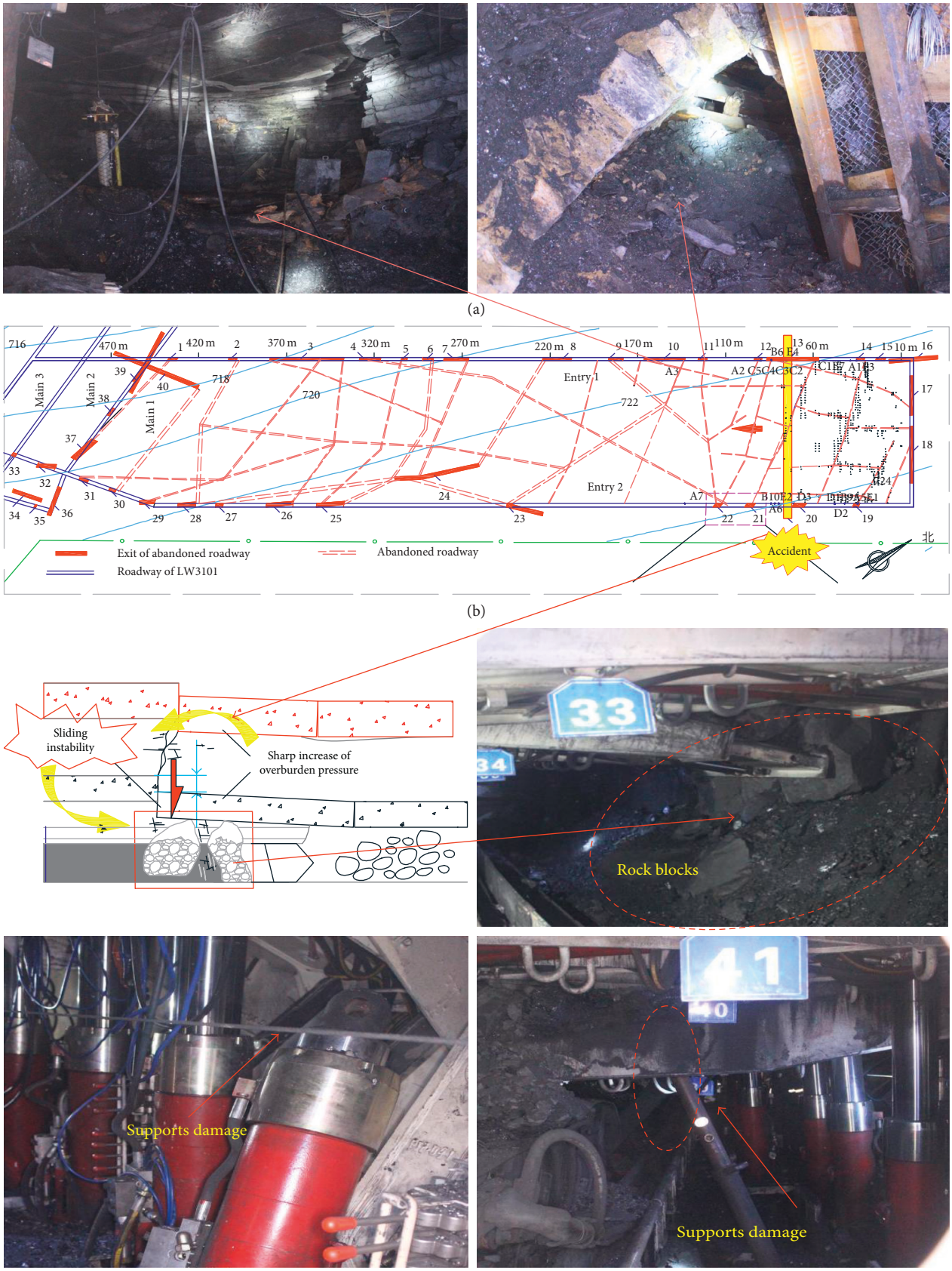

Figure 3: (a) Conditions of entry 1 during the drivage period. (b) Layout of LW3101 and abandoned roadways. (c) Sketch map of the strata behavior and photograph of the accident.

