minerals

Article

Experimental Test and Field Observations of an Electric Potential Monitoring Device for Dynamic Hazards during Mining Activities

Yue Niu [1,2,3,4,5], Enyuan Wang [2,4,5,*], Zhonghui Li [2,4,5,*], Tiancheng Shan [2,4,5], Mingfu Wang [6], Jiali Wang [6], Honghao Wang [7], Hongchang Liu [4], Junhai Ding [4], Jingkun Wang [4], Feiyang Luo [4] and Wei Shi [4]

1 State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China; y.niu16@cumt.edu.cn
2 Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou 221116, China; shantiancheng@cumt.edu.cn
3 School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China
4 School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China; 02201415@cumt.edu.cn (H.L.); 02203702@cumt.edu.cn (J.D.); 02201302@cumt.edu.cn (J.W.); 08204303@cumt.edu.cn (F.L.); 02203201@cumt.edu.cn (W.S.)
5 National Engineering Research Center for Coal Gas Control, China University of Mining and Technology, Xuzhou 221116, China
6 Xinzheng Coal Power Co., Ltd., Zhengzhou Coal Industry (Group) Co., Ltd., Xinzheng 451100, China; d.mingfu@163.com (M.W.); yuer_new@126.com (J.W.)
7 Yanghe Coal Industry Co., Ltd., Zhengzhou Coal Industry (Group) Co., Ltd., Xinmi 452370, China; wanghonghao617@163.com
* Correspondence: weytop@cumt.edu.cn (E.W.); leezhonghui@163.com (Z.L.)

check for updates

Citation: Niu, Y.; Wang, E.; Li, Z.; Shan, T.; Wang, M.; Wang, J.; Wang, H.; Liu, H.; Ding, J.; Wang, J.; et al. Experimental Test and Field Observations of an Electric Potential Monitoring Device for Dynamic Hazards during Mining Activities. *Minerals* **2022**, *12*, 852. https://doi.org/10.3390/min12070852

Academic Editors: Diyuan Li, Zhenyu Han, Xin Cai, Shijie Xie and Abbas Taheri

Received: 20 May 2022
Accepted: 28 June 2022
Published: 3 July 2022

Abstract: The EP (electric potential) signals can be generated during the deformation and fracture process of coal and rock mass. Meanwhile, the EP response is closely related to its stress state and damage evolution, which is expected to be used in monitoring and coal and rock dynamic disaster hazards. Based on this, this paper developed an EP monitoring device for mining to continuously monitor the temporal response characteristics and spatial distribution of coal seam internal EP signals in real time. Further, the experimental tests were carried out, whose results showed that the device has high monitoring sensitivity and little error for the EP signals and can reveal the loading state and damage degree of the coal and rock specimens during the deformation and fracture process. Moreover, the tests and application of EP monitoring were carried out during mining activities in the field. The results showed that the EP signals fluctuate during the coal mining stage and remain relatively stable during the maintenance stage. When the abnormal mining stress or the coal cannon phenomenon occurs, the intensity of EP signals increases rapidly and fluctuates violently, which has precursory response information for the hazards of dynamic disasters. Considering the advantages of sensitive response and nearly non-destructive monitoring, the study results can provide key monitoring equipment and research basis for field testing the EP signals during the mining process, to monitor and forecast the hazards of coal and rock dynamic disasters.

Keywords: EP monitoring device; experimental test; field application; coal and rock dynamic disaster; monitoring and forecasting

1. Introduction

Coal is an important raw material for energy resources, which is widely utilized in many fields, including thermal power generation, metallurgical industry, and chemical production [1]. However, most of the coal resources are hidden in the deep strata underground, which need to be mined. In the process of coal mining activities, as the coal mass is extracted from the original coal stratum, the structure changes, breaking its original stress balance state. It causes the deformation, damage, and instability in the coal and rock mass, leading to coal and rock dynamic disasters when reaching the critical conditions, such as rock burst, coal and gas outburst, roof collapse, etc. [2]. It is very important for real-time monitoring of the damage and failure process of coal and rock mass and accurate forecasting of its instability and failure [3]. This can reliably ensure the safety of coal mining activities, and contribute to avoiding miners' personal casualties, mechanical equipment damage, roadway deformation fracture, etc. [4].

