

Article

A Combined Method Utilizing Microseismic and Parallel Electrical Monitoring to Determine the Height of Water-Conducting Fracture Zones in Shengfu Coal Mine

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Abstract: The development of a water-conducting fracture zone is a critical factor in understanding and predicting water inrush from coal mine roofs, as these zones facilitate the inflow of water from overlying aquifers. However, traditional methods such as empirical formulas and drilling, as well as single physical investigations (such as transient electromagnetic), can only estimate the height of these fault zones and often cannot accurately obtain precursor information of roof water inrush during the mining process. In this study, a comprehensive evaluation of the 13,101 working face of the Shengfu Coal Mine in Shaanxi, China, is being carried out using microseismic monitoring and parallel electrical methods. On the basis of the microseismic results, the height of the water-conducting fracture zone is obtained to be 57 m. The average variation of the natural potential of the coal seam roof was obtained by the parallel electric method, which was all less than 250 mV, with no obvious anomalous seepage electric field and no large centralized water-conducting channels found. However, the decrease in resistivity and natural potential indicates the precursor information of water seepage when the fracture zone develops to 40–50 m. This approach aims to monitor the development of water-conducting fracture zones by combining microseismic monitoring with parallel electrical methods while simultaneously capturing changes in roof seepage. This will enhance safety and facilitate more informed decision-making in complex hydrogeological environments.

Keywords: coal mine; water inflow; water-conducting fracture zone; microseismic monitoring; parallel electrical methods



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1. Introduction

Coal remains a vital source of energy in the world today, playing a significant role in economic development and social progress [1,2]. In 2023, China's total energy consumption reached 5.72 billion tons of standard coal, with coal consumption increasing by 5.6% [3]. Coal was the source of 55.3% of the total energy consumption, affirming its position as a fundamental energy resource in the short term [1,3,4]. In recent years, coal mining has extended deeper underground, and the occurrence of water hazards in coal seam roofs has shown a new trend towards diversification [1,5–7], which significantly intensifies the risk of water inrush [8–11]. This indicates that water inrush from coal seam roofs remains one of the major mining hazards in China's coal production.

Since the 19th century, with the cantilever beam theory for roof failure, numerous methods for analyzing roof failure have been developed [12,13]. For example, a range of hypotheses and calculation methods have been put forward by scholars regarding the structures of coal seams. These structures include arches, beams, plates, and other forms [14–26]. By the 1990s, China had developed the widely recognized “three-zones” empirical formula

tailored to its specific mining conditions [27,28]. With the increasing complexity of disaster-causing factors and mechanisms in traditional inrush patterns, the development of roof water hazards in coal seams has become more varied and unpredictable. Consequently, the study of associated mechanisms and the development of prevention and control technologies have progressively become cutting-edge scientific issues [29–32]. In response, experts and scholars in the field have conducted extensive research, proposing concepts such as multi-factor coupled disaster-causing mechanisms and diversified prevention and control strategies and technologies [33–36].

However, new trends in economic and social development have driven profound changes in resource extraction methods and intensities, leading to a shift in roof water hazards away from traditional patterns. Emerging inrush patterns, such as those caused by “skylight” recharge and burnt rock water hazards, have become increasingly prominent. As a result, the theoretical calculations on the basis of the aforementioned methods are gradually becoming less applicable, often leading to significant errors. Moreover, multiple research results indicate that there is a risk of water inrush when the water-conducting fracture zone has not yet developed into the roof aquifer [37,38].

Therefore, in order to more accurately determine the precursor information of water inrush when the water-conducting fracture zone has not developed into an aquifer, comprehensively understand the water damage of coal seam roof, promote existing prevention and control technologies, and explore new technologies and directions, this study focuses on the 13,101 working face of the Shengfu Coal Mine. Following the principle of “complementary advantages”, we employed a combination of microseismic monitoring and parallel electrical monitoring during the mining process. By analyzing the seismic signals and resistivity changes detected, we assessed the height of the water-conducting fracture zone and identified abnormal seepage characteristics in the roof. The findings of this study will guide subsequent mining operations in controlling rock layers and preventing water disasters, ensuring safe and efficient mining. Additionally, these results can be applied to surrounding mines, offering significant economic and social benefits.

2. Study Area

Shengfu Coal Mine is located approximately 25 km northwest of Shenmu City, Shaanxi Province, covering an area of 15.0502 square kilometers, with an annual production capacity of 5 million tons. The coal mine is located at the northern end of the Loess Plateau in Northern Shaanxi, on the eastern edge of the Maowusu Desert, and belongs to the desert landform. The overall terrain is low in the southwest and high in the northeast, with a relative maximum height difference of 92 m. The structural unit is located on the gentle eastern flank of the Ordos syncline—the Shaanbei slope. According to the drilling exposure and contour map of the coal seam floor, the overall coal mine formation is a monocline structure with a southwest strike, a northwest dip, and a dip angle of less than 1° . There are only some wide and gentle undulations and a series of false integration surfaces formed by the large-scale uplift of the crust after the coal formation period in the area. The overall formation is a northwest, gently dipping monocline layer without magmatic activity. No major faults have been found; only some small-scale faults have been discovered.

The geological conditions around the mining area are complex, with Jinjie Mine to the south and Hongliulin Coal Mine to the east, making the hydrogeological conditions particularly challenging. Although pre-mining measures such as water drainage have been implemented, the actual mining process still encountered water inflow exceeding expectations, leading to the flooding of the working face.

