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Research Article

The Influences of Key Strata Compound Breakage on the Overlying Strata Movement and Strata Pressure Behavior in Fully Mechanized Caving Mining of Shallow and Extremely Thick Seams: A Case Study

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In order to analyze the impact of compound breakage of key strata on overlying strata movement and strata pressure behavior during the fully mechanized caving mining in shallow and extremely thick seams, this paper took the 1322 fully mechanized caving face in Jindi Coal Mine in Xing County as the engineering background. Under the special mining and geological condition mentioned above, UDEC numerical simulation software was applied to research the engineering problems, and results of numerical simulation were verified through the in-site measurement. The research results showed that during the fully mechanized caving mining in shallow and extremely thick seams, the inferior key strata affected by mining movement behaved in the mode of sliding instability and could not form the stable structure of the voussoir beam after breaking and caving. In addition, the main key strata behaved in the mode of rotary instability, and the caving rocks behind the goaf were gradually compacted because of the periodic instability of the main key strata. With the continuous advance of the working face, the abutment pressure of the working face was affected by the compound breakage and periodic instability of both the inferior key strata and the main key strata, and the peaks of the abutment pressure presented small-big-small-big periodical change characteristics. Meanwhile, the risk of rib spalling ahead of the working face presented different levels of acute or slowing trends. The actual measurement results of ground pressure in the working face showed that, in the working process, the first weighting interval of the inferior key strata was about 51 m and its average periodic weighting interval was about 12.6 m, both of which were basically consistent with the results of numerical simulation. The research has great significance in providing theoretical guidance and practical experience for predicting and controlling the ground pressure under the similar mining and geological conditions.

1. Introduction

Many areas in the west of China, mainly including Xinjiang, Inner Mongolia, and Shaanxi and Shanxi provinces, are rich in coal resources, accounting for 81.3% of total national resources. Among these coal resources, the reserve of both thick and extrathick coal seams take up more than 44% of total reserves, which has laid a solid foundation for safe and efficient production of coal resources and rapid economic development [1–3]. With the implementation of the national strategy for developing the western areas, the exploitation scale of coal resources in these areas has gradually expanded, and shallow-buried working face are becoming increasingly common [4–6]. At present, the Xing County mining area in Shanxi province which is under development has a total reserve of approximately 39.639 billion tons, and its average seam thickness is 12 m, which is regarded as extrathick coal seam. The distinguishing feature of occurrence of coal seam in the Xing County mining area is shallow-buried depth and thicker loess layers above the bedrock, which is similar to that in the adjacent Shenfu-Yuheng mining area, but also has significant differences. As for the Xing County mining area, the buried depth of coal seam is deeper than that in the Shenfu mining area, and the thickness of both coal seam and bedrock is larger than that in the Shenfu mining area, which belongs to the sandy-soil-rock-type bedrock coal seam with shallow-buried depth and thin thickness [7, 8]. Under the special mining and geological condition in the Xing County mining area, both the movement and breakage law of overlying strata and the pressure behavior law of stope in the mining process of shallow and extremely thick seams are significantly different from those in conventional mining.

At present, many scholars have conducted extensive research on the breaking mechanism and pressure behavior law of key strata in overlying strata under the conventional mining condition of shallow coal seams. Lai et al. studied the coupling mechanical properties of the "support-surrounding rock" in the large-height working face with shallow-buried and extremely thick coal seam and obtained the features, mainly including period, intensity, and range, of the pressure behavior of the roof in the large-height working face with shallow-buried depth and extremely thick seam [9]. Aimed at the fact that the key strata of shallow-buried seams in the Shendong mining area are easy to cave and cause many problems, such as roof failure due to weighting over great extent and dynamic hazards. Jiang et al. studied the initial breaking characteristics and caving mechanism of the key strata in shallow coal seams [10]. Xie and Zhao took the Qianshuta coal mine as the research background, and an integrated method, mainly including numerical simulation, theoretical analysis, and on-site measurement, was used to study caving feature and structure feature of the top coal during fully mechanized top-coal caving mining in the shallow-buried, hard, and extremely thick coal seam [11]. Wang et al. took the geological condition of the fully mechanized working face with a high mining height in the Sandaokou coal mine as the engineering background, and similar material simulation was applied to research the breaking laws of the key strata in the working face with large mining height and approximate shallow depth [12]. Yang [13] carried out research on the mechanisms of large-scale roof cutting and support crushing and pressure behavior law of the working face in the process of high-intensity exploitation of shallow-buried coal seams. Liu et al. built the height control model of the water-flowing fractured zone based on the background of a shallow thick coal seam in North Shaanxi. Through the experimental simulation and analysis of rock bearing capacity and fracture evolution rule, the control model of structural stability of the key strata layer was built and the effective protection of the coal seam in northern Shaanxi was realized [14]. Ju and Xu studied surface stepped subsidence related to top-coal caving longwall mining of extremely thick coal seam under shallow cover. The formation mechanism of the surface stepped subsidence case was explained. The surface subsidence profile after the sequent mining activity was predicted. The possible controls of the stepped subsidence were lastly proposed [15]. Wang et al. took the Shendong coal mine as the research background and investigated the form and stability of the roof-bearing structure of a shallow coal seam under longwall mining, in order to determine the fundamental mechanism of roof step-form subsidence [16].

