

Article

Study on Coal Seam Roof Failure Based on Optical Fiber Acoustic Sensing and the Parallel Electrical Method

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Abstract: As China enters the stage of deep coal mining, the accidents caused by roof failure pose increasingly serious threats. Current research on roof failure zones often use single methods, but single geophysical data may result in multisolution issues during interpretation. This paper employed similar simulation experiments, exploring the strain failure characteristics and the changes in apparent resistivity caused by stress variations, taking the 11-3106 working face of a mining area as the research object. Through optical fiber strain and apparent resistivity, the locations and degrees of fracture in postmining rock strata were identified. The feasibility of using distributed optical fiber sensing and the parallel electrical method for qualitative and quantitative analysis of mining-induced fractures was verified. The results showed that optical fiber strain increased significantly at the location of rock fracture, with apparent resistivity anomalies rising correspondingly. The peak strain region corresponded well with the region of apparent resistivity anomalies. In a similar simulation with a geometric ratio of 1:100, the height of the caving zone was measured to be 31.65 cm, with a caving-to-mining ratio of 6.33. In the field working face, the caving zone height was 29.47 m, with a caving-to-mining ratio of 6.01, consistent with the actual conditions of the 11-3106 working face.

Keywords: mining roof failure; safe mine recovery; optical fiber sensing technology; parallel electrical method; optical–electrical combined monitoring



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1. Introduction

With decades of sustained mining, shallow coal seams in China are depleting, and mineral resource development has entered the second deep space [1–4]. Deep rock masses exhibit stronger rheological properties than shallow ones, and under the combined effects of high stress, temperature, and humidity, geological disasters caused by strong stress have become more frequent [5–10]. Mining-induced rock mass rotation and failure create tensile and compressive fractures, providing major pathways for groundwater, gas, and slurry, posing significant threats to mine safety [11–14].

Numerous studies have been conducted to find out the failure mechanisms of coal seam mining roofs. Academician Qian, for example, conducted a series of studies on the failure mechanism of coal mining roofs and proposed the key stratum theory, pointing out that the movement of mining strata is a mechanical behavior of stress concentration and release before and after the failure of hard strata [15,16]. Li et al. analyzed the evolution law of mining-induced fractures in rock strata based on the key stratum theory. They proposed that in the study of mining-induced fractures, a combination of multiple technical methods should be employed to minimize the limitations of relying solely on electrical

methods [17]. Wang et al. analyzed the temporal and spatial coupling laws of stress and fractures during deep mining and found that the distribution of the fracture field exhibited a strong temporal and spatial pattern, with the damage range maintaining a synchronized and coordinated relationship with the mining progress [18]. Lu et al. used in situ experiments to analyze the mining-induced stress patterns in ultradeep mines over 1000 m and found that the support pressure remained stable after reaching a certain value [19]. Deng and Liang et al. analyzed the fracture inducement mechanism and three-dimensional spatial characteristics of overburden strata [20,21]. Wang et al. used FLAC3D technology to analyze the impact of thick sandstone at different positions and thicknesses on the development of fracture patterns. They found that the evolution of overburden mining-induced fractures gradually changed from rectangular and L-shaped patterns to a saddle-shaped form [22]. Li et al. made comparative revisions to the theory of fracture analysis of surrounding rocks using dynamics [23]. Wang et al. analyzed the electrical distribution patterns in different roof fracture zones. It was found that the apparent resistivity of the overburden changed significantly because of the impact of mining activities [24]. Kan et al. used the parallel electrical method to investigate the distribution of water-bearing layers in the roof [25]. Yang and Liu analyzed the dynamic changes in the resistivity of a coal seam mining roof under complex conditions using the parallel electrical method [26]. They validated the effectiveness of using resistivity for monitoring the roof and floor. Li et al. utilized the stress–strain sensitivity of fiber optics to study the interlayer fractures in coal mine underground reservoirs, successfully monitoring the development patterns of these fractures [27]. Liu et al. used distributed optical fiber sensing technology to analyze the optical fiber coupling of roof overburden fractures in experiments and validated the effectiveness of using fiberoptic strain peaks to characterize the overburden failure zone. [28]. These achievements have promoted research and development on coal seam mining roofs, and research results have become increasingly abundant, playing a non-negligible role in guiding mine production. However, in practical applications, because of the complex on-site environment, drilling, the parallel electrical method, and other single geophysical exploration methods are often used to detect roof fractures, which have problems such as insufficient accuracy and discrete data. With advancements in technology, the monitoring technology for deformation and failure of surrounding rocks in mining areas is bound to develop in the direction of diversified, multiparameter, intelligent, full-process monitoring [29,30].

This paper proposes the use of combined monitoring techniques with distributed optical fiber sensing technology and the parallel electrical method to monitor and analyze the roof failure process using different data parameters. By mutually correcting strain and apparent resistivity, the fracture locations and damage extent of the roof strata during coal seam mining can be calibrated. To achieve this, a similar model was constructed based on the actual working face conditions, and the fracture patterns of the mining roof were analyzed and summarized by simulating the mining process. A comparative analysis of the temporal and spatial variation patterns of the fiberoptic strain field and the apparent resistivity during roof failure was conducted, and the roof damage after mining in the 11-3106 working face was predicted. The simulation experiments revealed a clear periodicity in the roof strata collapse during mining, and the collapse shape of the roof after mining was saddle-shaped, validating previous studies on roof fracture patterns. During field measurements at the working face, distributed optical fiber sensing technology and the parallel electrical method successfully monitored the roof failure process, verifying the effectiveness of the combined techniques in monitoring roof conditions in mines. Compared with single monitoring methods, combined monitoring techniques are more sensitive to roof fractures, with the monitoring data mutually validating each other, reducing the impact of data nonuniqueness on the results, improving monitoring accuracy, and deepening the understanding of the monitored area.

2. Materials and Methods

During the mining process, roof strata are prone to fracturing under stress, and the presence of fractures can lead to changes in the electrical conductivity of the strata, manifested as an increase or decrease in apparent resistivity on the apparent resistivity map. Depending on its direction, stress applied to the strata can be broadly classified into tensile stress and compressive stress. Tensile stress exceeding the tensile strength causes longitudinal fractures and decreased conductivity, while insufficient support leads to bending and bedding separation fractures, also causing conductivity degradation. In the lateral regions, compressive stress exceeding the strata's bearing capacity causes compaction and closure of fractures, providing a physical basis for the parallel electrical method.

In optical frequency domain reflectometry (OFDR), Rayleigh scattering in optical fibers arises from the inhomogeneity of the fibers' refractive index. When light waves enter the fiber gratings, they undergo elastic collisions with particles in the medium, causing Rayleigh scattering. As the external environment changes, the reflection spectrum of Rayleigh waves shifts. Rayleigh scattering can be approximated as a weakly reflecting fiber Bragg grating (FBG) with a random period, and the spectral shift is linearly related to external strain and temperature. Using OFDR and optical fiber sensors installed in the roof, the locations of stresses and strains can be accurately calculated, with positioning errors typically controlled at the millimeter level. The analytical formula is:

$$\Delta\lambda/\lambda_0 = -\Delta v/v = K_T \Delta T + K_\varepsilon \varepsilon \quad (1)$$

where $\Delta\lambda$ is the shift in the Rayleigh scattering spectrum, λ_0 is the center wavelength of the linearly swept light, ΔT is the temperature change, ε is the strain, K_T is the temperature sensitivity coefficient of the spectral drift, and K_ε is the strain sensitivity coefficient of the spectral drift.