According to the stratigraphic column, there is a thick sandstone aquifer above the roof of the 3–1 coal seam, located relatively close to the coal seam, which increases the risk of water hazards. Additionally, the mine is adjacent to goaf areas of other coal mines, further heightening the threat of water inrush during the mining process. The 13,101 working face, as the first mining face of Shengfu Coal Mine, has a decisive impact on the overall

production of the mine, making it crucial to ensure that water inflow during the mining process remains controllable.

To address these challenges, this study focuses on the 13,101 working face, employing a combined monitoring approach of “Microseismic and Parallel Electrical”. On the one hand, the study aims to understand the relationship between cyclical roof collapse during mining and water inflow patterns; on the other hand, it seeks to achieve early warning of water hazards during the mining process, ensuring production safety (Figure 1).

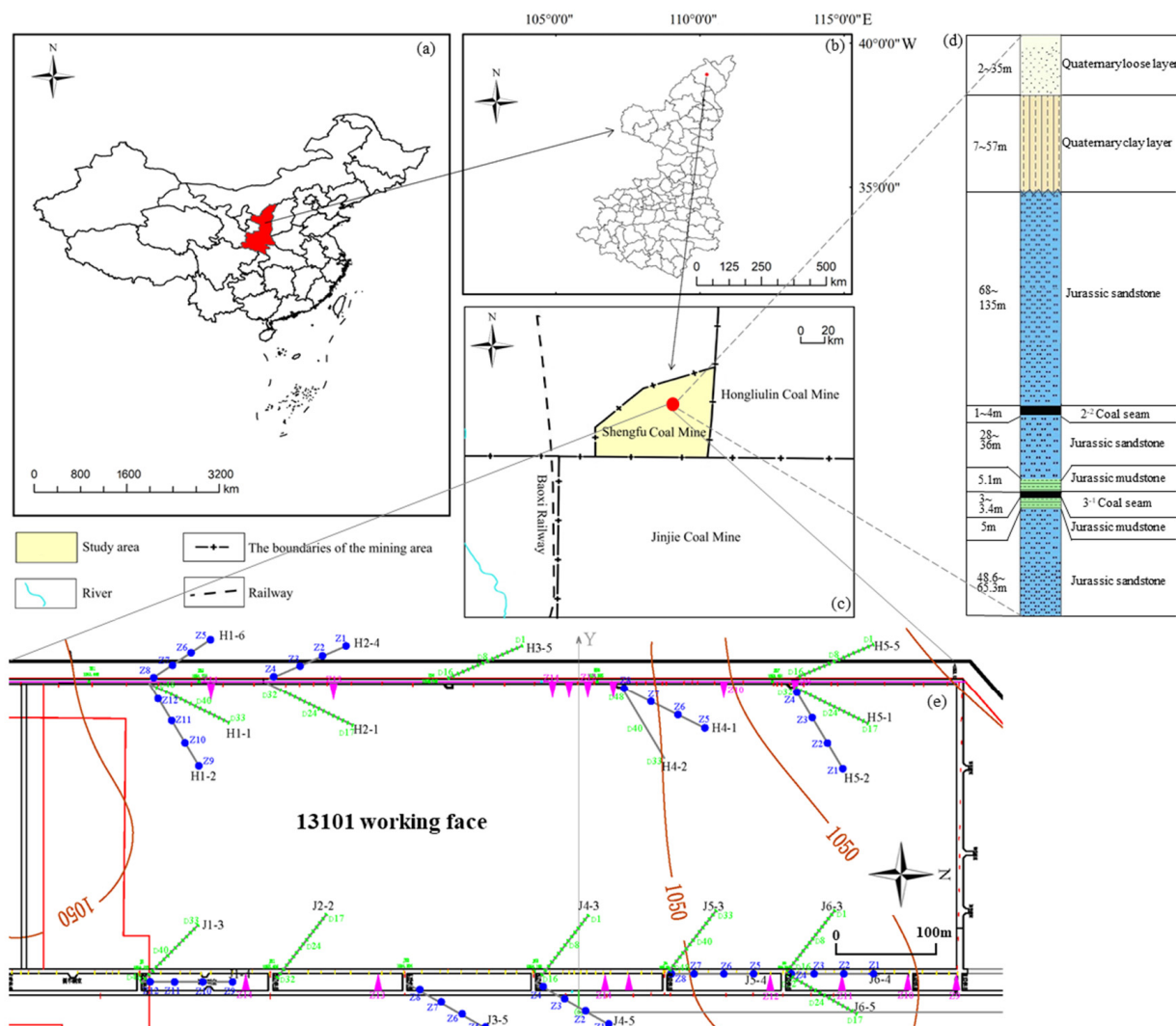


Figure 1. Location of the study area (The geographical location of the research area nationwide (a); Location of the region (b); Detailed location of the study area (c)); columnar diagram of geological strata (d); and 13,101 working face (e).

3. Materials and Methods

3.1. Microseismic Monitoring System

Under mining-induced conditions, the formation of water hazards in coal seams typically undergoes a process of incubation, development, and eventual occurrence. Field observations and research indicate that during the formation of water inrush channels, the rock mass undergoes fracturing, often accompanied by microseismic activity. Microseismic signals can effectively characterize the location, intensity, and focal mechanism of rock mass fractures. Therefore, microseismic monitoring technology is widely used in the activation and instability processes of water channel faults, collapse columns, and the development process of water inrush in goaf and roof and floor mining induced fractures under mining

disturbances. By deploying sensors to monitor seismic wave signals generated by rock fracturing under the disturbance of mining activities (Figure 2), the spatiotemporal information of rock failure induced by these activities can be obtained through localization algorithms. This enables the delineation of the spatial extent of floor damage caused by mining operations.

