

Research Article

Comprehensive Measurement of the Deformation and Failure of Floor Rocks: A Case Study of the Xinglongzhuang Coal Mine

Hao Liu,¹ Pu Wang^(b),² Weihe Zhang,³ Qiang Liu,³ and Lijun Su³

¹College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China ²College of Resources, Shandong University of Science and Technology, Tai'an 271019, China ³Yanzhou Coal Mining Co. Ltd., Yankuang Group, Xingloangzhuang Coal Mine, Jining, 272102 Shandong, China

Correspondence should be addressed to Pu Wang; 15854848872@163.com

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The isolated island panel 10304 of the Xinglongzhuang coal mine was used as the research subject to study the deformation and damage characteristics of the coal seam floor. The damage of the floor was studied using the borehole strain sensing method and borehole imaging technology, and FLAC3D was used to study the influence of abutment pressure on floor failure. The result shows that the floor under the superimposed area which is affected by lateral and advanced abutment pressure is damaged firstly, and the maximum depth reaches 26 m, other areas of the working face about 23 m. The degree of deformation and failure of floor rock at different depths is decreased. The deformation damage increases with the advancement of the working face until a certain distance at the same depth. The hole image can clearly show the influence range of the abutment pressure in front of the coal wall and influence the degree of the advancement and lag by means of the strain increment curve for each sensor probe and the images from different drilled positions. On the basis that the results of simulation and field measurement are consistent, the results can reflect the three-dimensional failure characteristics of the whole island working face floor in the process of coal mining more comprehensively and accurately; moreover, they also can provide important information for mine flood prevention and ecological environment protection.

1. Introduction

Mine water inrush accidents not only destroy the underground construction environment but also threaten the safe production of coal mines, and coal seam floor water inrush is a common type of coal mine water inrush accident [1–3]. When a coal seam is mined, the abutment pressure shifts to the deep part of the floor, causing deformation and damage within a certain range of the underlying strata of the floor [4–8]. A water inrush accident will happen if the floor damage zone communicates with the underlying aquifer when there is an aquifer in the underlying strata of the floor. Therefore, it is of great significance and practical application value to grasp the failure and deformation law of coal seam floors and determine the damage depth of the floors to guide safe coal mine production [9, 10].

In recent years, many scholars have studied the damage characteristics of coal seam floors and obtained many research results. At present, the research methods for the deformation and failure characteristics of the floor can be divided into three types, theoretical analysis and calculation methods, indoor simulation test methods, and software simulation methods. As for theoretical analysis and calculation methods, Cai et al. [11] regarded the rock mass of a floor as a semi-infinite uniform medium and, according to the law of abutment stress, proposed an analytical estimation formula for the maximum mining failure depth of the floor for a circular arch structure of overburden strata. Shi et al. [12] analyzed the influencing factors of multiple floor failures, and a multivariate linear regression analysis method was used to fit the nonlinear regression formula for predicting the depth of the damage of the floor. Liu et al. [13], who established a mechanical model for the failure degree of a floor based on the theory of elastic mechanics, used the matrix analysis method and the analysis of variance to determine the sensitivity of each main control factor on the depth

of damage of the floor. Yu et al. [14] analyzed the factors affecting the depth of floor failure, and the BP neural network was used to establish a prediction model for the depth of the floor failure. However, due to the complicated underground conditions, the theoretical calculation results are often not sufficiently accurate.

For indoor simulation test methods, Liu et al. and Song et al. [15–17] performed similar indoor simulations to analyze the failure deformation of the floor during the mining process. This method has high requirements for laboratories and is not widely used. For software simulation methods, Cai et al. and Zhu et al. [18–20] used FLAC3D and UDEC software. These two numerical simulation software programs are used to simulate the failure deformation of floors during mining. However, the deformation and failure characteristics of the floor are related to many factors, such as mining depth, working face size, water pressure, cohesion, and friction angle; the software simulation often fails to accurately grasp the actual situation on-site.

Compared with the above methods, the field measurement method is the most reliable and effective method to reveal the deformation and damage of the mining floor. The damage depth of the floor can be measured by various methods. At present, the most common methods are the borehole water injection method, borehole acoustic wave method, borehole imaging method, and borehole strain method [21-26]. The borehole water injection method and the borehole acoustic wave method arrange measuring points on both sides of the coal roadway and carry out comparative tests before and after the mining of the measuring points. Most of the roadways after mining are damaged under normal mining conditions unless special safeguard measures are taken. It is difficult to conduct comparison tests at the original points (measuring points before mining), and most of the measuring point data before mining is in the vicinity of the measuring point at present [27-30]. Since the deformation of the floor has a certain hysteresis with respect to the advancement of the working face, the deformation of the floor can reach a sufficient degree after the working face is advanced. Therefore, the reliability of the data obtained by these methods is relatively low. Compared with the borehole strain method, strain gauges at different depths of the floor can be used to continuously monitor the deformation of the floor during the mining process. According to the test data, the range of influence of the mining pressure and the stress concentration in front of the coal wall can be determined, and the test data of the probes at different depth positions can reflect the difference in the vertical deformation of the floor and thus determine the depth range of the floor failure.