The essence of coal and rock dynamic disasters is the damage and failure of coal and rock mass under the action of mining stress, which eventually leads to the loss of structural stability and dynamic failure of coal and rock [5]. The process belongs to the mechanical category [6]. However, coal mass is a material with significant inhomogeneity and anisotropy, which makes it difficult to accurately monitor the failure and its precursor information of the coal body using traditional mechanical methods [7,8]. Previous studies show that the deformation and rupture process of a coal body can generate significant electric potential (EP) signals, and the EP response is closely related to the damage evolution process and stress state of the coal body [9,10]. Studying the EP response characteristics of a coal body during damage and failure processes can indirectly monitor the damage evolution process of a coal body and identify the precursor information of instability and failure of coal and rock mass [11]. Eccles et al. observed abnormal signals of EP response before rock fracture under different experimental conditions [12]. Wang et al. found that the process of deformation and rupture of a coal body under loading results in charge separation through crack propagation, the triboelectric effect, the piezoelectric effect, and so on, and revealed the physical mechanism of the EP signals generated by the charge [13]. Niu et al. found that when the main fracture occurs inside gas-bearing coal, the EP intensity increases and mutates abruptly, verified by acoustic emission and crack propagation simultaneously [14].

Previous studies on the EP effect of coal and rock mass were mainly carried out using experimental study and theoretical analysis [9,15,16]. These studies have achieved fruitful results and have been widely recognized, and also clarified the potential of using the EP method to monitor and forecast coal and rock dynamic disasters [17]. However, the study on the EP effect of coal and rock lacks testing and application in the field during coal mining activities [18]. Compared with the laboratory study conditions, the interference of environmental signals is very complex in the process of field coal mining, and the change in mining stress and the evolution of coal damage are not controllable [19]. In order to guide the engineering practice, the experimental achievement must be tested and applied in the field, and it is the basis and premise for developing the monitoring equipment for EP signals of a coal body suitable for field coal mining activities [20]. The performance of the mine EP monitoring equipment must be guaranteed, and the validity of the test results should also be verified.

Therefore, in this paper, the mine EP monitoring device was developed independently, and the test effect of the device under laboratory experiment was tested, and then the application in the coal mining site was also carried out. The study results are expected to lay the equipment foundation and research basis for further monitoring and forecasting of coal and rock dynamic disasters with the EP monitoring method.

2. Development of the EP Monitoring Device for Mining

2.1. Monitoring Host

In this paper, the mine EP monitoring device was developed independently, and the host of this equipment is shown in Figure 1. The host surface includes a digital display screen, a control panel, multiple channel interfaces, etc. The host has a resolution of 0.01 mV for EP testing and a range of [−1500 mV,+1500 mV]. The sampling period is adjustable in the interval of 1~240 s. Each channel is connected to the electrode through a shielded cable and can measure EP signals independently. The host has a built-in large-capacity battery with a single power cycle of 30 days approximately, which can independently supply power to the motherboard and the screen. The whole machine has an explosion-proof function and can be applied to downhole testing. The host can use multiple channels to monitor the EP signals of different measuring points synchronously, continuously, and in real time. The sheet-shaped copper electrode is utilized as a sensor to receive EP signals, with high conductivity and low impedance, to sensitively monitor the input EP signal.

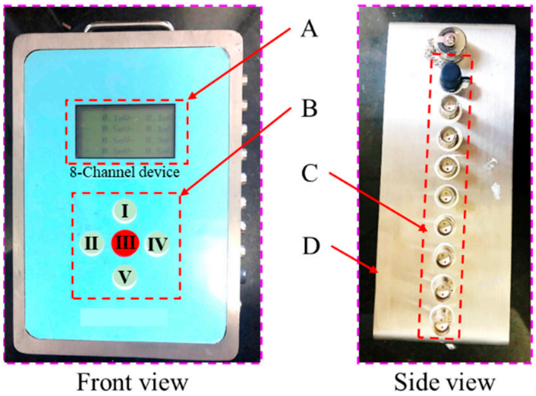


Figure 1. Physical photograph of the EP monitoring host for mining. I—project; II—subtraction; III—power Supply; IV-addition; V-choice; A—data display screen; B—operation panel; C—multichannel interface; D—explosion-proof enclosure.

This host can be regarded and equivalent to a special "voltmeter", and the process flow of measuring EP signal is shown in Figure 2. The electrode receives the EP signals and transmits them to the host through a shielded cable. After being amplified by the preamplifier in the host, the EP signals are converted from an analog/digital converter to digital signals, and then processed by the CPU and stored in memory. The stored data is transmitted to the data reading terminal by the wireless transmission module, and the display can show the measuring data in real time.