As shown in Figure 1, with increasing advancing distance of the working face, the overlying strata are destroyed, which changes the grating shape inside the optical fiber to a certain extent. Taking the Rayleigh spectrum unaffected by the external environment as the reference spectrum, the reference spectrum and the measured spectrum are mutually calculated to obtain:

$$\varepsilon = ((\Delta\lambda_1 \cdot K_T2) - (\Delta\lambda_2 \cdot K_T1)) / ((K_\varepsilon1 \cdot K_T2) - (K_\varepsilon2 \cdot K_T1)) \quad (2)$$

$$\Delta T = ((\Delta\lambda_1 \cdot K_\varepsilon2) - (\Delta\lambda_2 \cdot K_\varepsilon1)) / ((K_\varepsilon1 \cdot K_T2) - (K_\varepsilon2 \cdot K_T1)) \quad (3)$$

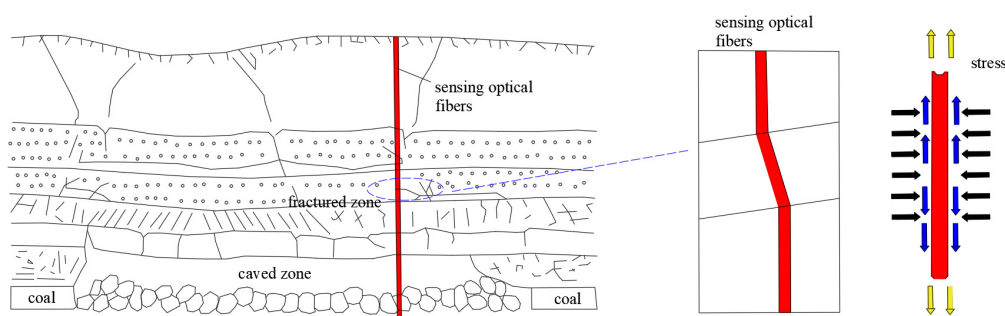


Figure 1. Schematic diagram of optical fiber deformation under stress.

Based on the time delay of the echo signal, the total time for the optical signal to travel from emission to return can be calculated. By calculating the time delay, the position of the strain point in the optical fiber is obtained, with the analytical formula

$$\Delta t = 2L/c \quad (4)$$

where L is the distance from the strain occurrence point in the fiber to the light source and c is the speed of light in the fiber.

The parallel electrical method is a high-density electrical method that integrates electrical sounding and electrical profiling, featuring multiple coverage overlays. It can explore positions within a certain range around boreholes and delineate the extent and degree of roof failure. Two supply electrodes, A and B, and two measuring electrodes, M and N, are buried in the monitoring area. When a current I is sent into the ground through supply electrodes A and B, a stable electric field is established in the uniform semispace, and the potential difference at MN is observed. The analytical formula is as follows:

$$\rho = 2\pi / (1/r_{AM} - 1/r_{BM} - 1/r_{AN} + 1/r_{BN}) (\Delta U_{MN}) / I = K (\Delta U_{MN}) / I \quad (5)$$

where K is the device coefficient, with units of meters. The value of K is related to the relative positions of the supply electrodes A and B and the measuring electrodes M and N.

As shown in Figure 2, as mining progresses, the upper rock strata above the coal seam generate fractures and delamination under stress. In areas with high rock damage, the strata either pile up haphazardly or lose their conductivity because of the development of fractures, bending, and breaking. The emergence of new fractures significantly increases the porosity of the rock mass. Although the rock mass remains continuous, its conductivity decreases significantly because of the development of fractures, affecting the changes in potential differences at different positions within the damaged area.

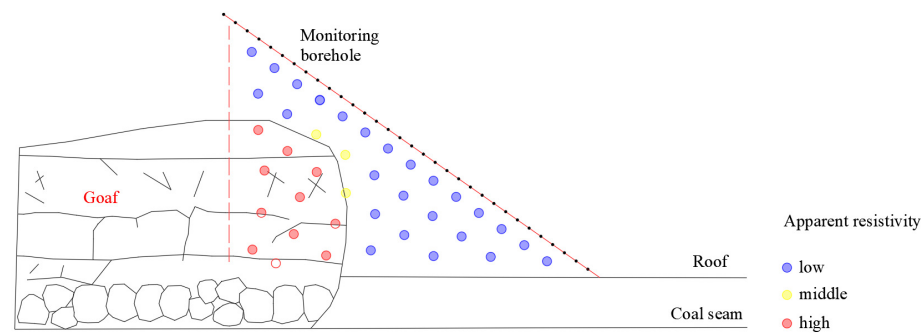


Figure 2. Schematic diagram of parallel electrical method monitoring.

To improve data accuracy, the model is divided into a three-dimensional grid during data processing. Because of the large monitoring range, logarithms are used to calibrate inversion data and model parameters to improve the stability of the inversion. To avoid redundant structures, smooth constraints are added to the least squares criterion to obtain a smooth model through inversion. The algorithm for solving the model modification Δm is as follows:

$$(G^T G + \lambda C^T C) \Delta m = G^T \Delta d \quad (6)$$

where C is the model smoothness matrix. By solving the Jacobi matrix G and calculating the inverse of the large matrix, the electrical data of each 3D grid can be obtained.

3. Experimental Test on Mining Strata Failure Model

3.1. Experimental Setup

The experiment employed a plane stress similar simulation experimental system, a network parallel electrical instrument, and an OSI-S distributed optical fiber sensing demodulator, as shown in Figure 3. The network parallel electrical instrument had a built-in 16-channel acquisition board that could connect multiple distributed base stations. The number of base stations was determined by the number of electrode channels required for the test, and each base station could support 16 electrode sensors. The OSI-S distributed optical fiber sensing demodulator employed distributed strain-sensing optical fibers with a specific strain coefficient set at 0.05 MHz/ $\mu\epsilon$. The equipment parameters were as shown in Table 1.

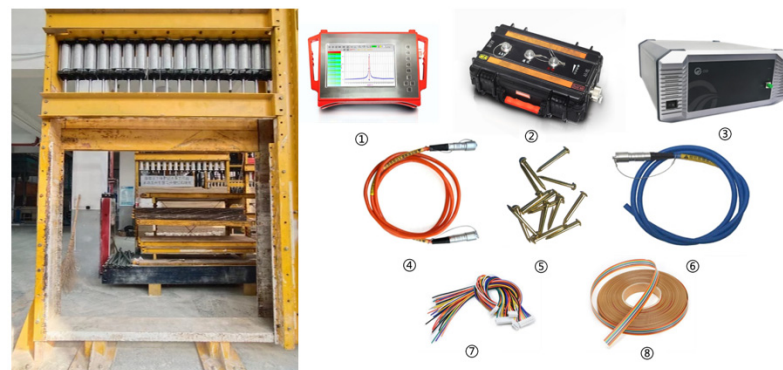


Figure 3. Monitoring equipment diagram.

Table 1. Equipment parameters.

Equipment	Highest Spatial Resolution	Measurement Accuracy	Measurement Range
OSI-S	1 mm	$\pm 1.0 \mu\epsilon$	$\pm 12,000 \mu\epsilon$
/	Maximum Emission Current	Measured Voltage Accuracy	Measured Current Accuracy
Network Parallel Electrical Instrument	2A	5%	5%

In Figure 3, picture ① is the host of the parallel electrical instrument; picture ② is the monitoring base station; picture ③ is the OSI-S distributed fiber optic demodulator; pictures ④ and ⑥ are the connecting wires of the monitoring system; picture ⑤ is the copper nail; and pictures ⑦ and ⑧ are the data connecting wires.