Therefore, to study the deformation and failure law for the floor of the island face in the Xinglongzhuang coal mine and to determine the depth of the floor failure, this test used the borehole strain sensing method and borehole imaging technology to obtain the floor stratum disturbance and reliable data on characteristics and the depth of damage during the mining process. This study provides a reliable basis for safe mining of coal mines.

2. Engineering Background

The Xinglongzhuang coal mine of Shandong Province is located in North China. According to the drilling data of the mine, the minefield strata are Quaternary, Jurassic, Permian, Carboniferous, and Ordovician from the top to the bottom, among which the Carboniferous Permian system (C-P system) is the main coal-bearing strata. Panel 10304 employed longwall mining with the top coal caving method. The No. 3 seam was mined with a thickness of approximately 8.9 m and a dip angle of approximately 8°. The horizontal elevation of the working face is -550~-380 m, the ground elevation is approximately 47 m, the working face is 2200 m long, and the width is approximately 200 m. Both sides of the 10304 working face have been mined out. The direct floor of the No. 3 seam is mudstone, and the main floor is sandstone. There is a confined aquifer in the minefield, which is located under the No. 3 seam floor, 28~46 m away from the No. 3 seam floor, with an average length of 36 m The average thickness of the aquifer is 5.2 m, the capacity of the water inflow is 0.018~0.26 L/s·m, and the highest water pressure is 5.8 MPa. Because the aquifer is close to the floor of the 10304 working face and the water pressure is large, the water inrush from the floor of the 10304 working face cannot be ignored. Figure 1 shows the hydrogeological and comprehensive column diagram of the No. 3 seam under the minefield. Because of the heavy abutment pressure of the island working face, the close distance between the floor of the 10304 working face and the aquifer, and the huge hydraulic pressure, the water inrush from the floor of the 10304 working face cannot be ignored.

3. Field Strain Measurement

3.1. Strain Test. The borehole strain test method involves burying the strain sensor probe at different depths of the working face by means of drilling and determining the degree of influence and depth of the floor by testing the degree of deformation of the rock strata at the position of the measuring points of the floor during the mining process. This type of probe [31] is sensitive to the deformation of the surrounding rock, and the degree of deformation of the surrounding rock can be visualized by the probe test data. When the working face is far from the probe position, the test data of the probe are relatively stable such that the mining pressure has not reached the measuring point. When the mining pressure is applied to the measuring points, the probe test data will change synchronously with the degree of influence.

Figure 2 shows the internal structure of the strain probe. Each strain probe has two axial strain points and two radial strain points. The outer wall of the probe is made of highelastic plastic material, which is evenly stressed, has high elastic sensitivity, and has good sensitivity to damage and deformation. It should be noted that when the test hole is severely deformed, which will cause the outer wall of the probe to be severely twisted or damaged, the test data may exhibit high dispersion, disordered fluctuations, or even failure (the strain gauge has no reading). Therefore, the abnormal condition

Geofluids

Strati- graphic	Thickness (m) <u>max-min</u> average		Stratum		Composition
Carbon- iferous Permian (C-P)	<u>6.2-10.4</u> 8.9				3#coal
	<u>_24.1-36.3</u> 				Sandstone and mudstone (water-resisting stratum)
	<u> </u>	$\left \right $	111.111.		6#coal
	<u>2.3-14.5</u> 8.3				water-resisting stratum
	<u>1.3-6.7</u> 5.2				Aquifer
	7 <u>168-222</u> 196				Siltstone, medium sandstone and mudstone

FIGURE 1: Comprehensive column diagram of the hydrogeology of the underlying strata.



FIGURE 2: Schematic diagram of the strain probe.

described above can also reflect the destruction of the floor stratum formations.

3.2. Borehole Imaging Method. Borehole imaging observation is a testing technique that allows the visualization of rock formations. In the floor borehole, the sliding rod is connected to the imaging probe, and the rock stratum structure image of the borehole hole wall of the working face is obtained by stretching and retracting the sliding rod. The degree of influence of mining on different depths of the rock strata under the floor is determined by observing the change in the rock structure of the drilling hole wall in the process of mining.