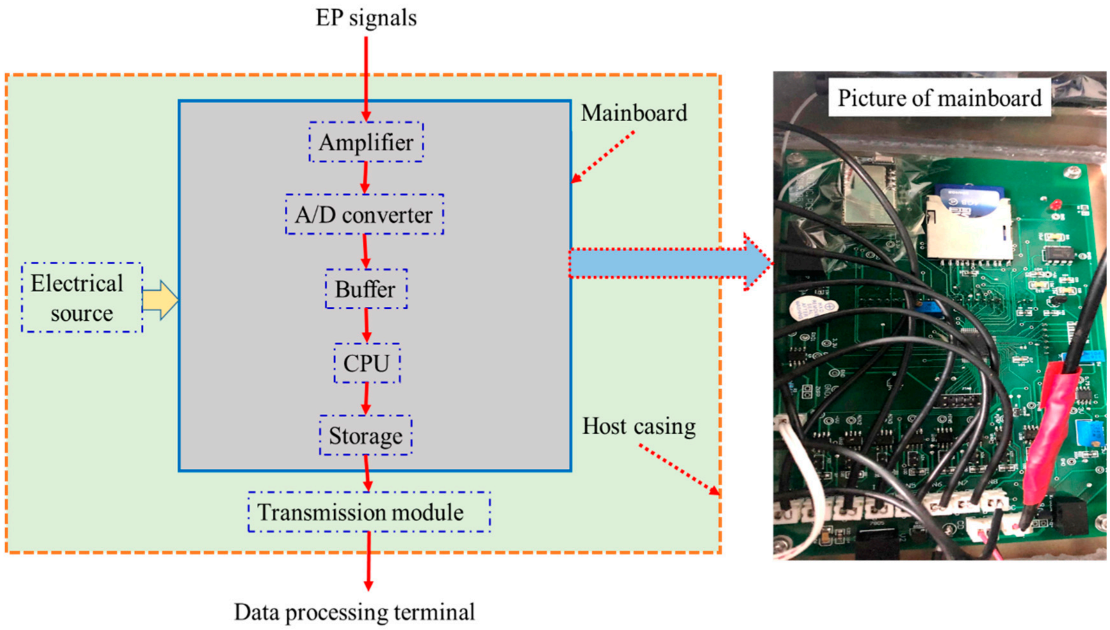


Figure 2. Schematic diagram of EP signal processing.

2.2. EP Data Analysis Software

As shown in Figure 3, the EP monitoring host is matched with self-developed EP data analysis software. The software imitates the Windows interface design with real-time display, historical inquiry, data analysis, forecasting, and other functions. After acquiring the EP data recorded in the EP monitoring host, it can query the EP historical data of different ID hosts, different channels and different time periods, conduct statistical analysis, and issue early warning information in time.

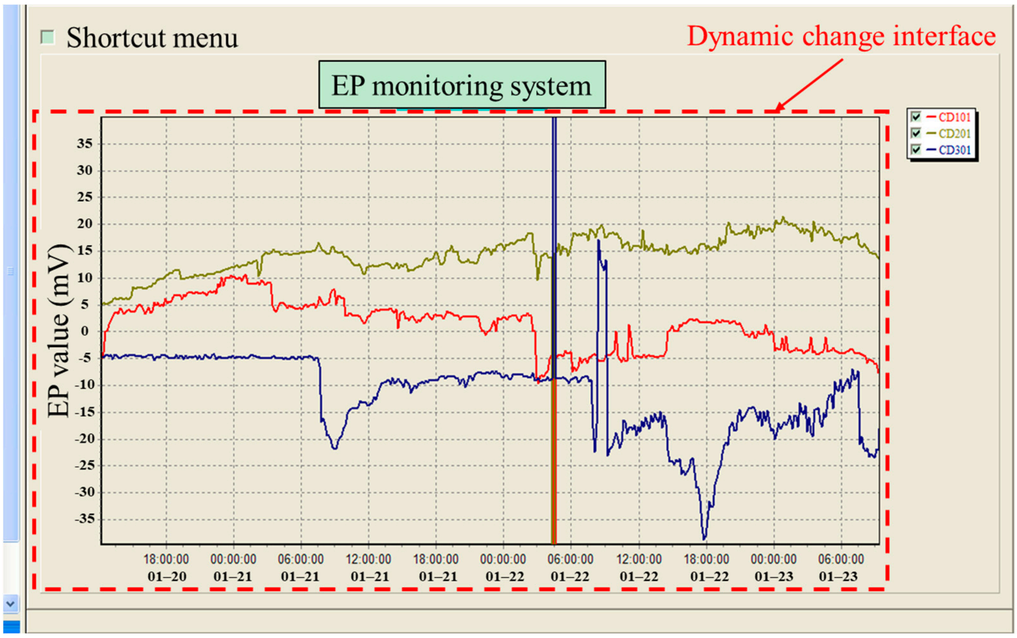


Figure 3. EP analysis software.