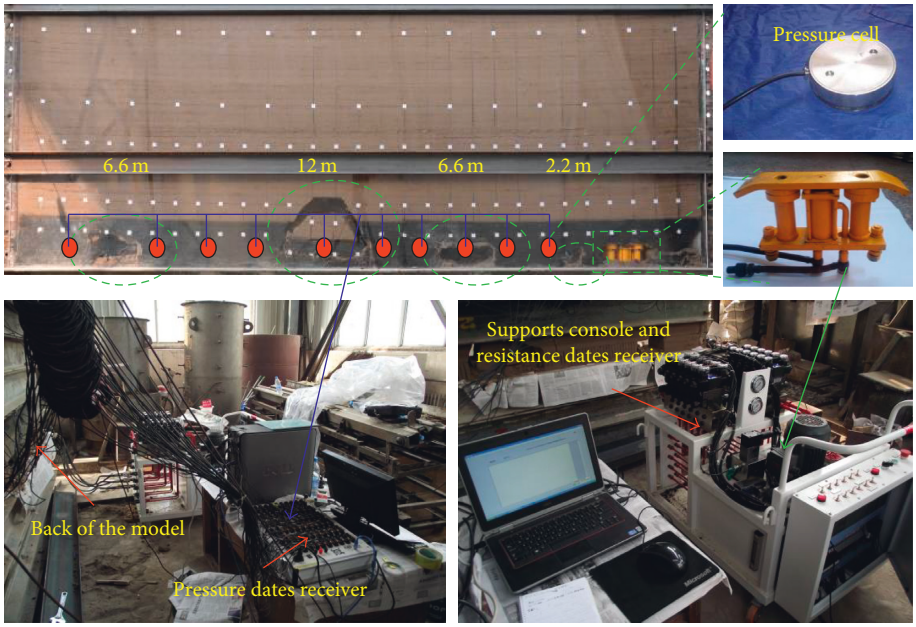

Figure 4: Experiment model and microsupport and real-time monitoring devices.