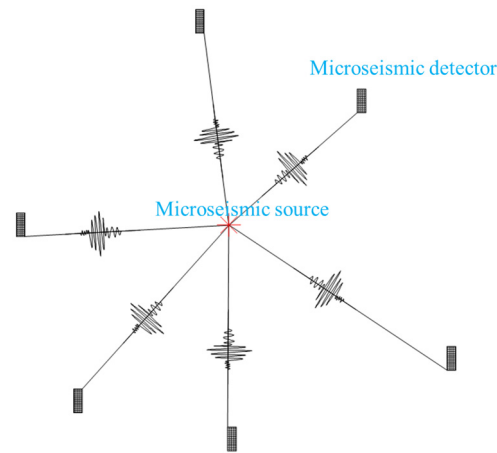


Figure 2. Schematic diagram of microseismic source localization.

Typically, the easily recognizable P-wave is selected for localization, as it offers high positioning accuracy and ensures precise source location. The shortest travel time from the seismic source to the i th microseismic detector can be expressed by Equation (1) [39].

$$T_i(H, V, X_i) = \frac{\sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2}}{V_p} \quad (1)$$

where (x_0, y_0, z_0) are the source coordinates; T_i is the time when the seismic source reaches the detector; (x_i, y_i, z_i) are the coordinates of the seismic detector; V_p is the propagation speed of P-waves in a medium.

After applying first-order Taylor linearization to $T_i(H, V, X_i)$, in each iteration process:

$$\delta\theta^{(n)} = (A^T \cdot A)^{-1} A \delta\gamma^{(n)} \quad (2)$$

where $\delta\gamma^{(n)}$ is the time residual vector at a point $\theta^{(n)}$ in space, and A is the $(n \times 4)$ partial differential matrix of the parameter θ in Equation (2).

$$A = \begin{bmatrix} 1 & \partial T_1 / \partial x_0 & \partial T_1 / \partial y_0 & \partial T_1 / \partial z_0 \\ 1 & \partial T_2 / \partial x_0 & \partial T_2 / \partial y_0 & \partial T_2 / \partial z_0 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \partial T_n / \partial x_0 & \partial T_n / \partial y_0 & \partial T_n / \partial z_0 \end{bmatrix}_{\theta^{(n)}} \quad (3)$$

Because most of the vibrations in the monitoring area cannot excite all detectors, and small mining vibrations are the basis for analyzing large vibrations and important information sources, the number of rows in the partial differential matrix A must be variable. Vibrations of different energy levels have different detectable distances, and only probes within the monitoring range can be excited and included in matrix A . Using the empirical formula ($E = \lambda r^q$) of energy E and detectable distance r , q is close to 2, and λ is a constant value. It is possible to determine the number of receiving probes at a certain energy source point, and it is required that at least 5 channels within the detectable distance can receive the waveform.

3.2. Response Characteristics of Parallel Electrical Method in Seepage Field

The parameters such as excitation current, natural potential, and resistivity in the geoelectric field signal can effectively characterize rock mass fracture, water seepage, or the combined effect of the two. Thus, electrical monitoring technology is widely used to explore the depth of bottom mining damage, the height of water-conducting fracture zone development in the roof, the activation of hidden geological structures (faults, collapse columns, etc.) [40,41], and the grouting effect. Therefore, due to the sensitivity of geoelectric parameters to water response, combined with microseismic information, it can effectively accurately describe the water-rich properties of water channels caused by mining disturbances.

During the process of rock mass failure, charge separation and electron emission occur. Unbonded electrons are released at the crack tip, forming a positive charge center. The crack surfaces formed during the propagation of fractures exhibit positive electrical characteristics, requiring the adsorption of negatively charged particles to reduce the surface energy of the crack [40]. Under these conditions, when water flows through the fracture surfaces, the negatively charged ions carried by the water are selectively adsorbed. Following the clues of the formation of the filtration electric field during water seepage through geotechnical materials, the qualitative characteristics of changes in the natural electric field caused by groundwater seepage are analyzed [41].

As shown in Figure 3, M represents the natural potential measurement point, and N represents the natural potential reference point. When the water head first enters the medium, the negative ions in the water begin to be adsorbed by the medium, causing an accumulation of remaining positive ions in the water. As the water infiltrates, more and more positive ions accumulate, and the filtration potential difference increases. Thus, as the water flow approaches point M, the potential difference between points M and N (UMN) also increases. When the distance between the water head and point M reaches its minimum, the number of accumulated positive ions in the vicinity of that point reaches its maximum, and UMN also reaches its peak value. When the natural potential rises by 600 mV continuously for 2 days, and the resistivity drops by 30% continuously, reaching the expected threshold, the monitoring system will predict the risk of water inrush.