3.2. Experimental Protocol

The similar materials used in the model were continuous and homogeneous media. First, the differential equation of the prototype can be expressed as:

$$\partial(\sigma_x)_p / (\partial x)_p + \partial(\tau_{xy})_p / (\partial y)_p + (f_x)_p = 0 \quad (7)$$

$$\partial(\sigma_y)_p / (\partial y)_p + \partial(\tau_{xy})_p / (\partial x)_p + (f_y)_p = 0 \quad (8)$$

The differential equation of the model is:

$$\partial(\sigma_x)_m / (\partial x)_m + \partial(\tau_{xy})_m / (\partial y)_m + (f_x)_m = 0 \quad (9)$$

$$\partial(\sigma_y)_m / (\partial y)_m + \partial(\tau_{xy})_m / (\partial x)_m + (f_y)_m = 0 \quad (10)$$

The similarity constants for the various physical and mechanical parameters are:

$$C_l = x_p / x_m = y_p / y_m \quad (11)$$

$$C_\sigma = \sigma_p / \sigma_m = \tau_p / \tau_m \quad (12)$$

$$C_\gamma = f_p / f_m \quad (13)$$

Substituting the similarity constants into the equation gives:

$$C_\sigma / (C_l C_\gamma) = 1 \quad (14)$$

According to the dimensional analysis method, the dimensionless similarity constants of the physical and mechanical parameters are 1, and the similarity constants of the dimensional quantities are the same. Therefore, we can obtain:

$$C_{\epsilon} = C_{\varphi} = C_{\mu} = 1 \quad (15)$$

From $\sigma = \epsilon \cdot E$, we get $C_{\mu} = 1$, and thus we can obtain:

$$C_E / (C_l C_{\gamma}) = 1 \quad (16)$$

The time similarity ratio can be expressed as:

$$C_{\rho} = C_{\gamma} \approx C_t^2 = \sqrt{C_l} \quad (17)$$

where the geometric dimensions are 1, γ is the unit weight, t is the movement time, σ is strength, E is the elastic modulus, f is force, ϵ is strain, μ is Poisson's ratio, C_l is the geometric ratio, C_{σ} is the stress similarity ratio, and C_{γ} is the unit weight similarity ratio.

The geometric ratio of the model was 1:100, with a length of 250 cm, a width of 30 cm, and a height of 200 cm; the similarity ratio of unit weight was 1.66, and the time similarity ratio was 0.1. To ensure that the experimentally obtained electric field–stress–strain relationship accurately reflected the characteristics of the model experiment, the experimental materials used were based on the similarity principle, with fine sand as the aggregate, lime and gypsum as the cementing materials, mica powder to simulate the interlayer spacing between upper and lower rock strata, and mixed black ink as a special marker for coal seams. The strata layout parameters are shown in Table 2.

Table 2. Strata layout parameters.

Serial Number	Lithology	Layer Thickness/m	Elastic Modulus/kPa	Ratio
1	Coarse Sandstone	7	103	755
2	Sandy Mudstone	4.5	141	555
3	Siltstone	1.3	156	728
4	Mudstone	5.2	112	564
5	Silty Mudstone	4.5	141	555
6	Fine Sandstone	2.8	220	428
7	Mudstone	10.8	112	564
8	Medium Sandstone	3.1	185	628
9	Mudstone	10.6	132	564
10	Silty Mudstone	5.3	141	555
11	Medium Sandstone	2.4	185	628
12	Silty Mudstone	16.6	141	555
13	Medium Sandstone	18.8	185	628
14	Silty Mudstone	9.1	141	555
15	Fine Sandstone	1.7	220	428
16	Medium Sandstone	6.7	185	628
17	Silty Mudstone	6	141	555
18	Coarse Sandstone	1.46	103	755
19	Silty Mudstone	8.66	141	555
20	No. 1 Coal Seam	7.60	112	564
21	Mudstone	8.20	112	564
22	Medium Sandstone	12.00	185	628

Table 2. Cont.

Serial Number	Lithology	Layer Thickness/m	Elastic Modulus/kPa	Ratio
23	Silty Mudstone	6.14	141	555
24	Limestone	1.50	202	355
25	Silty Mudstone	7.17	141	555
26	Coal Seam	0.30	112	564
27	Silty Mudstone	3.60	141	555
28	Fine Sandstone	11.60	220	428

Protective coal pillars of 25 cm were retained on both sides, with a coal seam inclination of 7° and a mining height of 5 m. A load pressure of 16.9 KPa was applied to the upper part. Two boreholes, a roof hole and a floor hole, were set in the roof and floor of the coal seam. The roof hole had an angle of 34° with the coal seam, and the floor borehole had an angle of 14° with the coal seam. Each borehole was equipped with 32 sensing electrodes with an electrode spacing of 6 cm, totaling 64 sensing electrodes. The OFDR fibers were distributed vertically to the model, 50 cm away from the model edge, with a fiber spacing of 50 cm. A coordinate system was established, with the left vertex of the model as the origin, the right and upper directions as positive directions, and the side edge as the XY axis, as shown in Figure 4. In order to better represent the relationship between the caving zone and the mining height, the concept of the caving-to-mining ratio, i.e., the ratio of the height of the roof collapse area after mining to the height of the coal seam being mined back, was used.

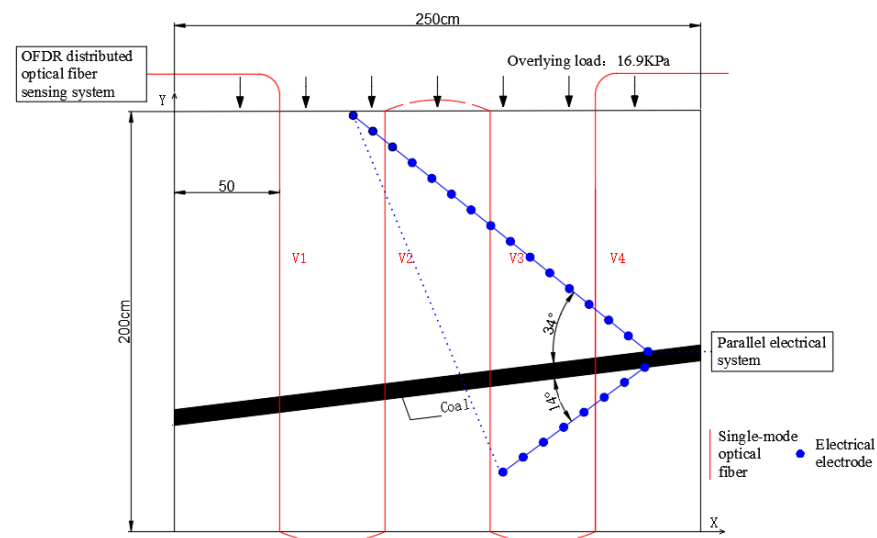


Figure 4. Experimental system deployment program.

3.3. Failure Process of Roof Rock Strata

The model started mining from a position 25 cm along the positive direction of the X-axis. Based on the development and changes in the caving zone and water-flowing fractured zone in the strata, the experimental process can be divided into four stages: the noncaving stage, the development stage of the caving zone, the development stage of the water-flowing fractured zone, and the stable stage of the water-flowing fractured zone.