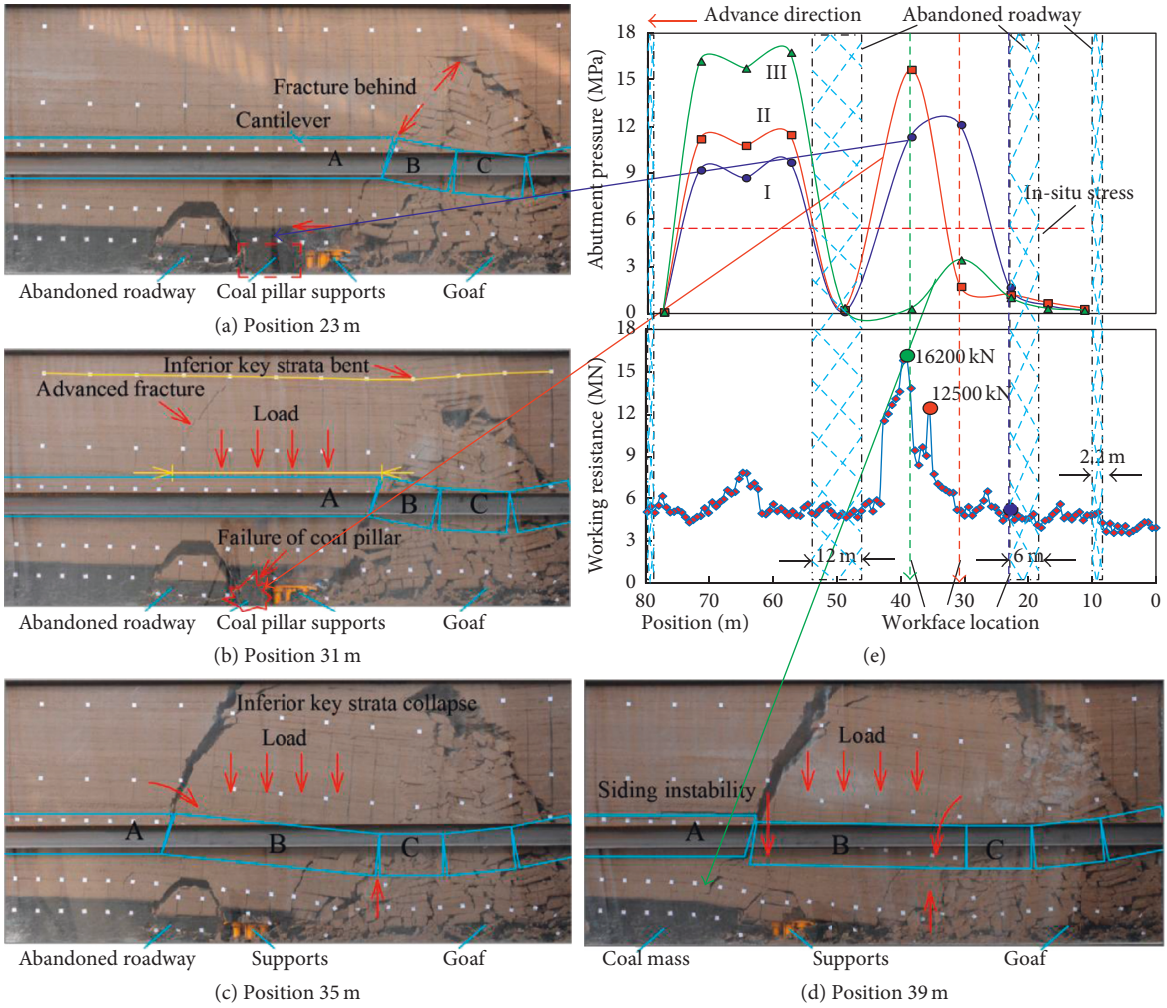

Figure 5: Result of the 2D similar simulation. (a) Position 23 m, (b) position 31 m, (c) position 35 m, and (d) position 39 m.