The research mentioned above is mostly based on the engineering condition of coal seams in the Shenfu-Yongheng mining area in China, the breaking mechanism of the key strata and pressure behavior law in the mining process of shallow-buried coal seams have been studied. However, there is little research on the influence of compound breakage of the key strata on the movement of overlying strata and pressure behavior law under the special mining and geological condition in Xing Country mining area. This paper takes the 1322 fully mechanized caving face of Jindi Coal Mine in Xing County mining area as a case study, and some research is conducted on the problems mentioned above. The research results are of great significance to enrich mine pressure theory and provide guidance for mine pressure control under similar mining and geological conditions.

2. Engineering Background

The Xing County mining area is located in the Lvliang mountain system and presents the typical landscape of Loess Plateau. The geographical location is shown in Figure 1. The coal seams of Xing County mining area mainly characterize sand-base bedrock with a shallow-buried depth and thin thickness, and the main structure of overlying strata is characterized by loess-thin bedrock-seam structure. In addition, the main feature of this type of overburden strata structure is that most of the loose layers of the quaternary system are made up of loess layers with large thickness, and the components of bedrock are mainly sandstone and mudstone. The 1322 working face of the Jindi Coal Mine in the Xing County mining area is located in the north-central region of the minefield, with 1324 working face in the west, the boundary pillar in the north, the industrial square pillar in the south, and the goaf of 1313 working face, south transportation roadway, and other major roadways in the east. The profile of 1322 working face is shown in Figure 2. The main exploiting seam at 1322 working face is 13# coal seam with a buried depth of 258 m~329.3 m, which is a shallow-buried coal seam; the thickness of coal seam is 8.8~13.65 m with an average thickness of 11.9 m, which belongs to extremely thick coal seam. The fully mechanized top-coal caving mining method was used to exploit the 13# coal seam with a mining height of 3.2 m and a roof caving height of 8.7 m. The inclined length of the working face is 180 m, and the strike length is 1230 m. The dip angle of the coal seam is 18°~25° with an average angle of 22°, which is a gently inclined coal seam. The thickness of immediate roof is 0.8~2 m. The immediate roof mainly consists of sandy mudstone, mudstone, and siltstone with sandstones distributing locally; the basic top is made up of medium-coarse sandstone; the floor is mainly made up of fine-grained sandstone, mudstone, and sandy mudstone.

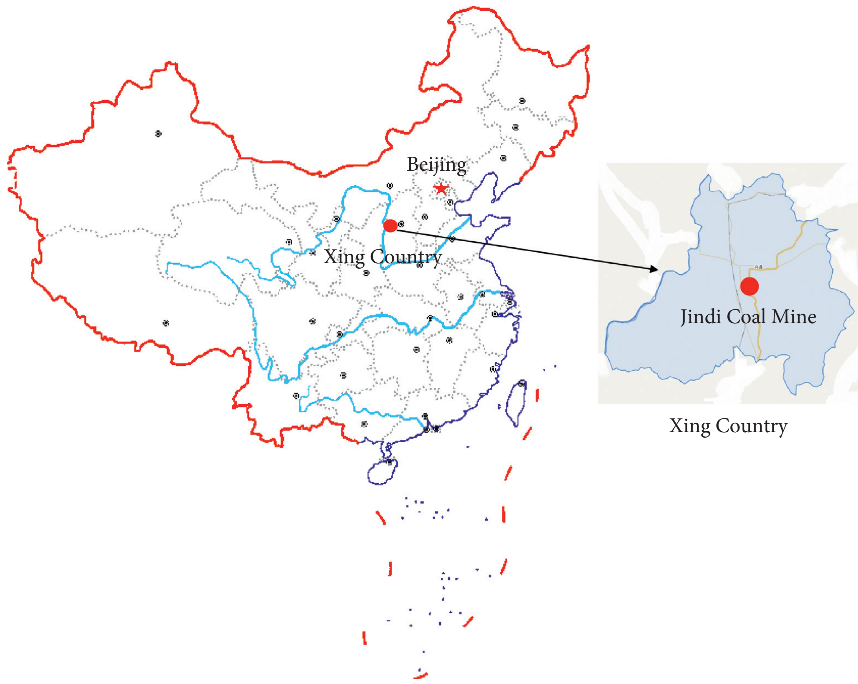


Figure 1: The geographic location of Jindi Coal Mine.

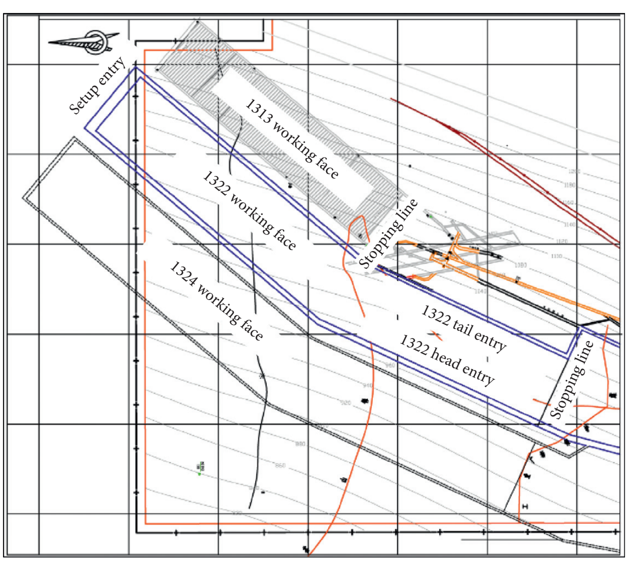


Figure 2: Overview of the 1322 working face at Jindi Coal Mine.