3.3. Layout of Measuring Points. According to the actual and test conditions of the 10304 panel, the observation hole is arranged in the roadway of the lower panel. The elevation of the roadway is -449 m, the vertical height of the distance

from the No. 3 seam is 41 m, three measurements are arranged, and holes 1 and 2 are strain test holes. Hole 3 is the imaging observation hole, as shown in Figure 3.

Considering the position of the aquifer in the lower part of the 10304 panel and referring to the existing empirical data of the floor breaking depth [32, 33], the test range for the destruction and deformation of the mining floor is controlled to a depth of approximately 30 m at the underlying distance of the coal seam. A schematic diagram of the drilling arrangement and floor rock formation is shown in the figure as follows.

As shown in Figure 4, the 1st and 2nd strain measuring boreholes are set up with 5 strain sensor probes. The top-down measuring points in the No. 1 test hole are 1-1, 1-2, 1-3, 1-4, and 1-5. The vertical heights from measuring points from the coal seam floor are 5.4 m, 12.6 m, 17.3 m, 24.1 m, and 29.8 m, respectively. The top-down measuring points in the No. 2 test hole are 2-1, 2-2, 2-3, 2-4, and 2-5. The vertical heights from measuring points from the coal seam floor are 6.2 m, 13.8 m, 20.1 m, 25.3 m, and 30.2 m, respectively.

According to the mining and geological conditions of the working face, there are no faults or other special structures between the strain test hole and the imaging observation hole. Accordingly, the design parameters of the imaging observation hole and the strain test hole are the same, and the drilling parameters are shown in Table 1.

3.4. Observation Methods. Considering that panel 10304 is fully mechanized for caving mining in thick coal seams and that the working face is an island working face, the mining stress is concentrated and the influence range is wide [34, 35]. The strain test range is designed to be 230 m, of which the advanced range is 150 m. The lagging range is 80 m, and



FIGURE 3: Panel 10304 borehole layout.

8.7m	3#coal		8.7m	3#coal	
6.5m	Medium sandstone		6.5m	Medium sandstone	
17.8m	Siltstone	17.3m	17.8m	Siltstone	6,241 15 8m
7.4m	Mudstone	24.1m	7.4m	Mudstone	
0.3m	6#coal		0.3m	6#coal	25.3m
5.1m	Siltstone	29.8m	5.1m	Siltstone	30.2n
4.6m	Limestone		4.6m	Limestone	
6.4m	Mudstone		6.4m	Mudstone	<u>75</u> °

FIGURE 4: Layout of strain boreholes.

TABLE 1: Design parameters of the boreholes.

Borehole parameters	
Opening diameter (mm)	110
Diameter (mm)	80
Borehole elevation angle (°)	75
Angle between the drilling hole and the strike line of the coal and rock seam	90
Hole depth (m)	38.3

the mine pressure induction and deformation of the measuring point in the recovery process are tested. For the observation frequency, the measurement is started when the distance between the end face and the test borehole is 150 m. When the distance between the end face and the test hole is 150~90 m, a set of data is measured every 20 m of the advancement of the working face. When the distance between the end face and the test hole is 90~60 m, a set of data is measured every 15 m of the advancement of the working face. When the distance between the end face and the test hole is $-40 \sim 60$ m ("-" represents advancing past the measuring point), a set of data is measured every 10 m of the advancement of the working face. When the distance between the end face and the test hole is $-80 \sim -40$ m, a set of data is measured every 20 m of the advancement of the working face. To avoid an abnormal situation during the test, three sets of data are measured for each observation. The interval between each set of data is approximately 30



FIGURE 5: The increment of axial strain and radial strain of the No. 1 hole.

minutes, and the average value is taken as the corresponding observation result.

4. Result Analysis of Field Observations

4.1. Result Analysis of the Strain Observation. In this paper, the strain is measured by the strain sensors which each has four strain gauges marked as a, b, c, and d. Among them, gauges a and b measure the axial strain, while gauges c and d measure the radial strain. However, during the process of actual measurement, abnormal points of strain response (corresponding to large discreteness) may appear, which is caused by the serious deformation, fracture, or rock outburst of the hole wall, thereby resulting in serious damage of the sensors; hence, these abnormal points should be removed [36]. Figures 5 and 6 depict the strain increment of the aforementioned four sensors in two borehole positions marked as Nos. 1 and 2.