The period from the beginning of mining to the first occurrence of caving in the roof is known as the noncaving stage, during which the roof strata maintained a complete structure and possessed strong bearing capacity. Stress concentration gradually bent the top strata, leading to the formation of interlayer fractures and microfractures. After reaching the maximum bearing capacity of the strata, the first caving occurred, filling the goaf, as shown in Figure 5a.

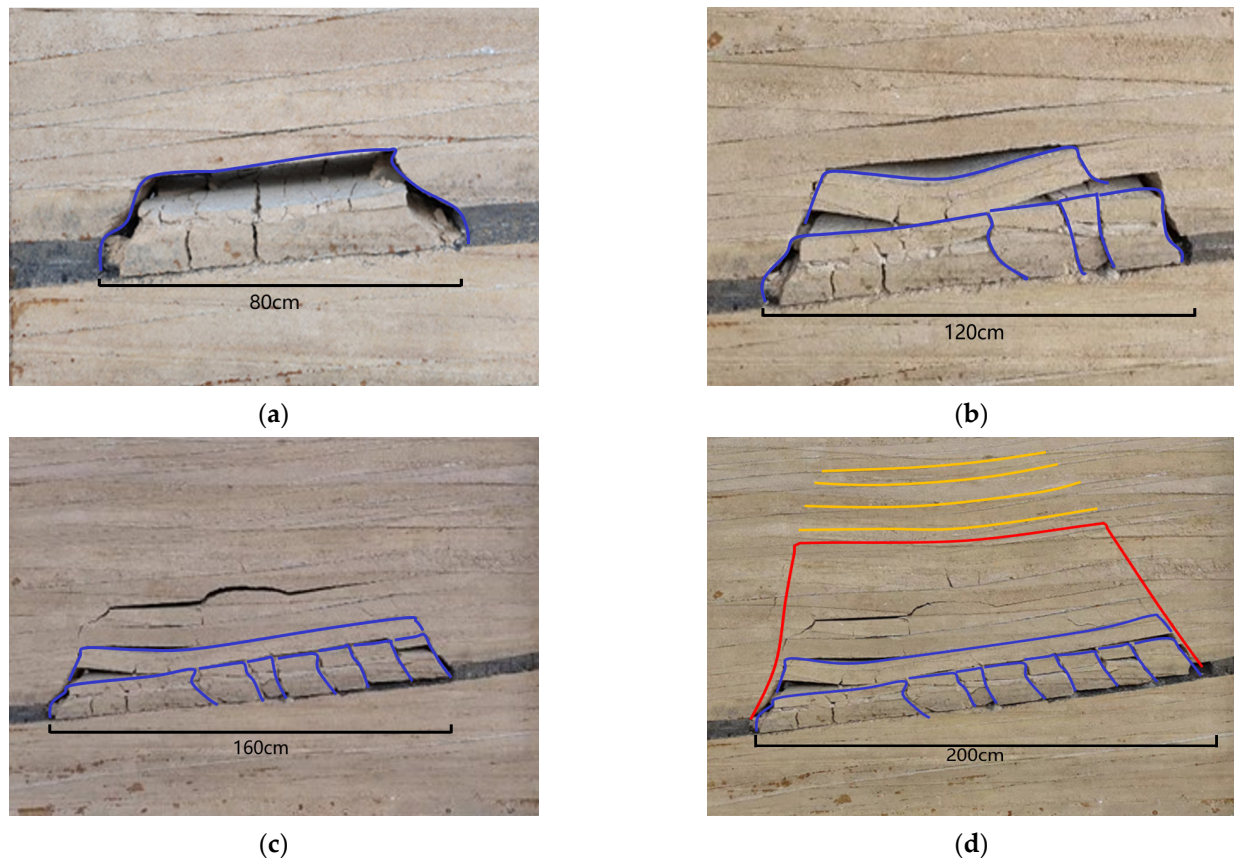


Figure 5. Diagram of roof development process. (a) Noncaving stage; (b) development stage of the caving zone; (c) development stage of the water-flowing fractured zone; (d) stable stage of the water-flowing fractured zone.

Following the initial caving of the coal seam roof, the roof structure changed, and its compressive resistance weakened, marking the onset of the development stage of the caving zone. As depicted in Figure 5b, during this stage, fractures appeared in the medium-grained sandstone of the roof. Delamination and vertical fractures rapidly developed upwards, and the caving zone expanded speedily forward with the excavation of the model. A large number of cracks appeared in the upper roof, with the caving zone reaching a height of 31.65 m, a caving-to-mining ratio of 6.33, and an angle of 62° . The rubble formed after the collapse exerted a filling and expansion effect on the goaf, hindering further collapse of the right-side strata.

As shown in Figure 5c, during the development stage of the water-flowing fractured zone, the stress concentration in the roof strata rapidly intensified, and vertical fractures quickly propagated upwards and eventually extended to a height of 65.15 cm. The strata bent towards the goaf, creating a detachment space of approximately 100 cm in length and 1.5 cm in width at the top. Microfractures in the central region closed because of the compression and bending of the overlying strata.

After the vertical fractures reached their maximum height, mining progressed to the stable stage of the water-flowing fractured zone. The water-flowing fractured zone extended forward with the excavation of the model, while the collapsed strata in the central goaf underwent compaction under stress, closing the fractures. As illustrated in Figure 5d, the overall structure of the two zones exhibited a typical “terraced platform” distribution, with the maximum height of the water-flowing fractured zone stabilizing at 92.28 cm above the top of the coal seam, resulting in a fracture-to-mining ratio of 18.45.

3.4. Analysis of Experimental Results

3.4.1. Periodic Collapse of Rock Strata

Under the influence of top stress, the roof strata exhibited two failure modes. First, when the strata with high stiffness and strength were subjected to huge shear force, they were directly cut off. Second, in strata with weaker stiffness and strength, horizontal and vertical fractures developed under stress. These fractures expanded, closed, and redeveloped under bending and tensile effects, leading to segmented shearing and sliding of the strata, eventually forming numerous, irregularly shaped collapsed rubble.

The failure of the coal seam roof showed obvious periodicity after the model mining entered the development stage of the collapse zone. As depicted in Figure 6, upon the formation of the goaf, influenced by the shear fractures in the already collapsed area, the immediate roof of the coal seam collapsed. With the gradual excavation of the working face, the old roof strata collapsed under shear stress, and new shear fractures emerged in the upper part. As the model mining progressed, these shear fractures extended downwards towards the working face, cutting through the strata, weakening their load-bearing capacity, and leading to the collapse of the old roof following the failure of the immediate roof. Meanwhile, the shear fractures from the previous collapse cycle were closed under compressive stress.