3. The Establishment of Numerical Model and Simulation Scheme

This paper took the 1322 fully mechanized caving mining face in Jindi Coal Mine as the engineering background, and the UDEC discrete element numerical model was established to study the movement law and pressure behavior law of overlying strata in the stope under the special mining and geological condition of sallow-buried and extremely thick coal seam.

3.1. The Establishment of Numerical Models. Taking the 1322 fully mechanized top-coal caving face in Jindi Coal Mine as the engineering background, the UDEC numerical simulation software was used to establish a discrete element numerical model to research the overlying strata movement and pressure behavior of the working face under the condition of the fully mechanized top-coal caving mining face in the shallow-buried thick coal seam. The length and height of the model were 500 m and 120.6 m, and the average buried depth of the coal seam was 266.6 m. As for the numerical model, a total of 17 layers of strata which contained both coal and roof and floor were established, and the topsoil layer was simplified and replaced by an equivalent stress of 2.63 MPa. Considering the influence of the mining boundary, boundary protection pillars with a thickness of 100 m were remained on both sides of coal seams. The horizontal constraint was imposed on the left and right boundaries of the model, and the vertical constraint was imposed on the bottom boundary of the model. The model was divided into 7871 blocks, 35874 cells, and 44648 nodes. According to the key strata theory [17–20], it could be obtained that there were two layers of the key strata within the coal-bearing strata. The main key strata of the overlying strata is the 9th layer of fine sandstone above the 13# coal seam, and the inferior key strata is the 2nd layer of gritstone above the 13# coal. The subsidence monitoring lines of overburden strata were, respectively, placed in the main and inferior key strata, and vertical monitoring lines of stress were arranged in the immediate roof. The numerical model established and boundary conditions are shown in Figure 3.

3.2. Selection of Mechanical Parameters. The physical and mechanical parameters of each stratum applied in the numerical model were measured by experiments in the laboratory, as are shown in Table 1. The mechanical parameters of jointed rock mass are shown in Table 1.

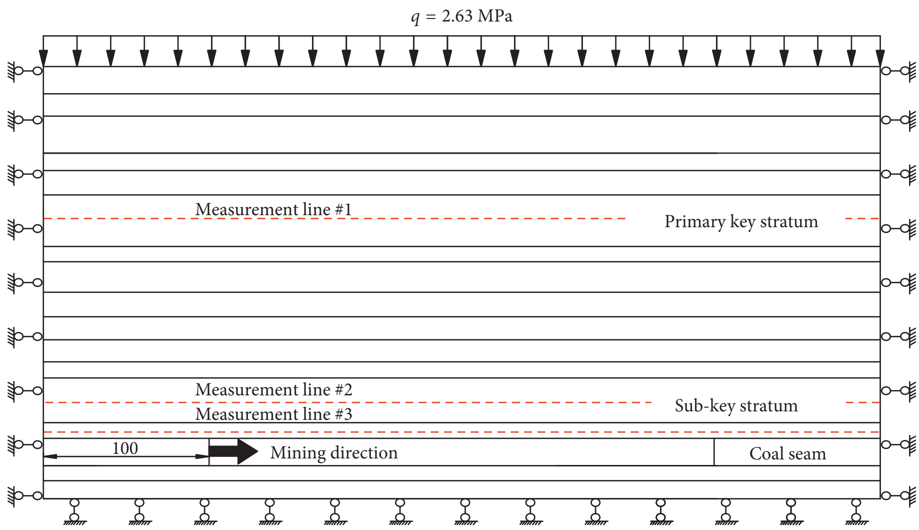


Figure 3: Schematic diagram of the numerical model and boundary conditions.

Table 1: Coal and rock interface mechanical parameters used in the model.

Strata number	Lithology	Normal stiffness (GPa)	Shear stiffness (GPa)	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)
1	Sandy mudstone	1.0	2.5	0	10	0
2	Siltstone	3.5	7.2	0	23	0
3	Sandy mudstone	1.0	2.5	0	10	0
4	Medium sandstone	3.5	7.0	0	20	0
5	Siltstone	3.5	7.2	0	23	0
6	Fine sandstone	4	8.2	0	22	0
7	Gritstone	3.6	8.0	0	14	0
8	Mudstone	0.6	2.3	0	20	0
9	Medium sandstone	3.5	7.0	0	20	0
10	Sandy mudstone	1.0	2.5	0	10	0
11	Siltstone	3.5	7.2	0	23	0
12	Mudstone	0.6	2.3	0	20	0
13	Gritstone	3.6	8.0	0	14	0
14	Sandy mudstone	1.0	2.5	0	10	0
15	Coal	0.5	2.0	0	16	0
16	Fine sandstone	4	8.2	0	22	0
17	Sandy mudstone	1.0	2.5	0	10	0

3.3. Numerical Simulation Schemes. This paper mainly researched the movement law and pressure behavior law of overburden strata at fully mechanized caving face with shallow-buried and extremely thick coal seam. As the fully mechanized top-coal caving face with shallow-buried and extremely thick coal seam continuously advanced, the emphasis of the research was to simulate the breaking law of the key strata at the fully mechanized top-coal caving face with shallow-buried and extremely thick coal seam and the pressure behavior law caused by the breakage of the key strata.