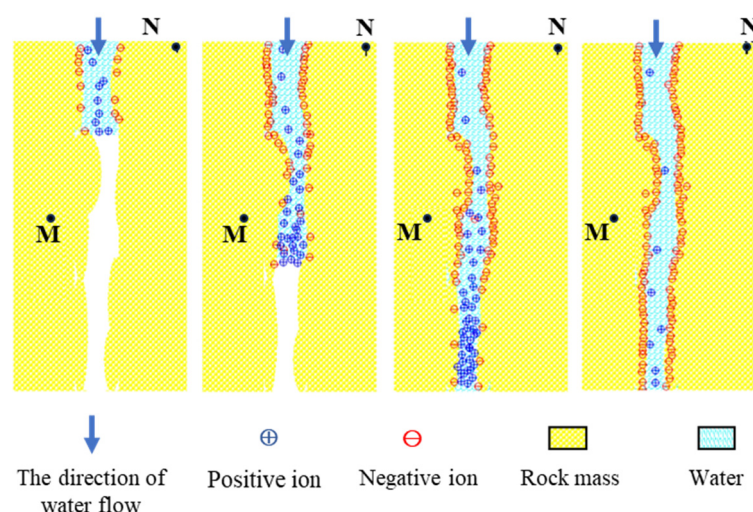


Figure 3. Schematic diagram of the principle of natural potential change during water seepage process.

3.3. Combined Method of Microseismic and Parallel Electrical Monitoring

The microseismic method uses the frequency of microseismic events to determine the degree of fissure development in real time, and accurate location analysis can be used to determine the position of fissure development. The electrical method can dynamically characterize the development of fractures or the seepage process of groundwater by monitoring the abnormal geoelectric field caused by rock fractures or water seepage. The coupling

monitoring technology of microseismic and electrical methods comprehensively utilizes microseismic signals, natural potential, resistivity, and other seismic electrical parameters to dynamically monitor rock mass fracture in real time and uses active source resistivity and excitation current to dynamically monitor the water filling or seepage of fractures in the rock mass. The two complement each other. Electrical monitoring data can effectively compensate for the difficulty of identifying whether the water channel is filled with water in microseismic signals, while microseismic monitoring can break through the limited scope of electrical monitoring and improve its ability to identify water channels and their water content, thereby effectively improving the accuracy of precise mine water hazard measurement. In general, for a fixed monitoring area coupled with microseismic and electrical methods, if the rock mass fractures without water seepage, the response characteristics of microseismic and geoelectric fields are that microseismic events frequently occur in this area, natural potential changes are significant, resistivity gradually increases in this area, and the excitation current of the electrodes in the fractured area will significantly decrease. If the rock mass fractures accompanied by water seepage, the response characteristics of the microseismic field and geoelectric field are that microseismic events frequently occur in the region, the natural potential shows a gradually increasing trend, the resistivity shows a gradually decreasing trend in the region, and the excitation current of the seepage head reaching the electrode in the region will significantly increase. If the rock mass in the monitoring area remains intact as a whole and is less affected by on-site mining disturbances, the response characteristics of microseismic and geoelectric fields are that microseismic events occur less frequently, and electrical parameters such as natural potential, resistivity, and excitation current remain relatively stable [40,41].

The main equipment for the microseismic–electrical parallel monitoring system is the YZD12-C microseismic–electrical parallel monitoring instrument produced by Anhui Huizhou Geology Security Institute Co., Ltd. in China, which is on the basis of the “distributed parallel intelligent electrode potential difference signal acquisition method” and “a geophysical instrument remote control system and method based on mine IoT technology”. The microseismic and electrical remote monitoring system consists of two parts: an underground acquisition system and a surface control system (Figure 4).

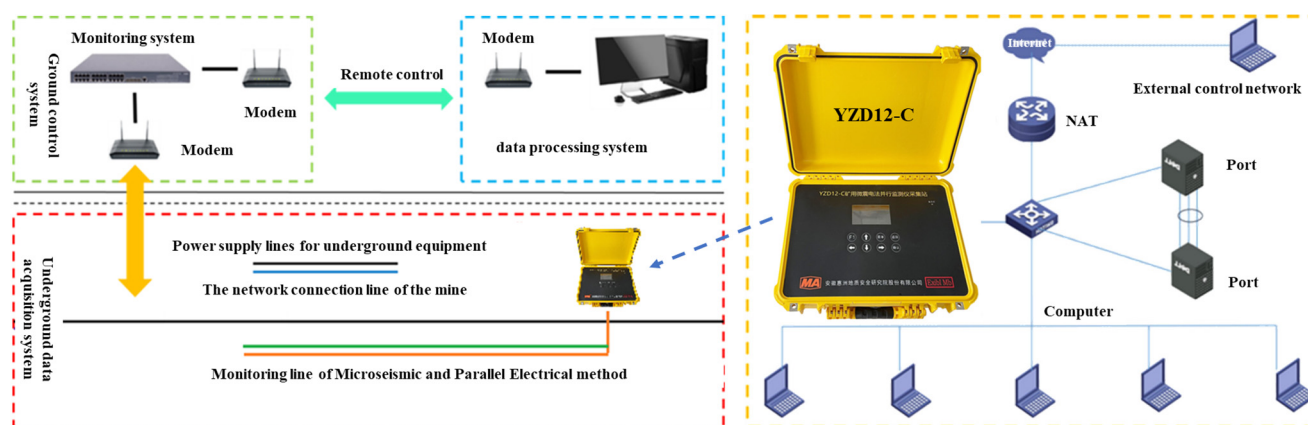


Figure 4. Schematic diagram of microseismic and electrical monitoring system.

The underground acquisition system includes an electrical method base station, a microseismic base station, electrodes, geophones, a multi-channel intrinsically safe power supply, and telephone interfaces, forming the underground electrical acquisition system. Multiple acquisition substations can be deployed underground. The surface control system consists of a computer, control software, and a modem. The surface control system communicates with the underground acquisition substations by sending instructions and transferring data through a mining network.