2.3. EP Monitoring System Inside Coal Seam

The purpose of developing the mine EP monitoring device is to test the EP signals in different zones inside the coal seam, analyze the correlation between the EP response and the coal and rock dynamic disasters, so as to locate and monitor the hazard zones where the disaster occurs. In order to achieve this goal, this paper designed and developed a multi-point test system for EP spatial distribution inside the coal seam in the field. It can realize the real-time monitoring of EP signals from measurement points at different locations and depths inside the coal seam and analyze the spatial distribution characteristics and dynamic evolution laws of the EP signals.

As shown in Figure 4, the test system consists of an EP monitoring host, push pipes, electrodes, shielding cables, inflatable capsules, flexible air conduits, etc. Among them, the pushing pipe is made of PVC, the length of the single unit is 1.5 m, and the different push pipe units can be connected together through the joint, which can realize pushing the push pipes to the depth of the coal seam. The inside of the push pipe unit is hollow, and a groove is opened in the middle of each unit, where capsules and electrodes can be placed. The electrode is selected as a thin sheet electrode made of copper, which has the advantages of sensitive response and corrosion resistance. The size of this electrode is 50mm $\times$ 30mm $\times$ 1.5 mm, which has a large coverage and moderate flexibility.

The test method of this system includes six steps. (1) An appropriate position in the coal seam underground is selected and the boreholes are drilled inside the coal mass. (2) The PVC pipes are used to transport electrodes to the designated positions in the boreholes, as well as cables, capsules, air conduits, etc. (3) The gas is filled into the capsule through the air conduits outside the borehole, which makes the capsule expand and deform. (4) The deformed capsule lifts the electrode fixed above the capsule, so that the electrode is fully contacted with the coal body on the borehole wall and the EP signals of the coal body are tested. (5) The electrodes are connected to the host outside borehole through shielded cables, and the host records the EP signals monitored in real time. (6) Multiple electrodes can be arranged in the same borehole to test the EP signals at different locations in the borehole.

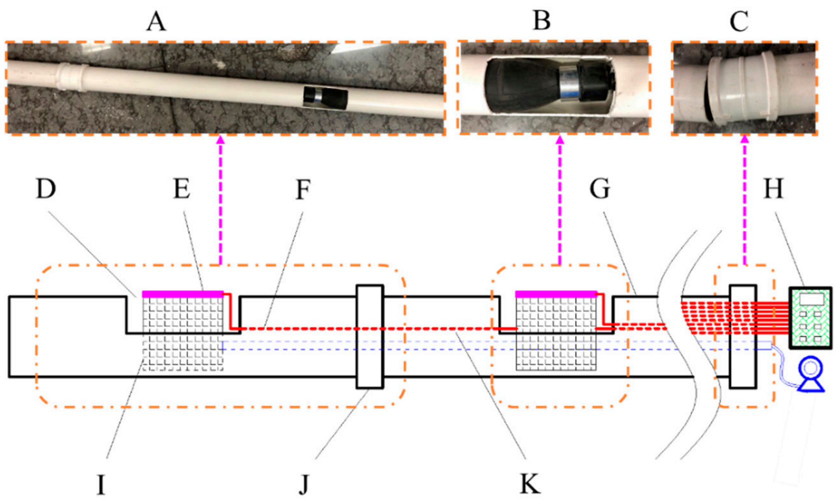


Figure 4. Structural diagram of the EP measuring system for mining. A—PVC push pipe; B—grooves; PVC; C—PVC push pipe joint; D—groove; E—electrode; F—shielding cable; G—PVC push pipe; H—EP host; I—inflatable capsule; J—PVC push pipe joint; K—flexible air conduits.

3. EP Monitoring Host Experimental Test Results

To verify the measuring effect of the EP monitoring host, the test work with two parts under laboratory conditions were carried out. On the one hand, the EP signals were emitted by the power supply to test the EP signal's response accuracy and its spatial distribution characteristics of the EP monitoring host [21]. On the other hand, the uniaxial compression experiments of coal and rock specimens were carried out to test the EP signal's response characteristics of the EP monitoring host during the deformation and fracture process of coal and rock mass [22]. Combined with the above experimental results, the test effect of the EP monitoring host was verified and analyzed.