In the process of numerical simulation, the length of excavation was 10 m every time and the total length of excavation was 300 m. The specific process of simulation is as follows:

(1) The initial stress calculation function of UDEC was used to generate the gravitational field to simulate the original stress state of the strata before excavation.

(2) Under the effect of the initial stress field, the movement and deformation characteristics and the pressure behavior law of overlying strata in the mining process of shallow-buried and extremely thick coal seams were simulated. A method of continuous excavation was applied in the simulation, and the length of excavation was 10 m every time, with a total excavation length of 300 m.

(3) At different advance distances of the working face, the movement, caving characteristics, and stress distribution of the overlying strata were compared and analyzed.

(4) The monitoring data of the survey lines #1 and #2 arranged in the main and inferior key strata were extracted, and based on the data obtained, the subsidence curves of the main and inferior key strata under the condition of different advance distances of the working face were respectively drawn; the

monitoring data of the survey line #3 placed in the immediate were extracted, and based on the data gained, the vertical stress curves of the survey line #3 under the condition of different advance distances were drawn. By comparing and analyzing the curves drawn, some conclusions could be obtained.

4. Study on Strata Pressure Behavior

4.1. Analysis of Overlying Strata Movement. Monitoring data of survey lines #1 and #2 placed in the inferior key strata and the main key strata were extracted, and subsidence curves of the inferior key strata and the main key strata under the condition of different advancing distances of the working face could be obtained, as are shown in Figures 4 and 5, respectively.

It is shown in both Figures 4 and 5 that when the continuous advance distance of the working face was 20 m, there was no obvious subsidence for the inferior key strata and there was almost no subsidence for the main key strata. When the working face advanced 50 m, the subsidence of the inferior key strata increased to 11 m, meaning that the inferior key strata caved for the first time. At the moment, the subsidence of the inferior key strata beside the working face rose dramatically to 8.5 m. It could be obtained that the inferior key strata showed the characteristics of sliding instability. There was no obvious subsidence for the main key strata, with only 0.3 m. When the continuous advance distance of the working face reached 70 m, the maximum subsidence of the inferior key strata was 11.5 m, which meant that the inferior key strata occurred the periodical caving for the first time. It could be obtained from the subsidence curves of the inferior key strata that the inferior key strata showed the characteristics of sliding instability at this time. In addition, the subsidence of the main key strata increased to 0.8 m. When the working face advanced 90 m, the inferior key strata occurred the periodical caving for the second time, and its subsidence was 12 m. Compared to the subsidence of the main key strata with the advance distance of 70 m, the subsidence of the main key strata with the advance distance of 90 m increased to 3 m, rising by 2.2 m and with an increment of 275%. At this time, the main key strata broke for the first time and they showed the characteristics of rotary instability. When the continuous advance distance reached 110 m, the maximum subsidence of the inferior key strata and the main key strata was 11.5 m and 4.2 m, respectively. Compared to the subsidence of the main key strata with the advance distance of 110 m, the subsidence of the main key strata with the advance distance of 150 m increased by 1.8 m, with an increment of 43%, which meant that the main key strata occurred the periodical breakage for the first time and they showed the characteristics of rotary instability. When the continuous advance distances of the working face were 200 m and 300 m, the maximum subsidence of the main key strata was 8.8 m and the subsidence of the inferior key strata also rose, meaning that the caving rocks located at the rear of the goaf were gradually compacted with the periodical instability of the main key strata.

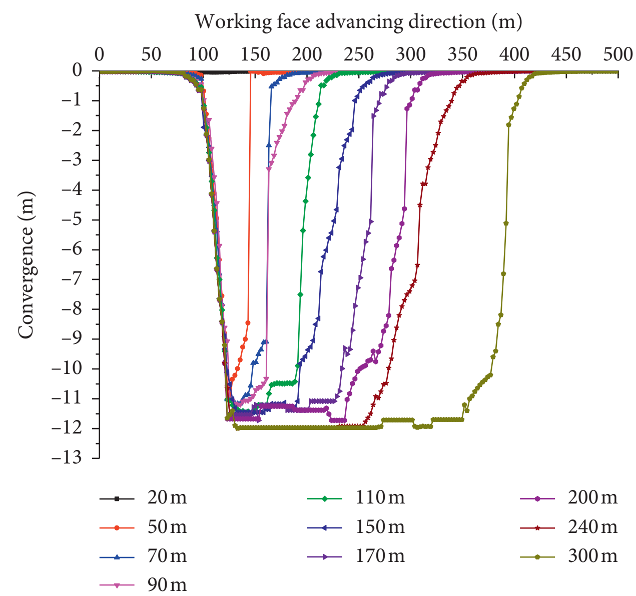


FIGURE 4: Subsidence curves of the inferior key strata.