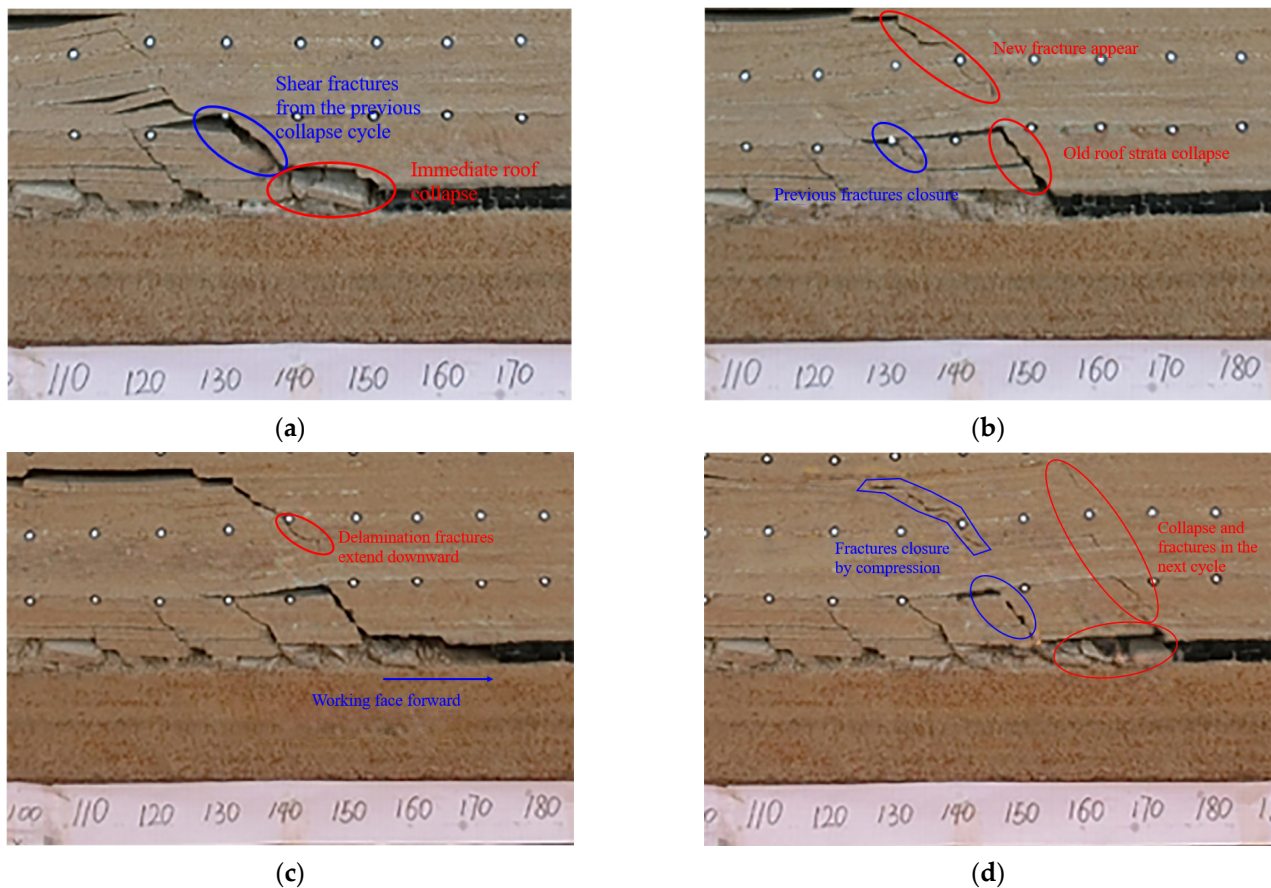


Figure 6. Periodic collapse of rock strata. (a) Rockfall; (b) New fracture appear; (c) Fissure enlargement; (d) Fissure closure.

3.4.2. Strain–Geoelectric Field Response

The strain curve of the optical fiber in the model is represented by the red dotted curve, with positive strain indicating compression and negative strain indicating tension. To make the strain curve clearer, it is filled with yellow. It is stipulated that the red area

in the apparent resistivity map represents the high-resistivity area, while the blue area represents the low-resistivity area.

According to the analysis of the apparent resistivity diagram and optical fiber strain diagram during the mining process, when the model was not excavated, as shown in Figure 7, the apparent resistivity profile was distributed between 120 and 300 $\Omega\cdot\text{m}$, with no high-resistivity anomaly response; the strains of optical fibers V1, V2, V3, and V4 were basically 0 $\mu\epsilon$, indicating that the model was basically stable.

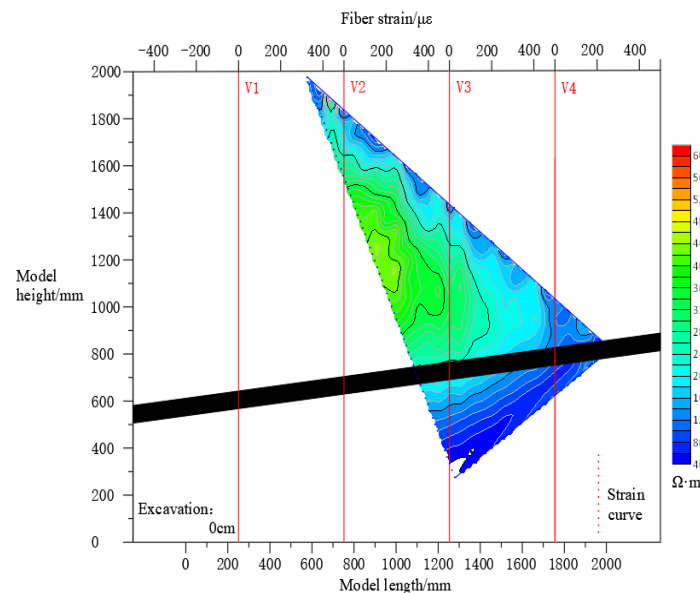


Figure 7. Diagram of model background.

Taking Figure 8a,b as examples, when the model was initially excavated and the coal seam roof had not yet collapsed, the stress concentration occurred at the position of the upper confined layer of the coal seam roof, causing microcracks in the rock strata and slight fluctuations in the geoelectric field. The apparent resistivity increased, and its range gradually expanded. As demonstrated in Figure 8a, when the model was excavated to 30 cm, positive strain occurred within the height range of 20~59 cm above the coal seam for optical fiber V1, with a maximum strain value of 140 $\mu\epsilon$. At the same time, small fluctuations in apparent resistivity occurred within the height range of 33~59 cm above the coal seam roof, with a maximum resistivity of 500 $\Omega\cdot\text{m}$. As indicated in Figure 8b, when the model was excavated to 60 cm, the working face approached optical fiber V2, and the rock strata above the goaf had not yet collapsed, resulting in significant stress concentration. Under stress, the positive strain of optical fiber V1 increased to 207 $\mu\epsilon$, and small fluctuations in apparent resistivity occurred within the height range of 32.9~60 cm in the upper part of the coal seam roof, with an expanded high-resistivity range.

As the model was excavated further, before the stress concentration in the coal seam roof reached the peak bearing capacity of the rock strata, negative strain facing the goaf occurred in front of the working face, and stress redistribution occurred after the roof strata collapsed. As displayed in Figure 8b–d, when the model was excavated to 60 cm and the roof had not yet collapsed, optical fiber V2 exhibited compressive strain of $-149 \mu\epsilon$, with the peak strain distributed within the height range of 20.5~60.55 cm above the coal seam roof. The strain direction confirmed the stress concentration above the goaf. After the model was excavated to 80 cm, the rock strata collapsed, releasing the concentrated stress. The boundary of the strain step caused by the collapse of optical fiber V2 shifted to the right, the peak strain decreased, the positive strain increased to 42 $\mu\epsilon$, and the negative strain narrowed to $-48 \mu\epsilon$. Subsequently, with the formation of new goafs, stress concentration resumed, generating positive strain with a value of 114 $\mu\epsilon$.