3.1. Test Experiment of EP Signals Emitted by the Power Supply

3.1.1. Test Results of EP Response Accuracy

The EP signals were emitted by the power supply, which were recorded by the EP monitoring host, and the test results are shown in Figure 5. The EP value of the power supply input is defined as the input EP value, and the EP value measured by the EP monitoring host is defined as the receiving EP value. The results showed that the receiving EP value was highly consistent with the input EP value, and they were almost linearly increased, and the error rate was controlled within 1.5%. It indicates that the EP monitoring host has high sensitivity to the input EP signals, and the test results are reliable.

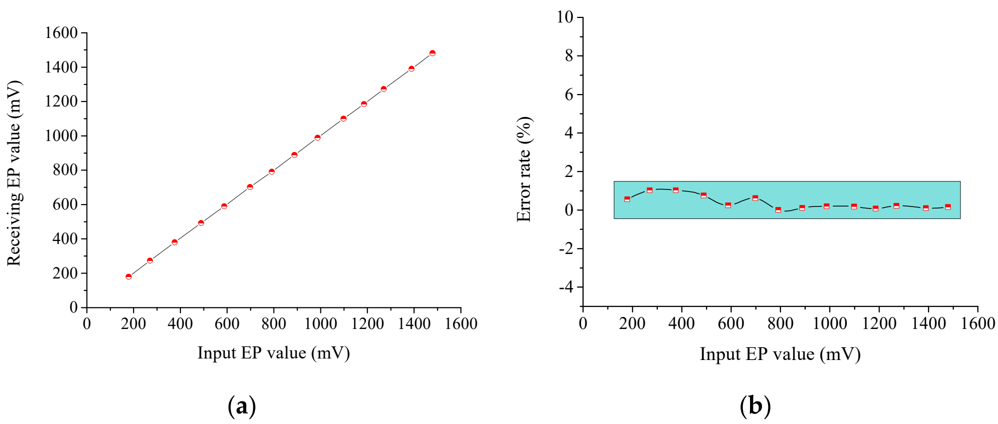
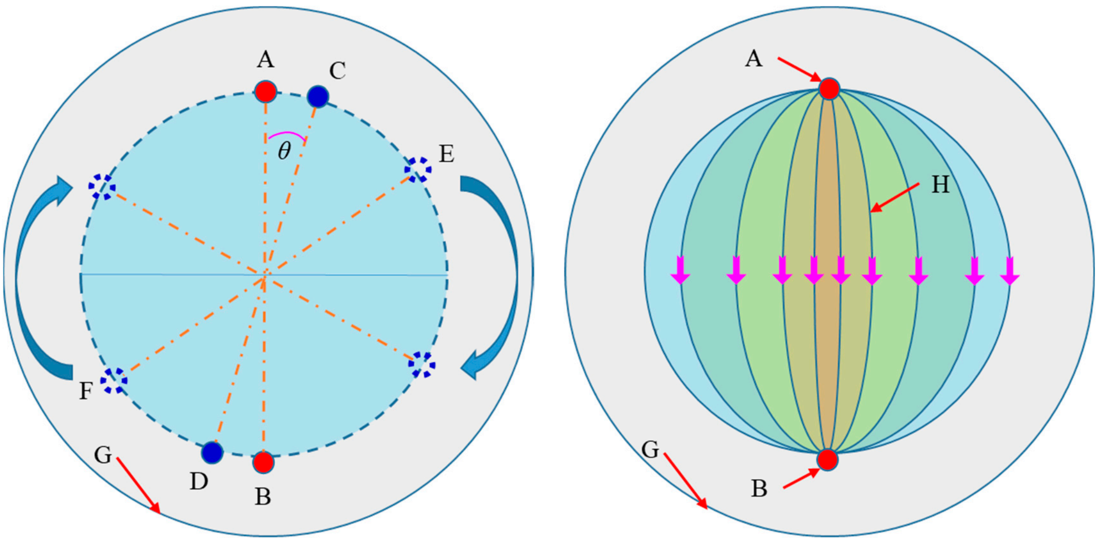


Figure 5. Experimental results of EP measuring emitted by power supply. (**a**) Value comparison of input EP and output EP; (**b**) error rate of comparison results.