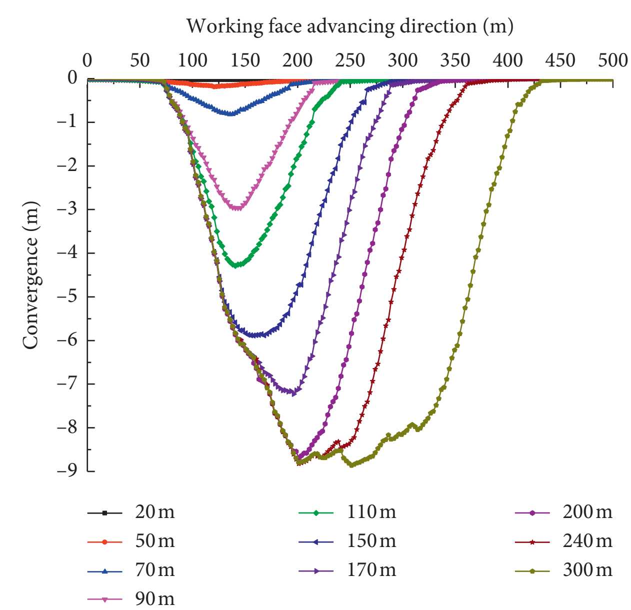


FIGURE 5: Subsidence curves of the main key strata.

4.2. The Impact of Key Strata Compound Breakage on the Strata Pressure Behavior. The plastic zone distribution of surrounding rocks in the working face under the condition of different advance distances of the working face is shown in Figure 6. The advanced support pressure and the subsidence of the main key strata under the condition of different advance distances are shown in Figure 7.

It is showed in Figures 6 and 7 that with the continuous advance of the working face, the maximum subsidence of the main key strata showed a gradually upward trend, and the abutment pressure ahead of the working face showed a wavy increasing trend. To be more specific, before the continuous advance distance of the working face reached 90 m, because the inferior key strata had occurred the initial caving and

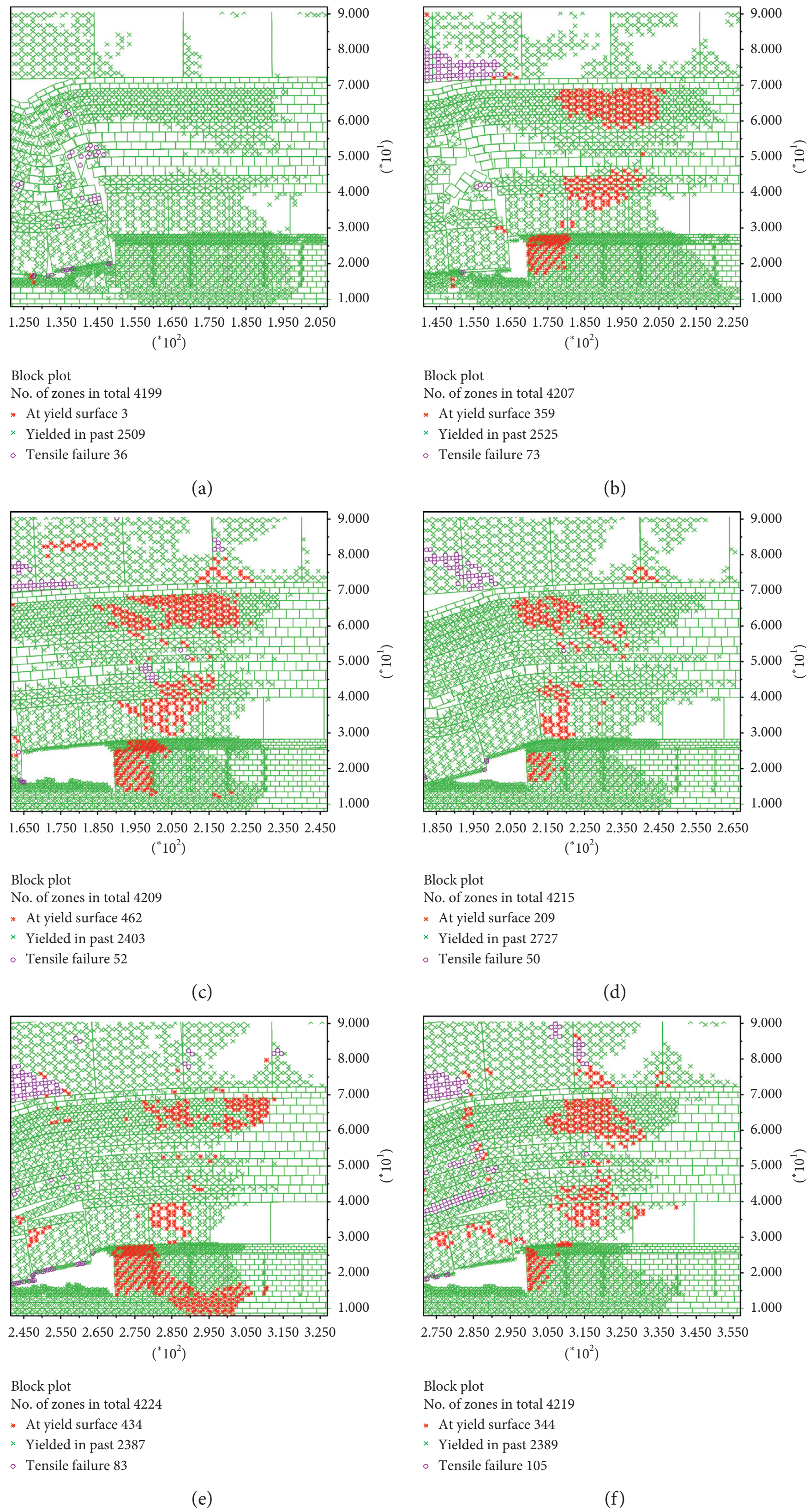


Figure 6: The plastic zone distribution of surrounding rocks in the working face under different advance distances of the working face. (a) 50 m. (b) 70 m. (c) 90 m. (d) 110 m. (e) 150 m. (f) 200 m.