In Figures 5 and 6, it can be seen that all the measuring points show the obvious advances and delay induction caused by the stratum behaviors during the mining process. For instance, when the distance between the face and the measuring holes is approximately 100 m, obvious strain appears successively at the measuring points, and it still exists with the advance exceeding 80 m, which indicates that the large range of floor is affected by mining activities.

Moreover, the strain response range for different depth measurement points is different. In Figure 5, the strain sensing range of 1-1-1-5 measuring points depicts $100\sim-80$ m, $80\sim-80$ m, $60\sim-80$ m, $50\sim-80$ m, and $50\sim-80$ m. And the results of the No. 2 borehole (shown in Figure 6) are similar to those of the No. 1 measuring hole, indicating that the influence range is affected by mining gradually from shallow to deep.

Compared with the measuring points with shallow positions of Figures 5 and 6, the strain increment and strain



FIGURE 6: The increment of axial strain and radial strain of the No. 2 hole.

fluctuation amplitudes of these deep measuring points (1-4, 1-5, 2-4, and 2-5) are relatively small, showing that the mining disturbances in the surrounding rock of the deep measuring points are mainly elastic waves and the rock does not have a large plastic deformation. Considering that the buried depth of measuring points 1-4 and 2-4 is 24~25 m from the coal floor, the elastic characteristics of the strain respond obviously, which is in sharp contrast with the straininduced anomaly with overlying measuring points. Therefore, both measurement points and the following locations are not destroyed by the mining pressure, so it can be determined that the floor failure depth is approximately 24 m during the mining process of panel 10304.

From the strain response of the measuring points, the strain response of all the measuring points shows an obvious

axial strain and weak radial strain. Since the test hole is arranged at a large elevation angle, the axial direction of the sensors is similar to the normal direction of the rock strata, and the radial component of the pressure is small, resulting in a weak strain. This indicates that the force of the sensors is mainly due to axial compression and axial extension, the radial force is weak, and the corresponding deformation of the floor is similar to the compression or tension that is close to the normal direction of the rock strata.

4.2. Imaging Observation Results. To obtain the necessary contrast basis, the observation is carried out when the distance between the face end and the imaging observation hole is 150 m, 38 m, -16 m, and -60 m, and four sets of video data at different stages of the imaging observation hole are



(a) L = 156 m



(0) L = 50 III

FIGURE 7: Continued.



(c) L = -16 m



(d) L = -60 m

FIGURE 7: Image of the damage and deformation at a vertical depth of 10-11 m ("L" is the distance from the face end to the measuring hole).

obtained. Due to the limited space of the article, only three observation results are given here, which are 10-11 m, 22-23 m, and 26-27 m (Figures 7–9) from the vertical depth of the floor. These results show the deformation and failure of the borehole wall during the mining process.

It is clear from Figures 7–9 that with the advancement of the working face, the wall of the hole 10~11 m from the floor

has gone through four stages: completion, fracture development, partial destruction, and global destruction. These stages reflect the gradual destruction process of the wall of the hole at shallow depths. There is local deformation damage to the hole of the wall at a depth of 22~23 m (Figure 8), and the floor depth is 26~27 m. There is no obvious trace of disturbance deformation, which indicates that the degree of



FIGURE 8: Image of damage and deformation at the vertical depth of 22-23 m.

deformation and failure of the rock mass at different depths during the advancement of the working face decreases with increasing depth.

According to the observation results, it is found that the degree of deformation of the surrounding rock of the hole is essentially changed at a floor depth of 23 m, which is not much different from the above strain test results. Based on the correlation analysis between the strain test results and the borehole imaging, the depth of the mining disturbance of panel 10304 can be determined to be approximately 23 m. Among them, the rock strata in the range of 0~23 m in the vertical depth of the floor are damaged by mining, mainly due to plastic deformation, and the range of plastic displacement is large. The rock strata below the failure zone are affected by mining, which is mainly due to elastic deformation, and it has a good bearing capacity and strong impermeability based on the intact structure results.

5. Numerical Simulation of Failure Characteristics of Floor Rocks

In order to explain the failure law of floor rock in panel 10304 well, FLAC3D numerical simulation software is used to simulate the development of the floor plastic zone. The model with $400 \times 300 \times 128$ is built according to actual conditions, as shown in Figure 10. Both sides of the working face are filled goaf, and the direction *y* is advanced direction. The monitoring plane is arranged at the position of *y* = 100 m. The Mohr-Coulomb constitutive model and Mohr-Coulomb failure criterion are used to calculate the mining failure characteristics of the coal seam floor. The geomechanical parameters of each stratum are shown in Table 2.