3.1.2. Test Results of EP Spatial Distribution

As shown in Figure 6a, 1500 mL of NaCl solution with a concentration of 5% was injected into a bathtub with a diameter of 50 cm, and the response of the EP monitoring host to the EP spatial distribution in the solution was tested in the water bath experiments [23]. The power supply was connected to the input positive electrode and the input negative electrode, and an electrostatic field was excited by the power supply in the solution; thus, generating an EP difference between any two points. The EP monitoring host was connected to the receiving positive electrode and the receiving negative electrode, and the EP difference (i.e., the EP value) between the two electrodes was tested. At the same time, the receiving positive electrode and the receiving negative electrode were connected with the voltmeter to verify the test results of the EP monitoring host.



(**a**) (**b**)

Figure 6. Schematic diagram of electrode arrangement for the water bathing experiment. A—input positive electrode; B—input negative electrode; C—receiving positive electrode; D—receiving negative electrode; E—potential position of receiving positive electrode after rotation; F—potential position of receiving negative electrode after rotation; G—solution boundary; H—electric field line diagram. (**a**) Schematic diagram of receiving electrode rotation relative to input electrodes. (**b**) Schematic diagram of electric field excited by input electrode.

As shown in Figure 6a, the positions of the input positive electrode and the input negative electrode were kept constant, and the positions of the receiving positive electrode and the receiving negative electrode were rotated synchronously along their midpoints to make a certain angle between the two sets of electrodes. As shown in Figure 6b, theoretically, as the angle increases gradually in the interval of [0°,90°], the distance between the receiving electrodes remains unchanged, but the EP difference between the electrodes will gradually decrease [24]. Similarly, the absolute value of the EP difference between the receiving electrodes should gradually increase as the angle gradually increases in the interval of [90°,180°].

The test results of the EP monitoring host and voltmeter under different electrode angles were recorded, and a Rose Diagram was drawn, shown in Figure 7. With the gradual increase in the angle, the EP signals tested by the EP monitoring host and the voltmeter tend to decrease and then increase, and reach the lowest value at an angle of 90° and the highest value at an angle of 180°. This is consistent with the theoretical analysis results, so the test results of the EP monitoring host can reflect the nonlinear distribution characteristics of the original EP signals in space.

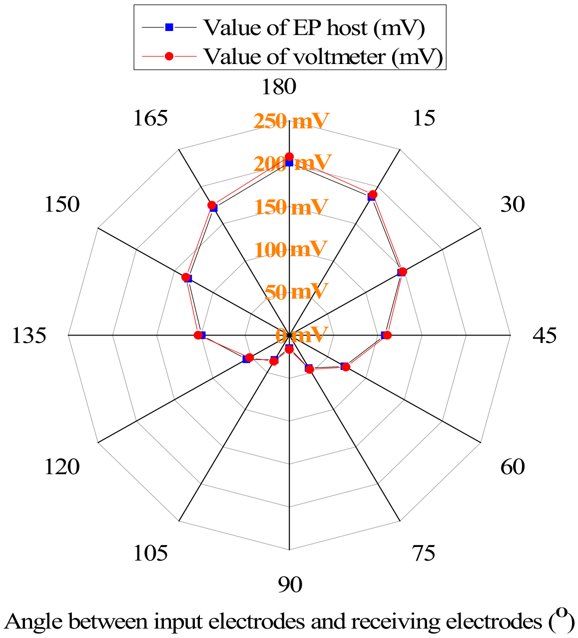


Figure 7. Experiment results of EP measuring in the water bathing environment.

3.2. Experiment Results of the EP Signals Test under the Uniaxial Compression Process

3.2.1. Test Results of Raw Coal Specimen

For mining activities, coal is regarded as a special rock, which contains more abundant pores and fracture structures. The coal's main component is organic matter, which can adsorb gas with stronger plasticity and weaker elastic modulus. The materials involved in coal rock dynamic disasters can be regarded as "coal", "coal rock", "coal-measure rock", or "coal and rock". In order to simulate the deformation and fracture process of a coal body in mining activities, the cylindrical raw coal specimens with the size of Φ50mm × 100 mm were made, and the uniaxial compression load was applied to the specimens until failure. The loading method is force control with rate of 100 N/s. The EP measuring points are arranged on the specimen surfaces, and the EP signals of the specimens during the loading process is tested using the EP monitoring host. The experimental results are shown in Figure 8.