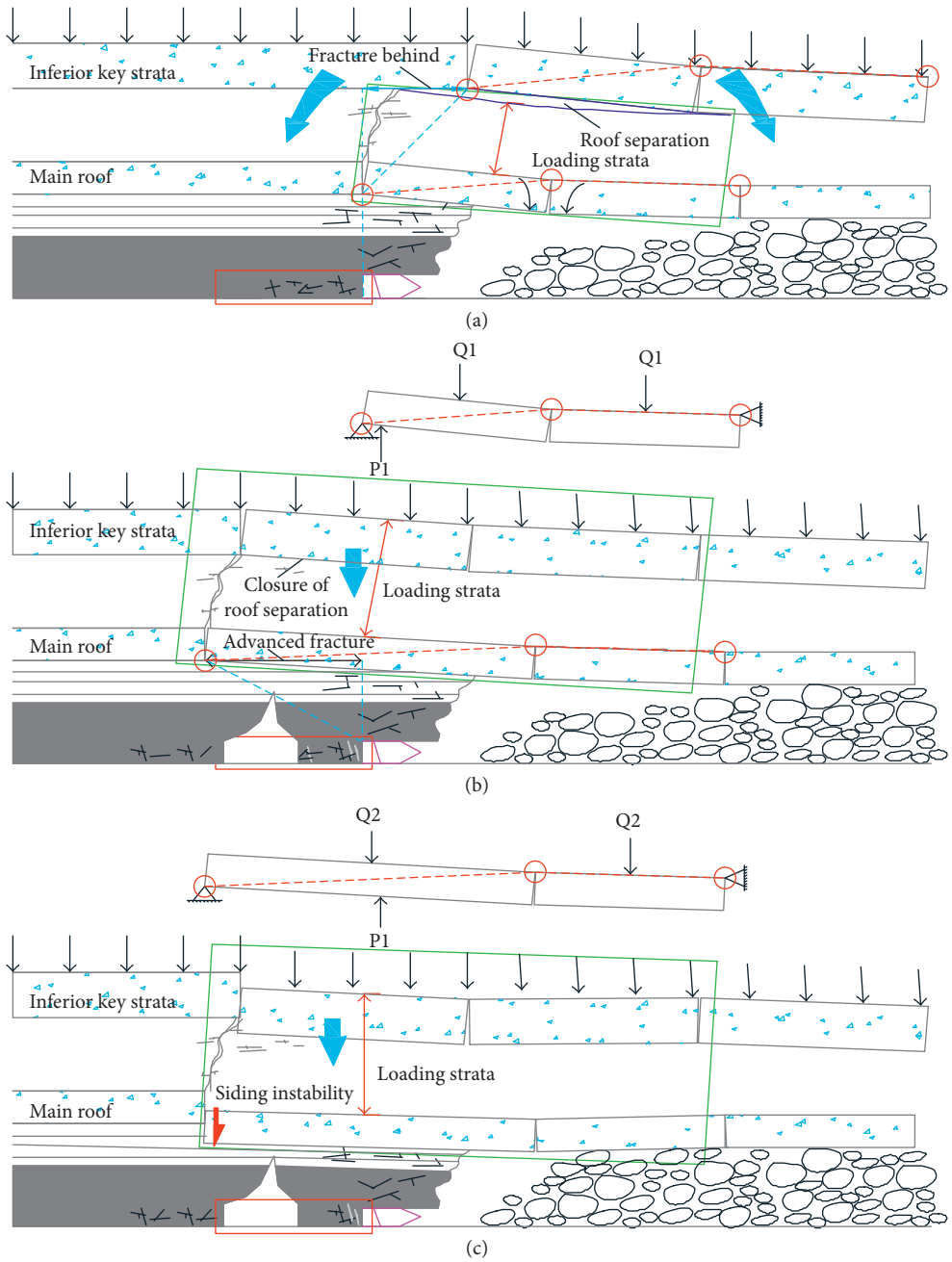

Figure 6: Evolution of the supports crushing accident.

Firstly, the coal seam and coal pillar which are seen as the foundations should be discussed [25].

With the coal pillar being excavated, the loading on it is a constant, but the pressure increased. There must be a moment when the coal pillar loses it stability. The critical width of the coal pillar can be calculated as follows.

The stress on the coal pillar can be estimated using Qian's equation [19], which is given by

$$\sigma = \gamma H\left(k + \frac{W_a}{2W}\right), \tag{1}$$

where σ is the stress applied to the coal pillar, γ is the unit weight of overlying strata, H is the buried depth of the coal seam, W is the width of the coal pillar, k is the stress concentration coefficient, $k = 1.5\sim5$, and W_a is the width of the abandoned roadway.

The pillar strength can also be estimated using Bieniawksi's equation [26], which is given by

$$\sigma_p = 0.2357\sigma_c\left(0.64 + 0.36\frac{W}{h}\right), \tag{2}$$

where σ_p is the compressive strength of the coal pillar, σ_c is the compressive strength of the coal sample, and h is the height of the coal pillar.

When the stress on the coal pillar σ reaches the limit σ_c, the critical width of the coal pillar W^* can be obtained as follows.