Figure 11 shows the development of the plastic zone of a plane with y = 100 m and the distribution of abutment stress of floor rock depicted in the monitoring plane when the island face advances to 10 m, 50 m, 70 m, 90 m, 110 m, and 150 m. If *L* is the distance between the monitoring plane and the working face, then *L* can be regarded as 90 m, 50 m, 30 m, 10 m, -10 m, and -50 m, respectively.

As shown in Figure 11(a), the monitoring plane has not been affected by mining activities when the working face advances 10 m (L = 90 m); it is only affected by the lateral abutment stress. A small part of the coal seam floor has plastic failure under the peak value of lateral stress, and the failure depth is only 4 m. With the continuous advance of the working face, the floor rock marked as area A is first destroyed under the superimposed influence of the advance abutment stress and the lateral abutment stress, and the



(c) $L = -16 \,\mathrm{m}$

(d) L = -60 m

FIGURE 9: Image of damage and deformation at the vertical depth of 26-27 m.

maximum failure depth is 22 m with L = 30 m. However, the floor rock marked as area B is not destroyed. With the working face gradually approaching the monitoring plane, the influence of the advance stress on floor rock is greater and area B starts to plastically fail. When L = 10 m, the maximum failure depth of the floor rock of area A is 26 m, while that of area B is 14 m; the abutment stress decreases rapidly, and the floor rock around 10304 goaf changes from triaxial to biaxial, causing the rock plastic failure of area B to develop rapidly. Then, the rock failure depth of area A is unchanged when L = -10 m, and the average failure depth of area B rises to 22 m. Since then, the mining activities have little influence on the depth and scope of floor failure on the monitoring plane.

Through the aforementioned analyses, the floor rock of the island working face can be roughly divided into area A and area B, according to the development characteristics and failure depth of the plastic zone of the floor. During the mining process, the floor rock of area A is first destroyed with the superimposing effect of the advance abutment stress and



FIGURE 10: Layout of the working face and the monitoring plane.

TABLE 2: The geomechanical p	parameters of each stratum.
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Rock	Density (g·cm⁻ ³)	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Friction angle (°)	Tensile strength (MPa)
Medium sandstone	2750	3.1	2.7	6.2	32	3.6
Siltstone	2600	2.6	1.6	4.7	30	2.5
3#coal	1400	1.1	0.3	1.2	22	0.6
Mudstone	2500	1.8	0.5	2.2	26	1.6
Limestone	2800	8.4	5	13.2	36	5.5

lateral abutment stress, which is earlier than area B. The plastic failure of the goaf floor presents an inverted saddle shape, and the maximum rock failure depth of area A is 26 m while that of area B is 22 m. The numerical simulation results are basically consistent with the measured results, indicating that the numerical simulation results are reliable; meanwhile, the limitation of the field measurement range is made up by methods of numerical simulation. Thus, the combination of the numerical simulation method and field measurement could more reflect comprehensively and accurately the 3D failure characteristics of the floor of the whole island working face affected by mining activities.

6. Conclusion

Using the strain sensing method and borehole imaging technology to observe and analyze the failure deformation law of the floor during the mining process of panel 10304 in the Xinglongzhuang coal mine, the following conclusions can be drawn:

(1) According to the correlation analysis between the strain test results and the borehole image, it can be determined that the depth of the floor damage is approximately 23 m during the advancement of panel 10304. The test results can provide a reliable basis for the safe mining of other working faces in the upper part of the aquifer in the Xinglongzhuang coal mine

- (2) The degree of deformation and failure of the rock mass at different depths of the floor during the advancement of the working face decreases with increasing depth. The deformation damage increases with the working face advancement until a certain distance is reached at the same depth
- (3) By means of the strain increment of each sensor probe and the borehole image at different positions, the influence range of the advancing abutment pressure in front of the coal wall and the influence degree of the advancement and lag can be reflected. The successful application of the integrated measurement method provides a new idea for studying the influence range of mining pressure and the influence degree of advancement and lag
- (4) Numerical simulation results show that the floor rock of area A is first destroyed firstly due to the superimposed influence of the advance abutment stress and







FIGURE 11: Abutment stress distribution and development of the plastic zone with plane y = 100 m.

the lateral abutment stress, which is earlier than area B. The plastic failure of the goaf floor presents an inverted saddle shape, and the maximum rock failure depth of area A is 26 m while that of area B is 22 m. The failure shape and failure depth are consistent with the results of field measurements

(5) On the basis that the simulation results of failure characteristics of the floor are consistent with the field measurement results, the combination of the numerical simulation method and field measurement could more reflect comprehensively and accurately the 3D failure characteristics of the floor of the whole island working face in the mining process

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 no conflicts of interest.

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