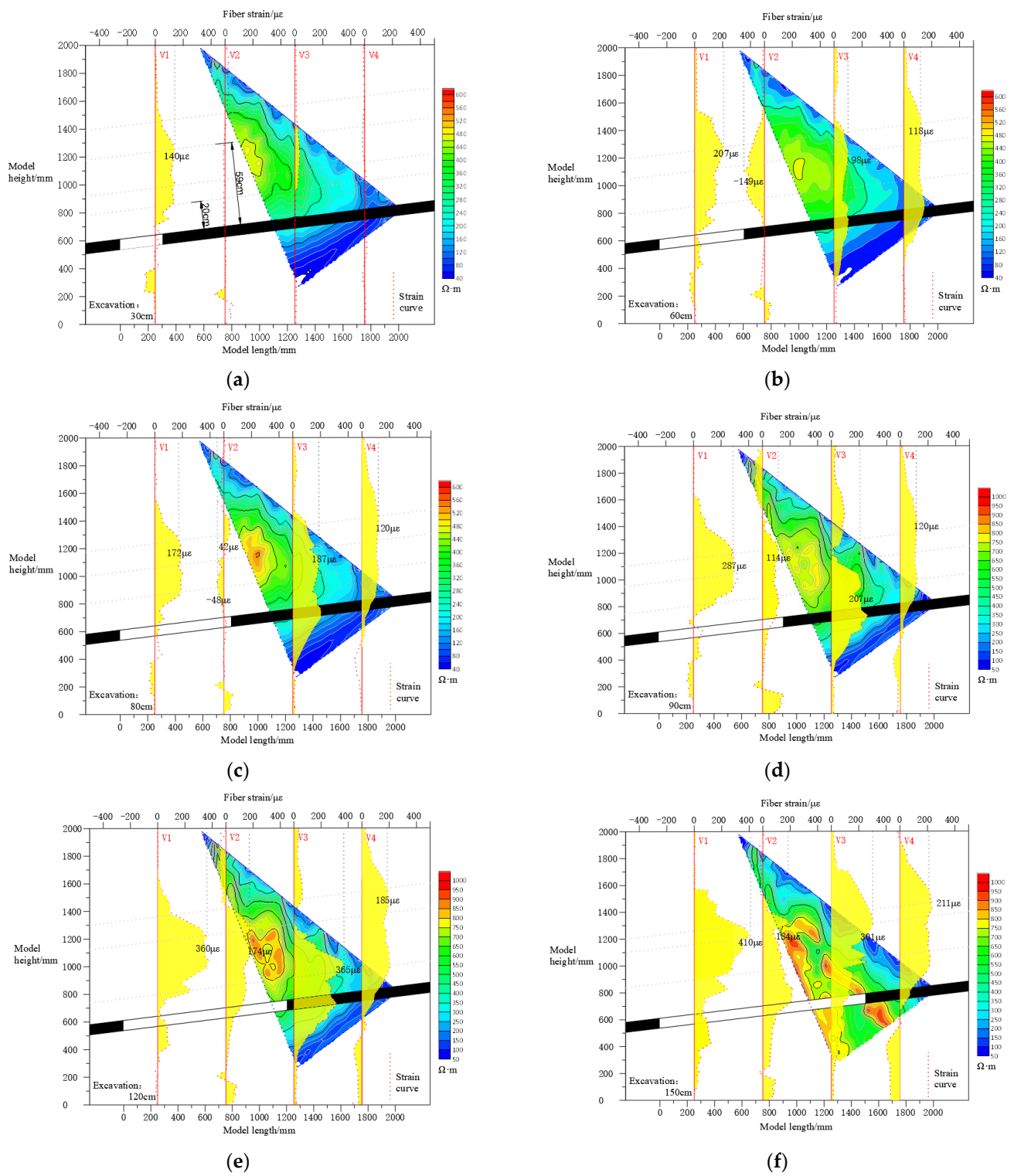


Figure 8. Cont.

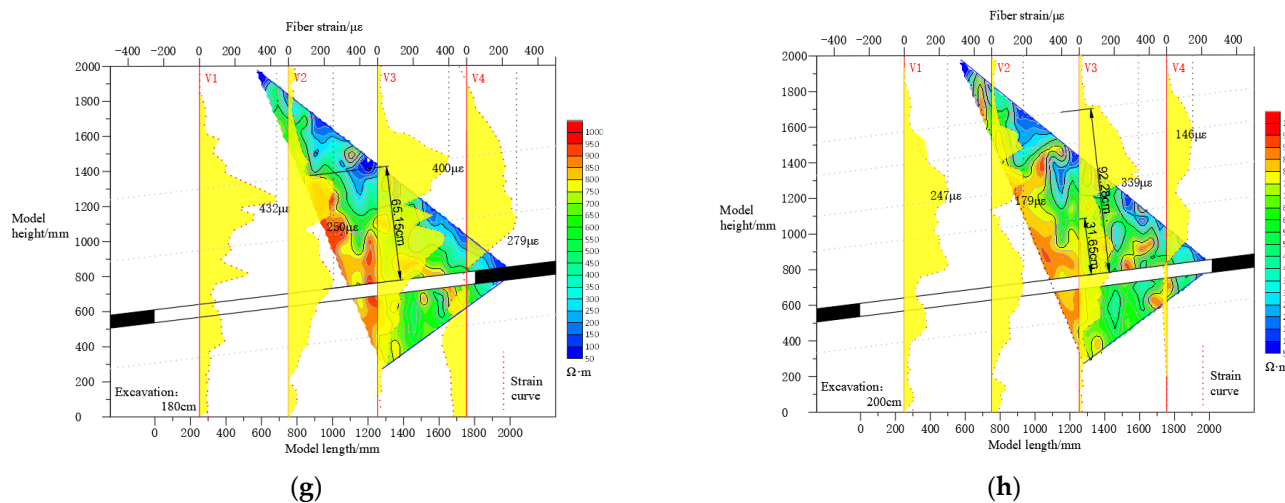


Figure 8. Diagram of experimental results. (a) Excavation 30 cm; (b) Excavation 60 cm; (c) Excavation 80 cm; (d) Excavation 90 cm; (e) Excavation 120 cm; (f) Excavation 150 cm; (g) Excavation 180 cm; (h) Excavation 200 cm.

After the initial collapse of the rock strata, the structure of the roof strata changed, weakening its bearing capacity. As mining progressed, the roof strata fractured and collapsed more densely. As shown in Figure 8e–g, the high apparent resistivity value rapidly rose to $1000 \Omega \cdot m$, reaching a height of 65.15 cm above the coal seam roof. Stress continuously concentrated in the rock strata and was released after each collapse. When mining entered the area covered by the apparent resistivity diagram, significant strain peaks existed at the locations of high-resistivity anomalies.

After the model excavation advanced beyond 180 cm and entered the stable stage of the water-flowing fracture zone, the model no longer underwent sudden changes in the water-flowing fracture zone due to stress concentration effects, and it was slowly deformed under stress. As demonstrated in Figure 8h, after the model excavation was completed, the range of abnormal apparent resistivity values extended to 86.3 cm above the coal seam roof, and the height of rock strata strain reached 92.28 cm above the coal seam roof. Because of the mining height of 5 m, with a fracture–mining ratio of 18.45, a large number of cracks appeared in the upper roof, with the caving zone reaching a height of 31.65 m, a caving-to-mining ratio of 6.33.

4. On-Site Monitoring and Rock Fracture Analysis

4.1. Monitoring System Plan

In the 11-3106 working face of a mining area, the mid-Jurassic Yan'an Formation coal seam is being extracted, with an average coal thickness of 4.9 m and a coal seam inclination angle ranging from 3.5 to 7.0 degrees. To monitor the deformation and failure patterns of the coal seam roof during mining, as well as its impacts, a monitoring borehole with an elevation angle of 39° and a controlled height of 80 m was arranged in the return airway of the working face. A single-mode optical fiber and parallel electrical sensors were embedded in the monitoring borehole, which deviates 30° from the return airway towards the working face and has a depth of 132 m, as shown in Figure 9.