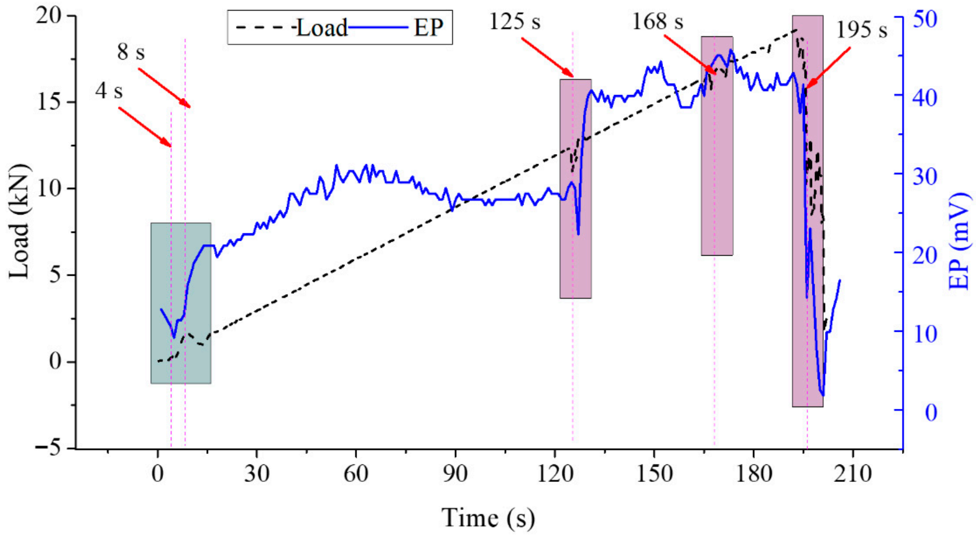


Figure 8. Experimental results of EP response on raw coal specimens under uniaxial compression.

It can be seen from Figure 8 that with the increase in load, the damage degree of the coal body was increasingly aggravated. When there was a small abrupt change in the load, indicating that the specimen was severely damaged in the local position. When the load suddenly decreased to the residual value, it showed that the specimen structure lost stability and dynamic damage occurred. Meanwhile, with the increase in load, the EP signal intensity showed an increasing trend. When the specimen was severely damaged locally, the EP signals fluctuated several times.

In details, (1) in the early loading stage, there was a small abnormal fluctuation in the process of load increase, and the EP intensity also showed an abnormal response that fluctuated to a valley value and increased rapidly at the corresponding moments (4 and 8 s). This was because the raw coal specimen contained abundant pore and fissure structures, which would inevitably cause some damage to the internal structure of the specimen during the specimen preparation process. Even at a low load level, small damage and rupture might occur, resulting in fluctuations in EP signals [11]. (2) At 125 s, the load fluctuated abnormally again, and the EP intensity increased in a stepwise manner. At this time, under the action of higher load, the relatively serious deformation and rupture occurred inside the specimen, resulting in load fluctuation. At the corresponding time, the cracks inside the specimen expanded rapidly, resulting in a sudden increase in EP intensity. (3) When the loading process continued to 168 s, the load showed significant abnormal fluctuations again, resulting in violent fluctuations in the EP signals again. (4) At 195 s, the main fracture of the specimen occurred, and the load rapidly decreased to the residual level, where the EP signals showed a sudden drop mutation again. This was basically consistent with the previous laws of test results by using high-precision EP monitoring equipment suitable for laboratory conditions [14].

The experimental results indicate that the independently developed EP monitoring host can effectively measure the EP signals generated during the deformation and fracture process of the raw coal specimen. The response characteristics of the EP signals can reveal the stress state of the coal body and have cumulative enhanced response characteristics (i.e., "memory effect") for the damage and deformation of the coal body. When the specimen is severely damaged or even the main fracture occurs, the EP signals have abnormal response characteristics. It is manifested as "↑" and "↓" type mutations, which can monitor and forecast the instability and fracture of the coal body.

3.2.2. Test Results of the Concrete Specimen

The brittle fracture of raw coal occurs during the uniaxial compression. However, in most cases during mining activities, due to the limitation of the mining space and the effect of the lateral stress of the surrounding rock, the deformation and fracture of coal and rock often show strong plastic characteristics. Meanwhile, the concrete material has strong plasticity. Under the uniaxial compression test conditions, the concrete specimen can have obvious plastic deformation before reaching the failure strength without sudden fracture, which is more in line with the characteristics of actual deformation and fracture of coal and rock mass at the excavation and mining site. At the same time, the production process of concrete can better avoid the initial damage of the specimens. Previous studies have shown that concrete can also generate abundant EP signals during the deformation and fracture process [25,26]. In order to further simulate the deformation and fracture of coal and rock mass in mining space, the concrete specimens were prepared in this section, and the uniaxial compression test was carried out. Additionally, the EP signals generated at different positions during the deformation and fracture of the specimens were tested by the EP monitoring host. The concrete specimens are cubes with dimensions of 150 mm × 150 mm × 150 mm. The loading method is displacement control and the loading speed is 0.25 mm/min. The test results are shown in Figure 9.