4. Application Results and Analysis of the Height of Water-Conducting Fracture Zone

4.1. Results of Microseismic Monitoring

The 13,101 working face commenced coal extraction in March, and by July, more than 600 m had been advanced. We categorize the mining process into three stages on the basis of two-month mining periods. This paper focuses on analyzing microseismic monitoring data collected from March to July. Microseismic monitoring captures seismic events and acoustic signals generated during the fracturing of coal and rock, reflecting the stress and damage conditions within the coal–rock mass. Generally, the frequency and magnitude of microseismic events correlate closely with the degree of stress concentration and damage in the coal–rock mass. An increased frequency of microseismic events indicates heightened stress concentration and more severe damage to the coal–rock mass.

Between 13 May and 23 May, during the second phase of mining, the microseismic events near the roof of the working face significantly increased, with a daily maximum of 169 events (Figure 5). This surge indicates intense activity within the rock mass, consistent with the observed initial collapse of the immediate roof. During this period, roof movement intensified, leading to breakage and collapse of the main roof, which marked the peak of the initial roof pressure. Subsequently, from 23 May to 4 June, rock mass activity became more frequent, with an average daily count of 62 microseismic events. At this stage, the roof beam exhibited fractures, and monitoring of support resistance revealed the first instance of periodic roof pressure.

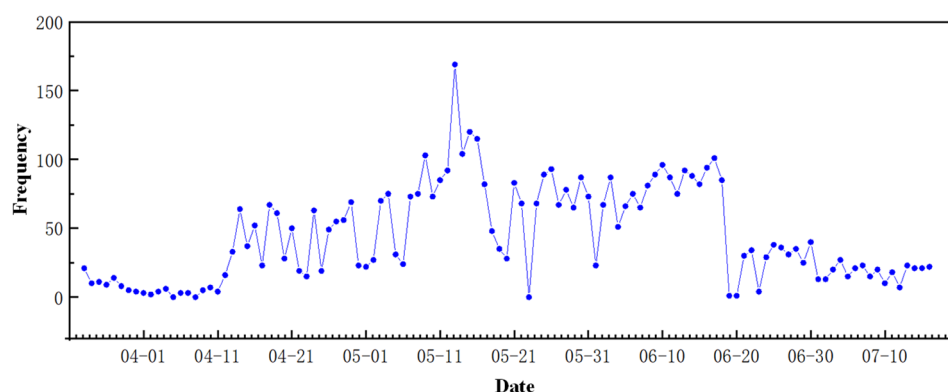


Figure 5. Monitoring of microseismic frequency in 13,101 working face.

From 20 June to 13 July, the frequency of rock mass activity significantly decreased, with fewer than 50 microseismic events recorded per day, and no significant roof failure or periodic pressure was observed. Analysis of the total microseismic energy indicated that on 13 May, the daily total energy of the microseismic events peaked at 18.01 KJ, coinciding with the first recorded roof pressure event as monitored by support resistance. On that day, the detection of 169 microseismic events underscored the capability of microseismic signals to provide early warnings of periodic roof pressure. When the daily total energy exceeds 6 KJ, it indicates that the roof is likely under significant pressure.

Figure 6a illustrates that the maximum microseismic energy in the 13,101 working face reached 3.8 KJ, corresponding to a magnitude of approximately 0.8 M. This suggests that initial mining activities resulted in roof breakage, which led to a heightened frequency of microseismic events and subsequent damage to the roof beam. After 10 April, there was a significant reduction in microseismic energy, indicating that while the overlying roof was disturbed during face advancement, no severe breakage occurred. Between 13 May and 23 May, the total microseismic energy recorded reached 18.01 KJ, indicating intense rock mass activity in this region, consistent with the observed collapse of the immediate roof. During this timeframe, the basic roof experienced breakage and collapse, marking the peak of initial roof pressure.