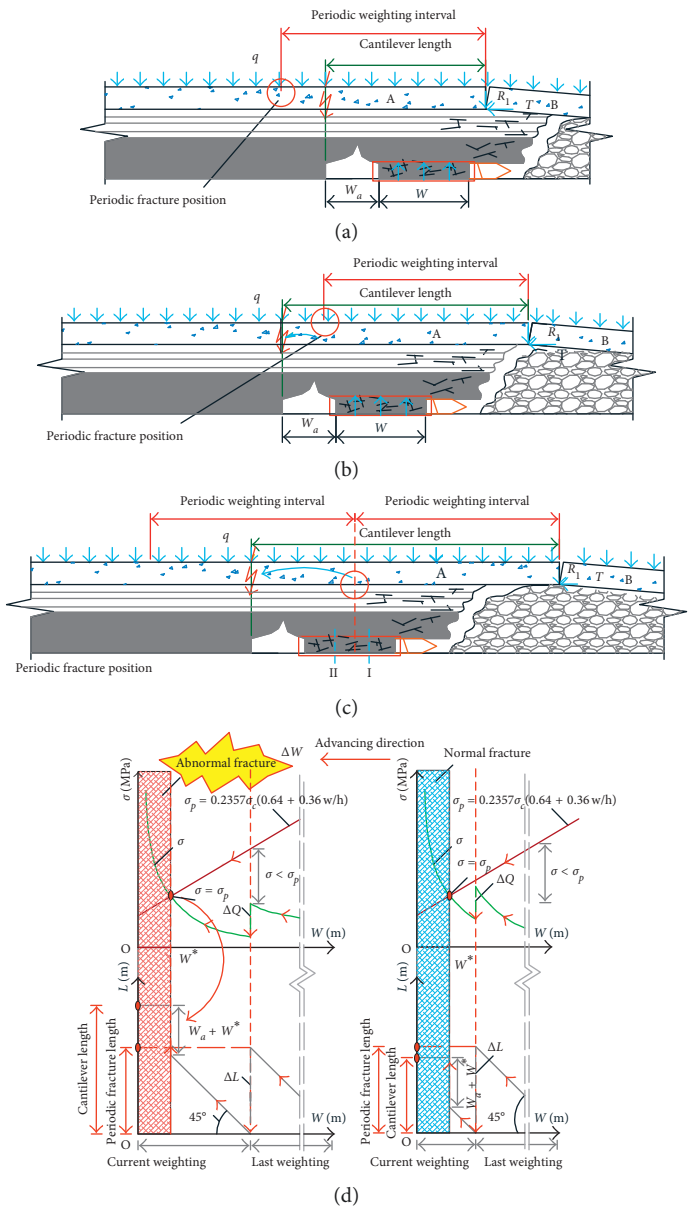

Figure 7: Relative positions of the abandoned roadway and fracture position.

$$W^* = \frac{-b + \sqrt{b^2 - 4ac}}{2a}, \tag{3}$$

where $a = (0.085\sigma_c/h)$, $b = -((\rho \cdot g \cdot H/2) - 0.15\sigma_c)$, and $c = -\gamma H(1 + (B/W))$.

Once the coal pillar loses its stability, it cannot support the overlying strata. Thus, the hanging length of the main roof increases. However, whether the abnormal fracture would take place or not also depends on the hanging length limits which are also called the periodic weighting interval.

Figure 7 shows three relative positions between the abandoned roadway and periodic fracture position. Based on this, the abnormal fracture can be predicted.

In Figure 7(a), both the abandoned roadway and the coal pillar are within the scope of the next periodic weighting interval. As can be seen, the cantilever is shorter than the interval. As a result, even the coal pillar breaks down and the roof strata would not suffer the abnormal fracture.

In Figure 7(b), the abandoned roadway is partly within the scope of the interval and the coal pillar is also within the scope of the interval. As a result, the cantilever is longer than the interval. Once the coal pillar breaks down, the roof would suffer an abnormal fracture.

In Figure 7(c), the abandoned roadway is beyond the scope and the pillar is partly within the scope. As a result, the cantilever is far longer than the interval. In this case, the critical width of the coal pillar is important. If the coal pillar breaks down in position I, the roof would suffer an abnormal fracture. If the coal pillar breaks down in position II, the roof would not suffer abnormal fracture.