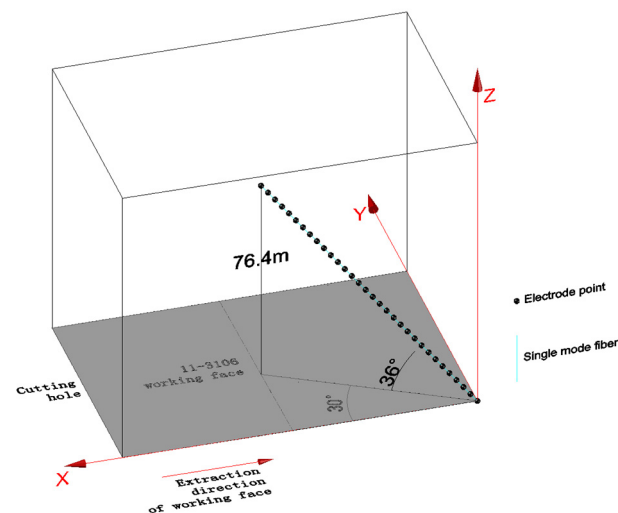


Figure 9. Schematic diagram of the monitoring system.

4.2. Result Analysis

Based on the above analysis, since the strain peak and apparent resistivity values at the rock failure location were significantly greater than those in the structurally intact areas of the rock strata, the peak optical fiber strain and abnormally high apparent resistivity can be used as criteria for judging the failure of the roof strata. In the diagram of the on-site monitoring results, the monitoring results are composed of two parts: the apparent resistivity results graph and the fiber strain graph. Taking Figure 10(a1,a2) as an example, Figure 10(a1) shows the apparent resistivity results graph, and Figure 10(a2) shows the fiber strain graph at the same moment.

As shown in Figure 10(a1,a2), when the working face was mined to a distance of 95 m from the monitoring borehole orifice, the monitoring area was not significantly affected because of the relatively far distance between the working face and the borehole. The apparent resistivity mainly ranged from 300 to 1000 $\Omega \cdot m$, and no significant strain was detected by the optical fiber monitoring system. However, after the working face entered the monitoring range, microfractures occurred in the strata ahead of the working face under the action of stress, resulting in strain generation and an increase in apparent resistivity. As indicated in Figure 10(b1,b2), when the working face advanced to a position 80 m from the borehole orifice, a positive strain of 6579 $\mu\epsilon$ was generated at a height of 20–30 m in the monitoring area under stress, accompanied by an increase in apparent resistivity ahead of the working face. There was a 1700 $\Omega \cdot m$ apparent resistivity high-resistance anomaly above the monitoring height of 50 m, and the optical fiber exhibited a positive strain of 2473 $\mu\epsilon$, which was relatively small. This indicates that the destruction of the water-conducting fracture zone occurred in the upper part of the coal seam roof.

As shown in Figure 10(c1,c2), an abnormal change in apparent resistivity occurred below the height of 50 m above the monitoring borehole, with a high-resistance anomaly in the goaf appearing below the height of 20 m, with a maximum abnormal value of 1900 $\Omega \cdot m$. The optical fiber strain exhibited a uniform distribution, decreasing gradually from bottom to top, with the peak strain occurring at a height of 30 m above the monitoring borehole. This indicates that the rock strata within a 30 m range above the monitoring borehole were continuously deforming and collapsing under stress, and according to physical experiment results, this value roughly corresponds to the boundary between the water-conducting fracture zone and the caving zone, indicating that the collapse and failure of the roof strata mainly occurred below 30 m.

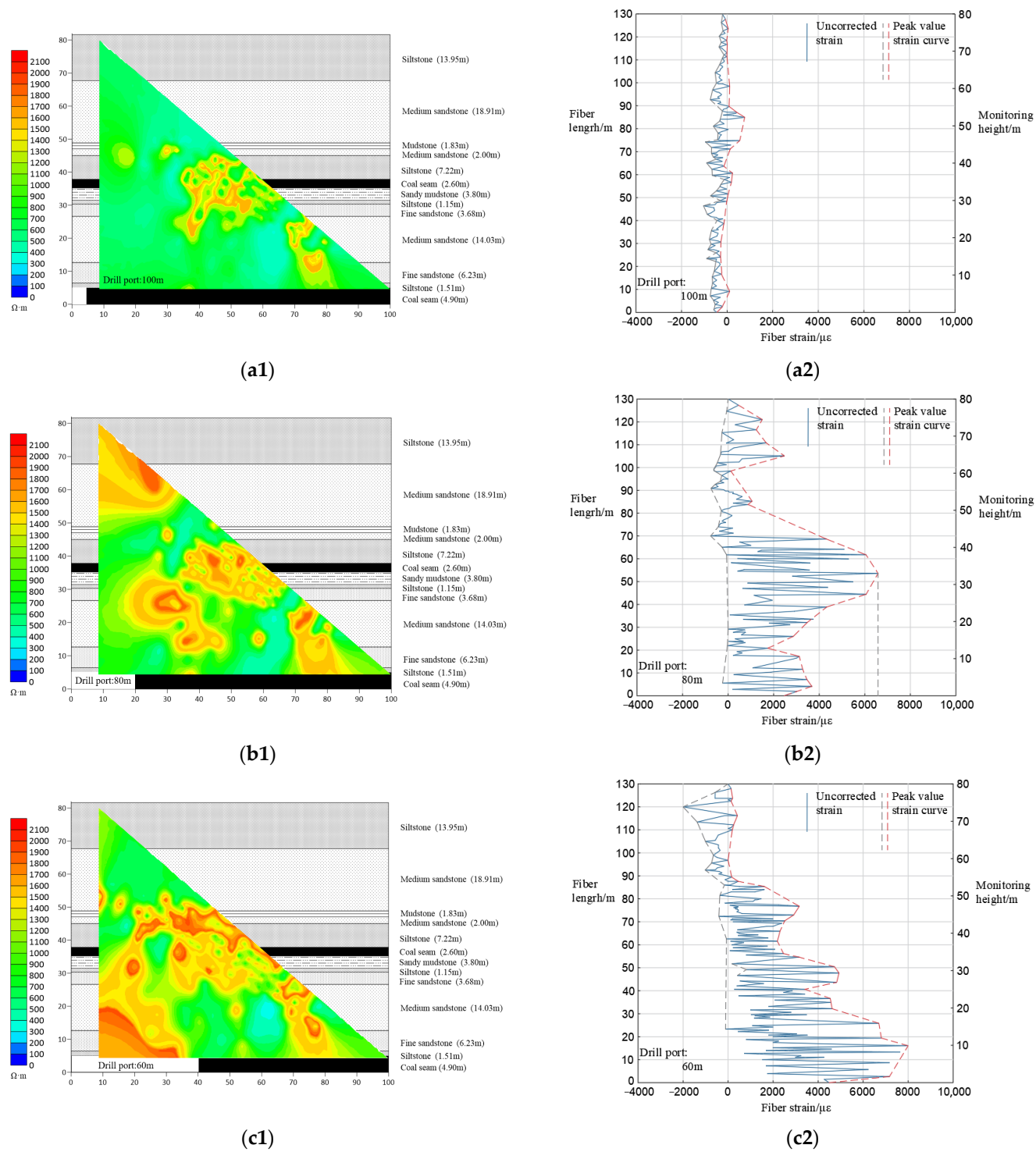


Figure 10. Cont.