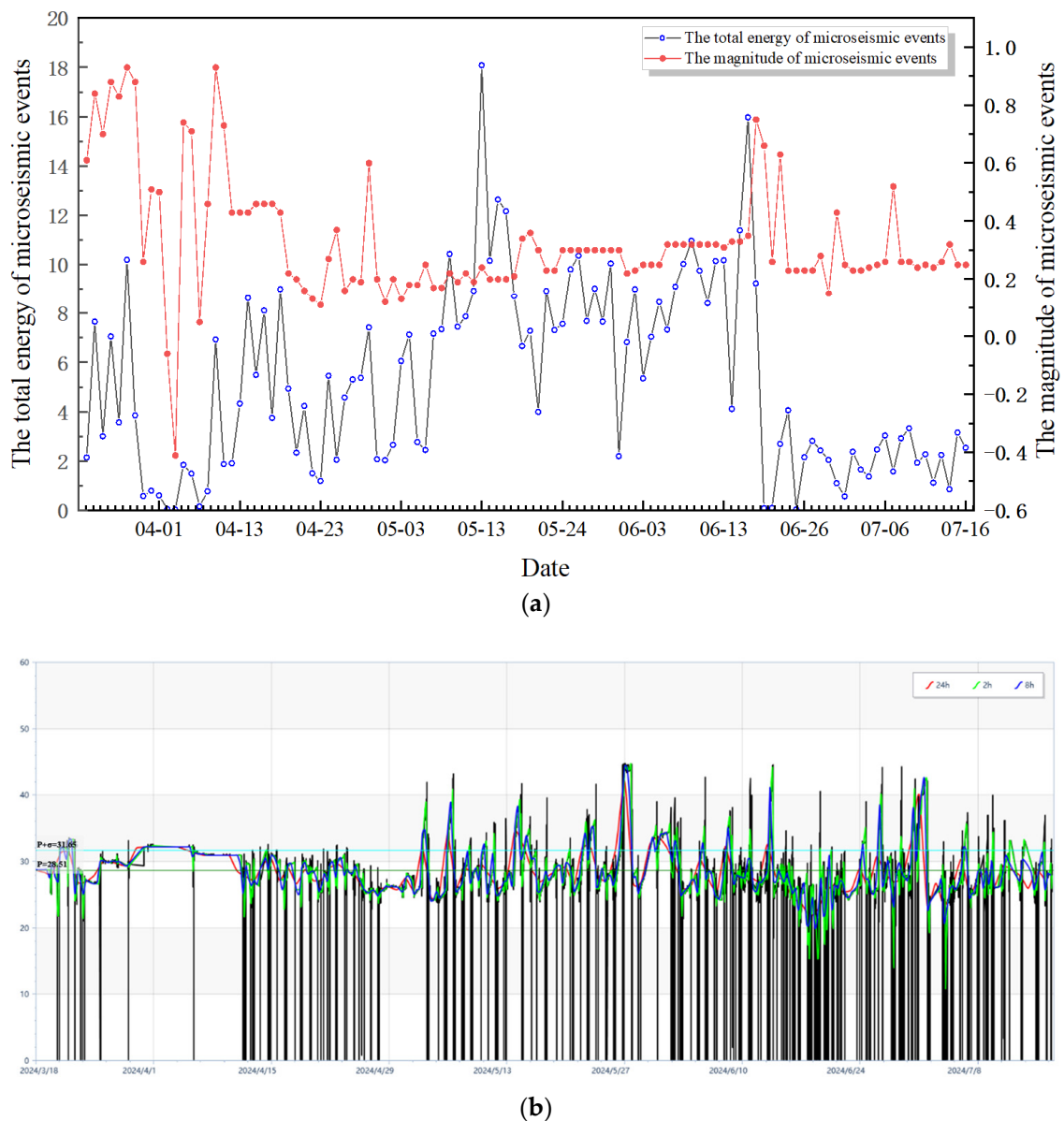


Figure 6. The total energy and magnitude of microseismic events (a) and resistance curve of hydraulic support (b).

Following the commencement of the second stage, microseismic energy gradually decreased and stabilized at around 0.4 KJ. During this phase, the working face advanced by 10 m, establishing a periodic roof pressure interval of 10 m, marking the first instance of periodic roof pressure in the main roof. After 10 June, microseismic energy increased again, peaking at 16.24 KJ, coinciding with an 8 m advancement of the working face and indicating the second occurrence of periodic roof pressure. After 1 July, the daily maximum microseismic energy decreased to 0.3 KJ, signifying that the roof had once again undergone periodic breakage, marking the third occurrence of periodic roof pressure.

Figure 6b shows that the 13,101 working face experienced four instances of periodic roof pressure, with an average interval of 10.3 m and an initial roof pressure interval of 170 m. Through the analysis of microseismic monitoring data, we established a correlation between roof failure and changes in microseismic energy, thereby providing a foundation for predicting periodic roof pressure.

4.2. Results of Parallel Electrical Monitoring

Figure 7 presents the parallel electrical resistivity results at varying heights above the coal seam during the second and third stages of mining. Although microseismic events were recorded during the first stage, no significant damage was observed, and the roof remained largely intact. Consequently, this area predominantly exhibited high resistivity characteristics, with resistivity values ranging from 55 to 155 $\Omega \cdot m$. Therefore, the focus of this analysis is on the changes in resistivity following the occurrence of roof damage.

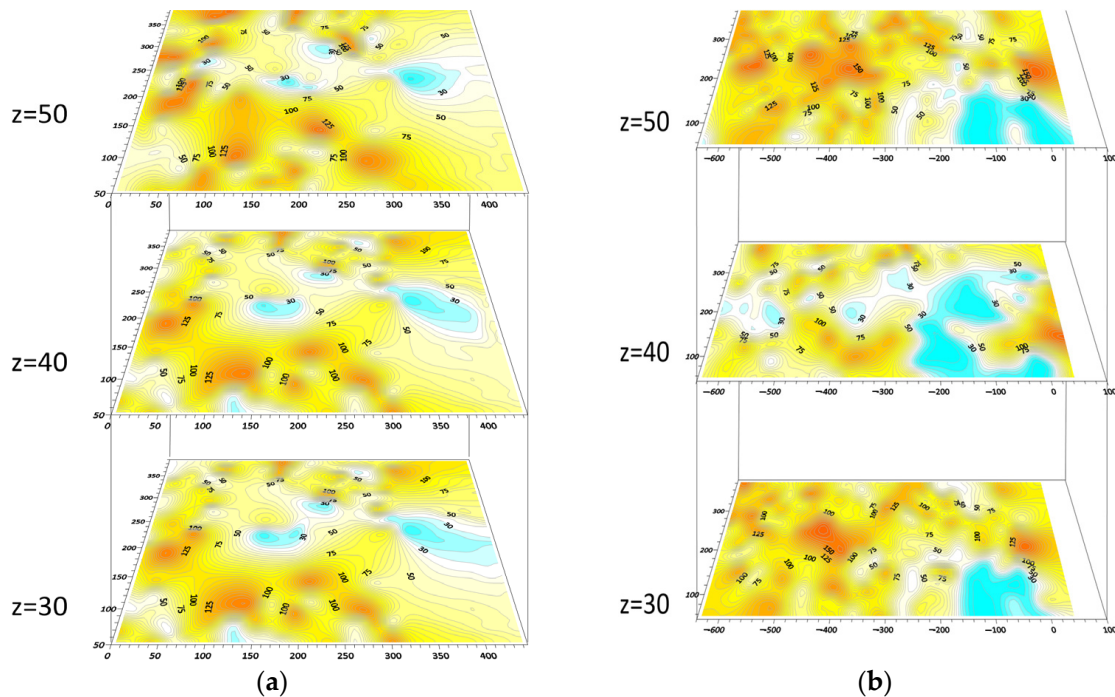


Figure 7. Parallel electrical method results at different heights from the coal seam roof at the second stage (a) and third mining stage (b).