Figure 7(d) shows the relationship between stress on the coal pillar, strength of coal pillar, and cantilever length. As can

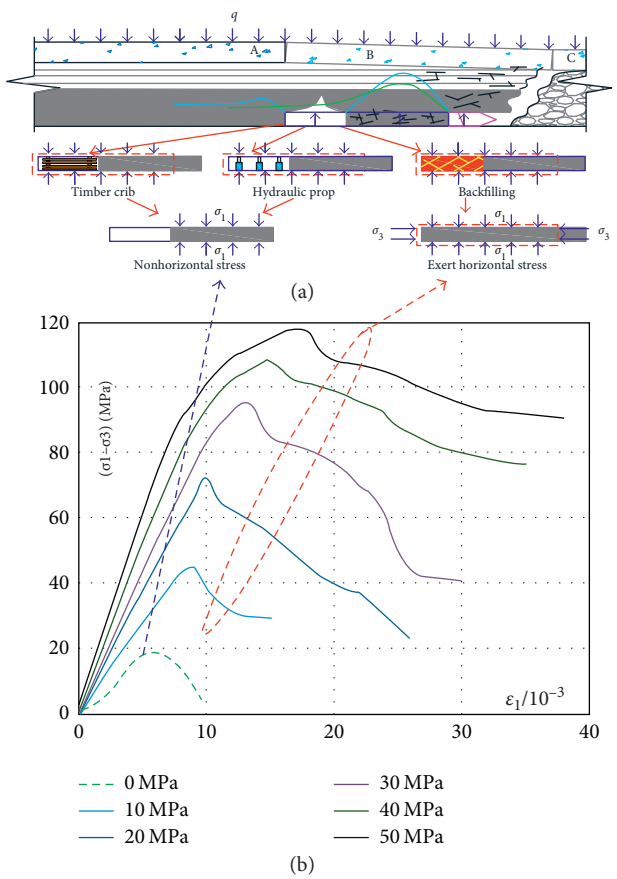

Figure 8: Schematic diagram for preventive measures.

be seen, the stress increases as the width of the coal pillar decreases, and its variation agrees with a hyperbolic law. The strength decreases with the decrease in the width of the coal pillar and conforms to the linear law. Once the stress increases to the strength, the coal pillar collapses and the cantilever length increases by $W^* + W_a$. A comparison of the periodic weighting interval and cantilever length can conclude whether an abnormal fracture would take place (Figure 7(d)).

4.2. Strategy for Preventing Accident. The above analysis points out the key factors (stability of the coal pillar and hanging length of roof strata) that may induce the supports crushing accident. Therefore, the principle to prevent a supports crushing accident should aim at these two factors. Considering that the hanging length of the roof strata is hard to control, prevention measures should be taken to maintain the stability of coal pillar.

As can be seen in Figure 8, the abandoned roadway backfilling technology can exert horizontal stress on the coal pillar and transforms its uniaxial compression state to triaxial compression state. This improvement transform coal pillar to integrated coal from a view point of mechanics. Then, the coal pillar will hardly lose it stability.

5. Industrial Test and Implications

5.1. Field Test of the Partial Backfilled Technology (PBT). The LW3101 workface needs to cross about 15 abandoned roadways in 420 m length, which is the most complicated situation that can be found in the literature. Based on the principle, the following schemes were put forward.

Firstly, the workface length is set as 84 m which is a relative short longwall face with the current technology to reduce the numbers of abandoned roadways and relieve the intensity of the rock behavior. Meanwhile, other measures have been taken to avoid an accident. These measures include stopping caving top coal, reducing cutting height, and waiting for roof weighing when longwall face is close to the roadway.

Secondly, abandoned roadways are backfilled 24 m long along the workface to exert a horizontal force to maintain the stability of the coal pillar. This method reduces the length of the workface which need to cross the roadway. At the same time, the 24 m long backfilled zone makes grouting easy to be conducted in the field.