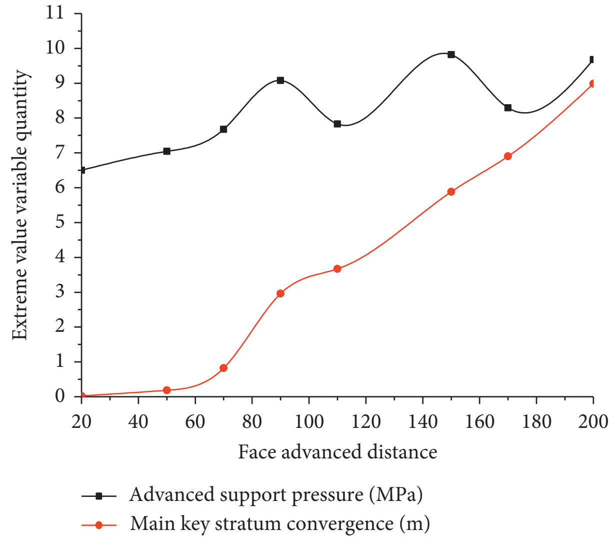


FIGURE 7: The advanced support pressure and the subsidence of the main key strata.

periodical caving, the fracture in the main key strata developed, but the main key strata did not break and lose stability, and they could still be regarded as the supporting body of the overlying strata. At the moment, both the maximum abutment pressure ahead of the working face and the maximum subsidence of the main key strata increased with a relatively slow speed. The rib ahead of the working face had the risk of spalling. When the working face advanced 90 m, the main key strata located at the anterior and upper side of the coal rib broke and lost the stability because of stretching, and they broke for the first time. At this time, both the maximum abutment pressure ahead of the working face and the maximum subsidence of the main key strata increased dramatically with a fast speed, which increased risk of rib spalling ahead of the working face. After the working face had advanced 90 m, the main key strata affected by different levels of stretching occurred the periodical breakage. When the working face advanced 110 m and 170 m, because the abutment pressure ahead of the working face was affected by the compound breakage and periodical instability of both the inferior and main key strata, the maximum abutment pressure showed a downward trend compared with that when the advance distances of the working face were 90 m, 150 m, and 200 m. The maximum of the abutment pressure ahead of the working face presented small-big-small-big periodical change characteristics. Meanwhile, the risk of rib spalling ahead of the working face presented different levels of acute or slowing trends. The maximum of the abutment pressure occurred 10 m~40 m ahead of the working face, with an affected area of 110 m~160 m.

5. Field Test

In the mining process of 1322 fully mechanized top-coal caving face, the working resistance of the hydraulic support was measured in situ. By analyzing the monitoring results of working resistance of 4 supports placed at 1322 fully mechanized top-coal caving face, the working resistance distribution of 4 supports could be obtained along with the continuous advance of working face at the initial mining stage, as are shown in Figure 8.

It could be concluded from Figure 8 that with the continuous advance of the working face, the working resistance of the hydraulic support increased steadily. When the advance distance of the working face reached 50 m, the working resistance values of the 25#, 50#, and 60# supports soared, which were close to the rated working resistance of the hydraulic support. This meant that the inferior key strata of the working face collapsed for the first time, resulting in hydraulic supports placed at the working face crushing with a large area. The first weighting interval of the inferior key strata was about 51 m, which was basically consistent with the results obtained from numerical simulation.

The working resistance distribution of the 4 hydraulic supports along with the advance of the working face at the normal mining stage is shown in Figure 9.

It could be obtained from Figure 9 that, at the normal mining stage, when the working face advanced from 567.9 m to 698.3 m with advance distance of about 130 m, the working resistance of 4 hydraulic supports occurred the peak pressure for 8~10 times, meaning that the roof regularly broke and caved for many times. The average periodical weighting interval of the roof at the 25# and 50# support was about 15.1 m and 12.1 m, respectively. The average periodical weighting interval of the 4 supports was about 12.6 m. There was no significant difference in the average periodical weighting interval of each support. The pressure duration of the roof in the middle of the working face was relatively longer, while the pressure duration of the head and tail was relatively shorter.

6. Conclusion

This paper took the 1322 fully mechanized caving face in Jindi Coal Mine in Xing County as the engineering background. Under the condition of different advance distances, UDEC numerical simulation software was applied to analyze