During the retreat of the working face, electrical resistivity was monitored through resistivity slices along each roadway. Analysis of these slices at different time intervals reveals that during the second phase of monitoring, resistivity values did not exhibit significant changes. In most regions, resistivity remained above 50 $\Omega \cdot m$, with only minor areas displaying a slight decrease to approximately 30 $\Omega \cdot m$. Notably, no significant low-resistivity anomalies were detected during this phase.

However, transitioning from the end of the second phase into the third phase, relatively low-resistivity regions began to emerge, particularly around the retreat position and within the goaf. These low-resistivity areas expanded, as illustrated in the resistivity spatial slices, indicating the development of fractures in the overlying strata above the goaf. These fractures facilitated water infiltration from the roof's aquifer, leading to a reduction in resistivity in these regions.

Analysis of natural potential variations over time indicates that during the monitoring period of the first stage, while some fluctuations were observed, the overall trend exhibited minimal change, remaining relatively high (Figure 8). However, toward the end of the first stage, a decrease in natural potential was recorded. At this time, signs of dampness were noted on the walls of the retreat face.

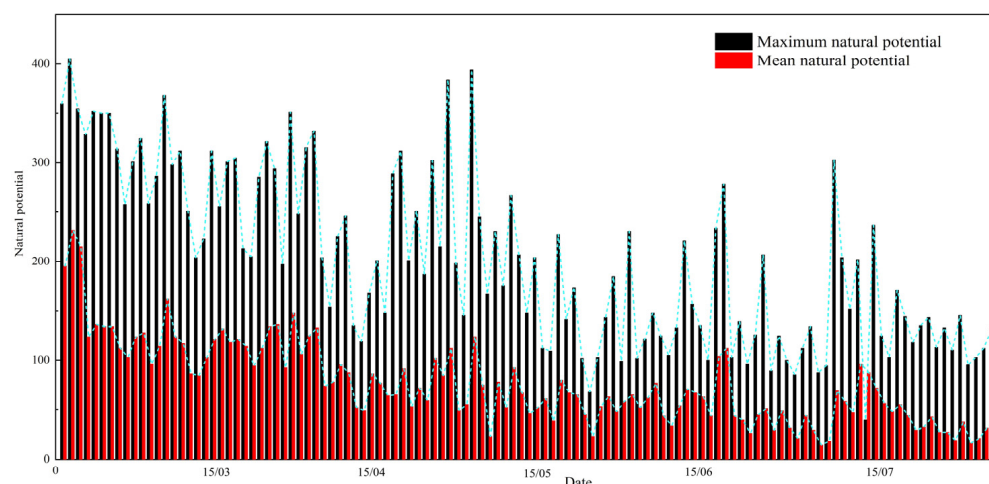


Figure 8. Changes in natural potential.

During the monitoring period following the first stage, the natural potential continued to decline, with water dripping observed near the head of the working face. This suggests that certain fractures induced by mining had extended into the aquifer above the roof, facilitating water infiltration.

Nevertheless, throughout the monitoring period, the maximum variation in natural potential was less than 400 mV, with the average change remaining below 250 mV. No significant or sustained increases in natural potential were detected, nor was there a clear trend indicating the presence of abnormal seepage-related electrical fields.

4.3. Analysis of the Height of Water-Conducting Fracture Zone

Microseismic events are projected onto the working face to illustrate the planar and sectional distribution patterns of microseismic activity across different mining stages (Figure 9). Analysis of the planar distribution of microseismic events reveals that their spatial arrangement is closely associated with the retreat position of the working face, primarily concentrated within approximately 100 m before and after the retreat area (Figure 9a). Thus, the planar distribution of microseismic events correlates with the roof damage characteristics observed at various time intervals.

The sectional distribution of microseismic events indicates that, although the number of events was relatively low in the early stages of mining, the variation in height was significant. This suggests that stress concentration prior to the first roof weighting caused considerable fluctuations in the range of microseismic activity (Figure 9d). Such stress concentration resulted in a broad distribution of microseismic events, reflecting the complex processes of stress accumulation and release prior to roof failure. During the early stages of retreat, the maximum height of fracture development was minimal, with microseismic events predominantly concentrated in the roof at depths of 0–30 m (Figure 9d). As the retreat face advanced from the first to the second stage, microseismic events became concentrated between 50 and 60 m in the roof, with the maximum height reaching 57 m. At this stage, the retreat length was approximately 220 m. This significant increase in microseismic activity marked the occurrence of the first weighting event of the roof, after which the height of fracture development stabilized.

From the analysis of the spatial and temporal distribution of microseismic events, it was determined that the maximum height reached by these events was 57 m above the coal seam roof, indicating the maximum development height of the water-conducting fracture zone. Most microseismic events were concentrated in the 0–30 m height range, reflecting areas of severe roof damage. This zone represents the primary region for caving distribution.