It should be noted that the backfilled body does not necessarily contact the roof. The main purpose of the technology is to maintain the stability of the coal pillar and prevent falling rock blocks. Thus, the backfilled body is made up of two layers. The soft layer which changes the uniaxial compression of the coal pillar to the triaxial compression is a mixture of woods, gangues, coal blocks, and low-strength cementing body. The hard layer which ensures the supports to contact roof and prevents gangues pouring into the workface is made up with high-strength cementing body. Figure 9(a) shows the backfill plan in the field.

Figure 9(c) records the work resistance during the mining period. The result shows that the maximum work resistance in both areas is less than 3000 kN, and the periodic weighting interval is 10.2 m~11.6 m. An abnormal weighing accident never appears again.

5.2. Implications. The longwall face advancing toward the roadway is a common case that can be seen in the literature. However, according to the literature review in Introduction, it can be found that mechanical essence especially the loading mechanism associated with structural characteristics of the main roof and the strata behavior has not been discussed. Similar to the present popular topic gob-side entry, the structural characteristics and the strata behavior above the roadway cannot be omitted.

Based on the similar simulation experiments, we found the difference in the structural characteristics and the strata behavior between mining ingerated coal seam and coal seam made up of coal pillar: the main roof fractures ahead of the workface and induces the fracture of the higher strata. The abnormal fracture properly explains the loading mechanism, but the preventive measures should be studied further. The key factors (stability of the coal pillar and hanging length of roof strata) inducing the abnormal fracture is found in Section 4. We found that if the coal pillar could be well maintained, it will effectively prevent the abnormal fracture. Thus, the confined compression support strategy is proposed and put into practice to improve coal pillar's stability.

Notably, different coal seams present great varieties in geological and production conditions, which lead to differences in strategy in accordance with its specific situations.

Figure 9: Field backfilled plan and the effects.

However, the loading mechanism and key factors presented in this study are necessary in the support design of predriven roadways or abandoned roadways in other coal mines.

6. Conclusions

The aim of this case study carried out at Jingcheng City, Shanxi Province, China, was to investigate the longwall face and roadway stability while advancing toward a abandoned roadway, based on a case study, similar simulation experiments, mechanical analysis, and field tests. This study contains the following three original aspects:

(1) A similar simulation experiment was conducted for accident reconstruction. To detect the mechanical characteristics in the experiment, the abutment pressure and the working resistance were monitored by specified devices. The experimental dates can be validated against the field accident. Thus, the experiment can provide more reliable and realistic structural characteristics and strata behavior characteristics.

(2) The experiment showed the unique structural characteristics of the main roof and strata behavior characteristics when the long face advanced toward the roadway. The advanced fracture of the main roof and instability of inferior key strata lead to a sharp increase on the load on supports and then lead to the supports crushing accident. This finding indicates that the advanced fracture should be paid more attention for the accident prevention.

(3) In order to detect the factors that lead to the advanced fracture, a mechanical model was used and the main factors were found: stability of the coal pillar and hanging length of roof strata.

(4) A new support strategy was proposed which aims to increase the stability of the coal pillar and reduce the roof weighting intensity by the partial backfilled technology which backfilled the abandoned roadway partly in length and height. Other measures have been taken to avoid an accident. These measures include stopping caving top coal, reducing cutting height, and waiting for roof weighing when longwall face is close to the roadway. This strategy provides sufficient details to allow its application in other coal mines.

The test site is located at Jincheng city, Shanxi Province, China. The average overburden depth of related panels is 210 m. The accident took place when measures were rarely taken when it advanced toward an abandoned roadway. The experiment shows that the advanced fracture of the main roof and inferior key strata instability took place in this period and then induced the accident. The mechanical analysis shows that the collapse of the coal pillar caused the advanced fracture of the main roof. Consequently, a new support strategy which aims to maintain the stability of the coal pillar was proposed and applied in the field. The field tests indicated that an accident never happens, and the work resistance is no more than 300 kN which is within the ability of the support. The key factors and the strategy proposed above could also be used for similar conditions.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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