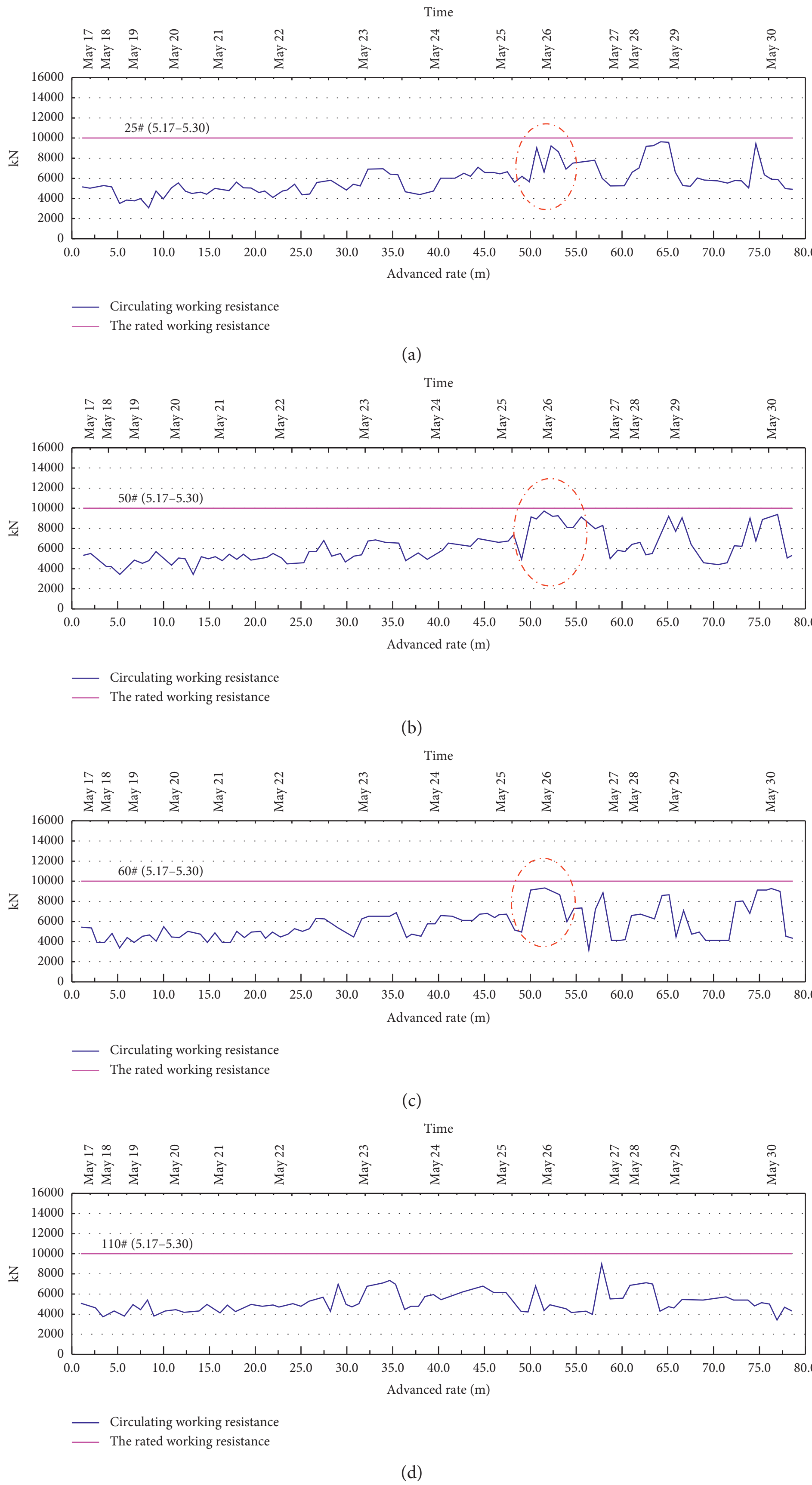
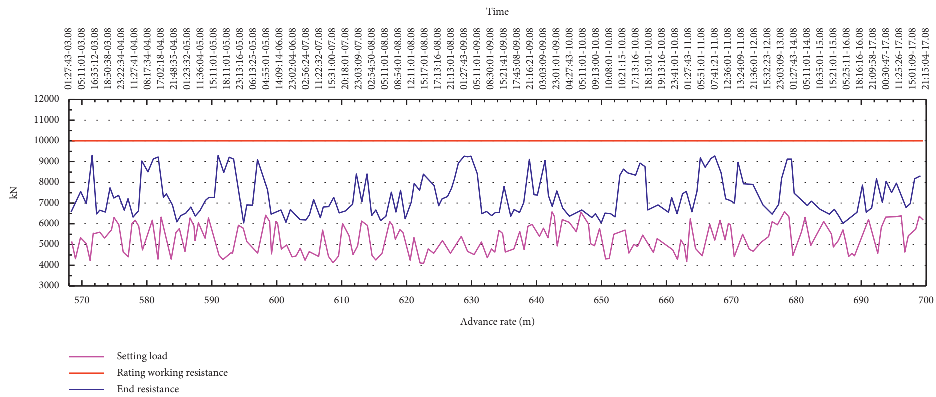
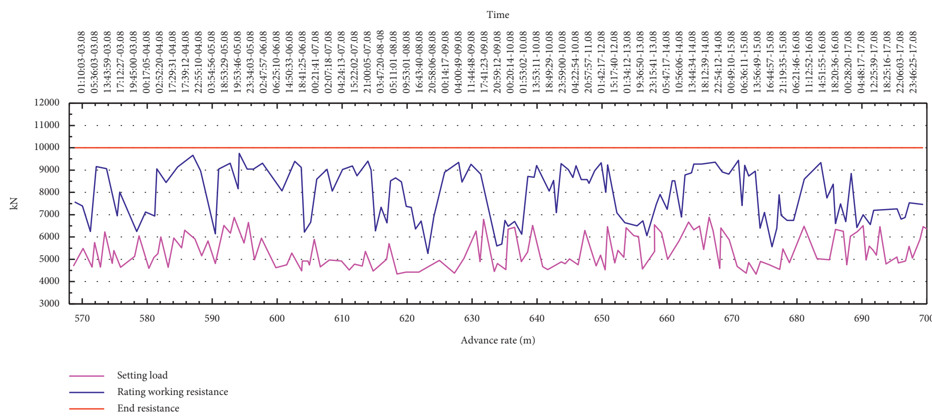


Figure 8: The working resistance distribution of hydraulic supports placed at different parts of working face at the initial mining stage. (a) 25# support. (b) 50# support. (c) 60# support. (d) 110# support.