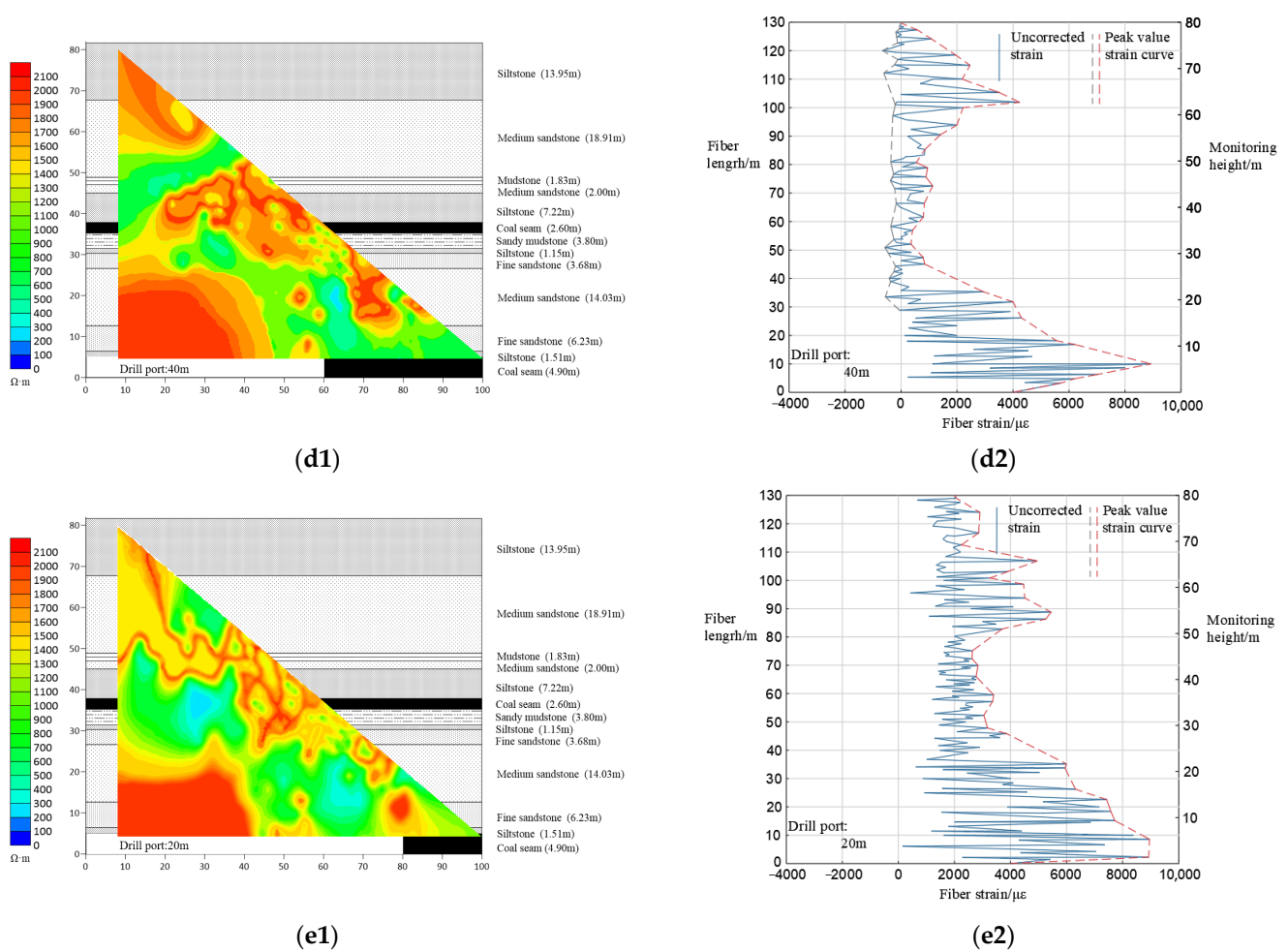


Figure 10. Diagram of on-site monitoring results. (a1) Parallel electrical method—drill port 100 m; (a2) Optical fiber acoustic sensing—drill port 100 m; (b1) Parallel electrical method—drill port 80 m; (b2) Optical fiber acoustic sensing—drill port 80 m; (c1) Parallel electrical method—drill port 60 m; (c2) Optical fiber acoustic sensing—drill port 60 m; (d1) Parallel electrical method—drill port 40 m; (d2) Optical fiber acoustic sensing—drill port 40 m; (e1) Parallel electrical method—drill port 20 m; (e2) Optical fiber acoustic sensing—drill port 20 m.

As the mining working face advanced to a certain height, the height of roof failure gradually stabilized and extended forward with the mining process. As displayed in Figure 10(d1,d2,e1,e2), when the working face advanced to a distance of 40 m from the monitoring position, the peak optical fiber strain was concentrated at a height of 0–27.71 m in the monitoring area, with a maximum strain value of 8922 $\mu\epsilon$. The high-resistance anomaly of apparent resistivity ranged from 1600 to 2100 $\Omega \cdot m$, mainly distributed at a height of 0–29 m. After the working face advanced to a distance of 20 m, the optical fiber strain height fluctuated slightly, and the high-resistance range of apparent resistivity decreased slightly but remained at a height of 28 m above the monitoring borehole. By incorporating the strain locations and peak positions with the abnormal points of apparent resistivity into the detection algorithm, it can be seen that the optical fiber strain locations corresponded well with the changes in apparent resistivity. It was determined that the height of the caving zone in the 11-3106 working face was 29.47 m, with a caving-to-mining ratio of 6.01, which further verified the accuracy of the combined monitoring method using optical fiber sensing technology and the parallel electrical method.

5. Conclusions

1. By simulating the fracture development in roof strata during coal mining through similar experiments, it was observed that within the peak range of optical fiber strain, the rock strata were severely damaged with high apparent resistivity. The measured height of optical fiber strain was 92.28 cm above the roof strata of the model coal seam, and the abnormal range of apparent resistivity was 86.3 cm, with a maximum value of 1000 $\Omega \cdot \text{m}$. Based on these findings, the height of the caving zone was determined to be 31.65 cm, with a caving-to-mining ratio of 6.33. Meanwhile, the height of the water-flowing fractured zone was 92.28 cm, with a fracture-to-mining ratio of 18.45.
2. As the goaf area gradually expanded during coal mining, before the first collapse of the roof strata, the strata structure remained intact with strong bearing capacity, leading to negative strain towards the goaf in front of the working face. After the roof strata collapsed, the fractured area developed periodically and progressively with the advancement of the working face. Once the working face reached the monitoring area, the abnormal range of apparent resistivity in the damaged area expanded rapidly, with the apparent resistivity value increasing to five times the background value. The strain height remained stable after advancing to a certain distance, while the fractures in the already collapsed area were compacted and closed under stress, and the apparent resistivity decreased slightly.
3. The application of distributed optical fiber sensing technology and the parallel electrical method in the field measurement of the failure height of the “two zones” (caving zone and water-flowing fractured zone) in the 11-3106 working face revealed a larger range of optical fiber strain and a maximum high-resistance abnormal value of apparent resistivity of 2100 $\Omega \cdot \text{m}$. The measured height of the caving zone was 29.47 m, with a caving-to-mining ratio of 6.01. The peak value of optical fiber strain corresponded well with the range of apparent resistivity anomalies, verifying the reliability of using the combined technology of distributed optical fiber sensing and the parallel electrical method to monitor and study the fracture of mining-induced strata.

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