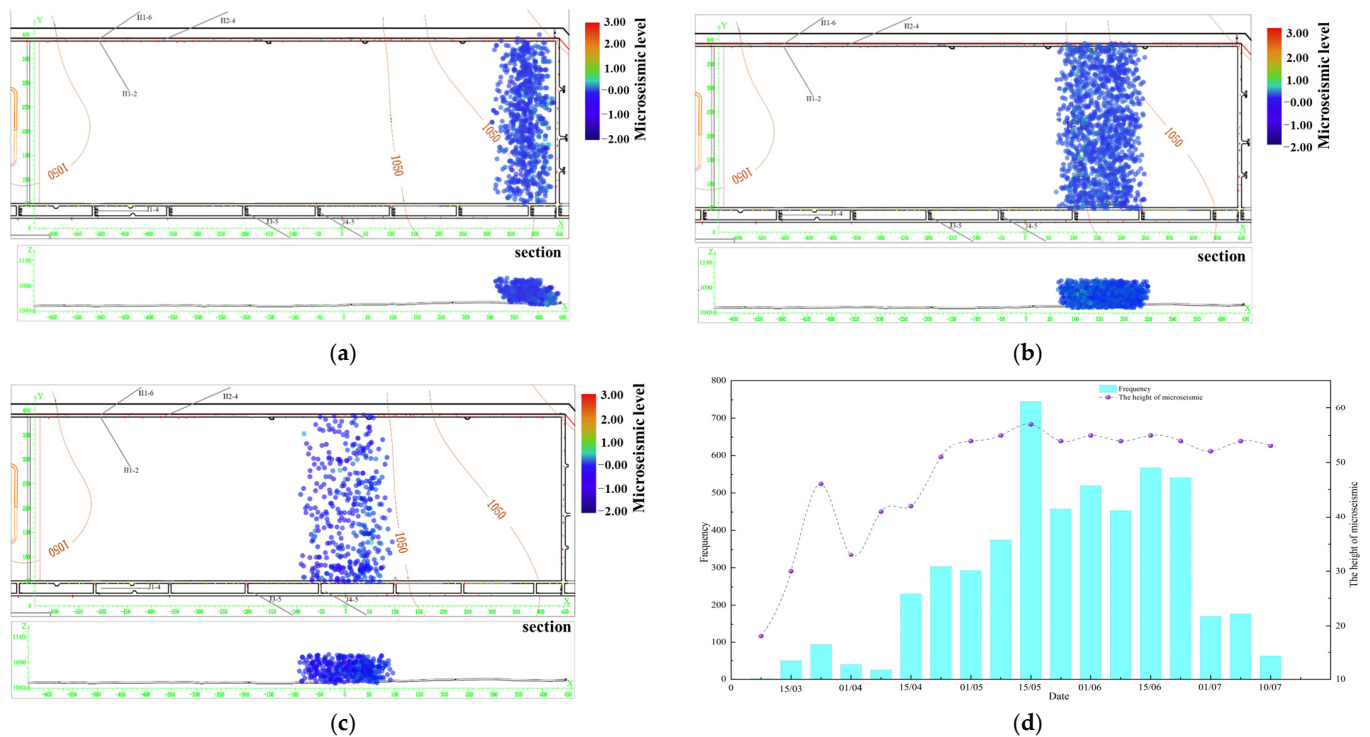


Figure 9. Plan and profile distribution of microseismic in first (a), second (b), and third (c) mining stages and the map of microseismic frequency and height (d).

In conjunction with the parallel electrical resistivity monitoring results, it was observed that from the late first stage into the second mining stage, the natural potential exhibited a significant downward trend. This trend suggests that within a height range of 40–50 m above the coal seam, some fractures have developed that may affect the roof aquifer, leading to the emergence of water inrush precursors. However, despite the detected fracture development, the overall changes in natural potential and apparent resistivity remained within normal ranges. This observation underscores the necessity for enhanced monitoring of roof water inflow.

5. Conclusions

In this study, the combination of microseismic monitoring and parallel electrical methods was applied to assess the water-conducting fracture zone in the Shengfu coalmine. On the basis of the analysis of microseismic monitoring and parallel electrical resistivity results, it can be concluded that the maximum height of the water-conducting fracture zone in the 13,101 working face reached 57 m, with most microseismic events concentrated within the 0–57 m range, indicating severe roof damage in this area. The first periodic roof pressure and roof collapse were effectively captured by microseismic signals, providing early warnings of roof failure. The parallel resistivity monitoring confirmed that fractures developed above the goaf, as indicated by the decrease in resistivity and natural potential. Although the development of cracks indicates a potential risk of water inrush, the overall changes in natural potential and resistivity are low and still within normal ranges, emphasizing the necessity of continuous monitoring to prevent water-related hazards.

This approach not only provides real-time fracture development monitoring but also enables the detection of changes in water pathways, offering a more comprehensive understanding of the potential water inrush risks. Furthermore, the combination of microseismic and parallel electrical monitoring has demonstrated significant potential for enhancing early warning systems for water hazards. By integrating real-time microseismic data and resistivity changes, a data-driven threshold model can be established to provide timely warnings of potential water inrush events. For example, when the height of the fracture

zone exceeds a critical value and resistivity declines sharply, the system can trigger a warning, prompting necessary interventions.

In future applications, this method could be further optimized by developing more detailed and systematic early warning models supported by real-time data processing and statistical analyses. This will strengthen its utility in diverse mining environments and improve the overall safety and stability of mining operations.

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