(a)



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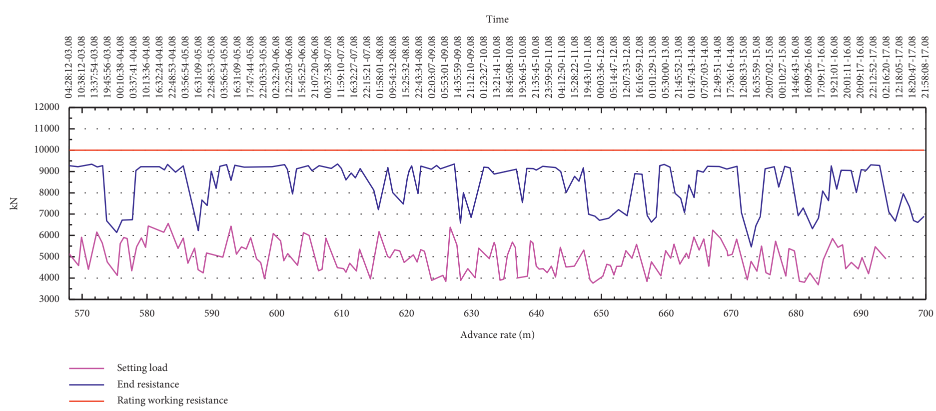

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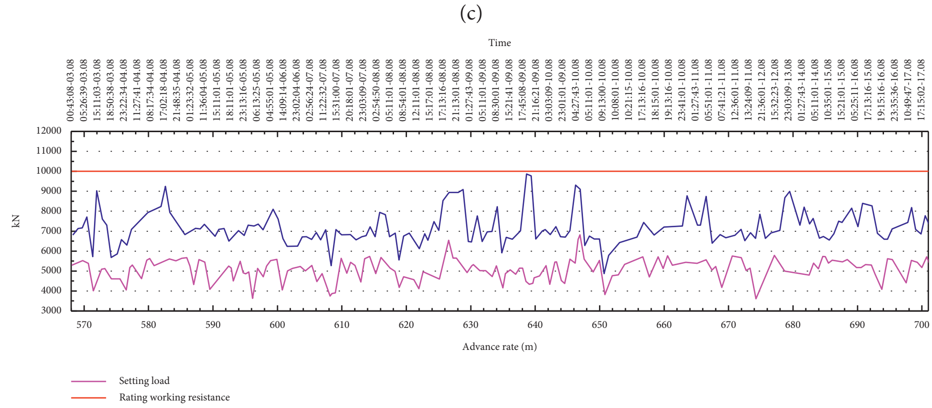

(d)

Figure 9: Working resistance distribution of hydraulic supports at different positions of working face at the normal mining stage. (a) 25# support. (b) 50# support. (c) 60# support. (d) 110# support.

overlying strata movement and strata pressure behavior during the fully mechanized caving mining in shallow and extremely thick seams. The impact of compound breakage of both the inferior and main key strata on strata pressure behavior was analyzed, and the results of numerical simulation were verified by in situ measurement. The conclusions are as follows:

(1) After the inferior key strata above fully mechanized caving face in shallow and extremely thick seams broke and caved, they could not form stable block structure of the voussoir beam. The initial caving distance of the inferior key strata was 50 m, and the inferior key strata presented the characteristics of sliding instability. In addition, their periodical caving distance was about 20 m and showed the characteristics of sliding instability of the step voussoir beam.

(2) The initial and periodical caving distances of the main key strata above fully mechanized caving face in shallow and extremely thick seams were about 90 m and 50 m respectively, presenting the characteristics of rotary instability. The caving rocks behind the goaf were gradually compacted because of the periodic instability of the main key strata. With the continuous advance of the working face, the maximum subsidence of the main key strata showed a gradually increasing trend.

(3) With the continuous advance of the working face, the abutment pressure ahead of the working face presented a wavy increasing trend. After the working face had advanced 90 m, because the abutment pressure ahead of the working face was affected by the compound breakage and periodical instability of both the inferior and main key strata, its maximum presented small-big-small-big periodical change characteristics. What is more, the risk of rib spalling ahead of the working face presented different levels of acute or slowing trends. When the main key strata occurred the initial breakage and periodical breakage, the maximum value of the advanced support pressure was relatively large, and the location of the maximum was away from the working face with a relatively large affected area.

(4) It could be obtained from the in situ measurement of strata pressure behavior in the mining process of the working face that the initial weighting interval of the inferior key strata and the average periodical weighting interval were about 51 m and 12.6 m, respectively, which were consistent with the results obtained by numerical simulation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

Acknowledgments

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