Figure 9 shows that the EP signals are tested at different measuring points under the action of load, and the response characteristics of the EP signals are basically consistent, which show an increasing trend with the load increasing. Different from raw coal, concrete has strong plasticity and weak brittleness. The damage process of the specimen is relatively stable, and there is no significant load mutation characteristic, so the change in EP signals is relatively stable. When the load level is low, the specimen undergoes transverse expansion deformation under the action of axial stress, and the damage degree is higher [27]. In this process, the abundant EP signals are generated due to crack propagation and friction between crack surfaces, and the EP intensity increases with the increase in fracture surfaces. At the later stage of loading, with the increase in the load level, the deformation and fracture of the specimen are intensified, and the cracks gradually converge and coalescence, forming the macroscopic fracture zones. The charges are constantly accumulating and neutralizing each other, which leads to a slow increase or even a decrease in the EP intensity too varying degrees, but the EP intensity is still at a high level on the whole.

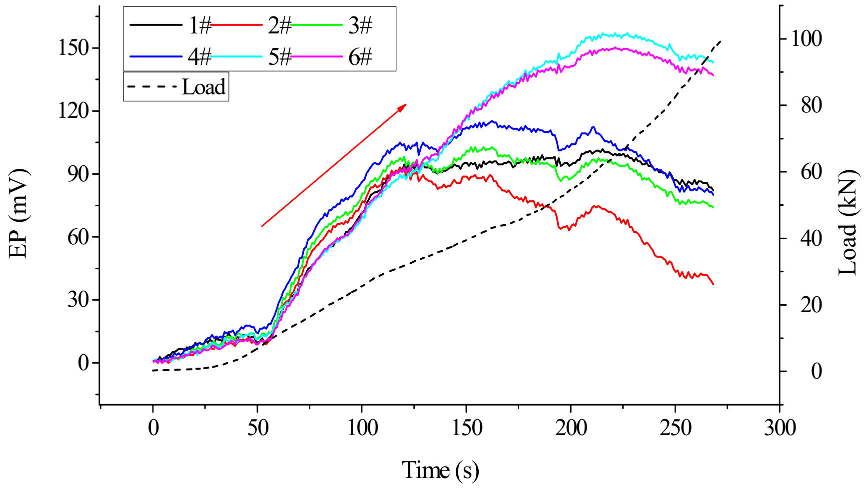


Figure 9. Experimental results of EP response on the concrete specimen under uniaxial compression.

There are also some differences in the EP response characteristics of different measuring points, which are closely related to the degree of deformation and rupture of the measuring points on the specimen surfaces. Among them, the 1~3# EP measuring points 0were arranged on the front surface of the specimen, and the 4~6# EP measuring points were arranged on the rear surface of the specimen. The average value and standard deviation of EP intensity at different measuring points are shown in Figure 10. The EP response of 1~3# was relatively weak, which showed that the average value and standard deviation of EP were lower, and the weakest was 2#. Relatively, the EP response of 4~6# was stronger, which showed that the average value and standard deviation of EP were higher. It meant that the EP response was more intense, and the strongest was 8#. It could be seen from the physical maps of the specimen surfaces with deformation and fracture (the yellow dotted line indicates the crack propagation trajectory) that the crack propagation was less near the 1~3# EP measuring points on the front surface, and the plane near the 2# EP measuring point was the most complete. Meanwhile, the crack propagation near the 6~8# EP measuring points on the rear surface was greater in number and larger in scale (the crack lengths were longer and the widths were wider), and the crack propagation was the most abundant near the 8# measuring point. The crack propagation was the macroscopic manifestation of the internal local severe damage. In the region with abundant crack propagation, the damage localization of the specimen developed more intensely, which led to a higher mean value for the EP signals of the measuring point at this position. Additionally, the larger the standard deviation was, the more intense the EP response was. Therefore, the EP monitoring host could effectively monitor the EP signals generated during the deformation and fracture of materials such as coal and rock and could identify the damage degree of different local positions of the specimen.

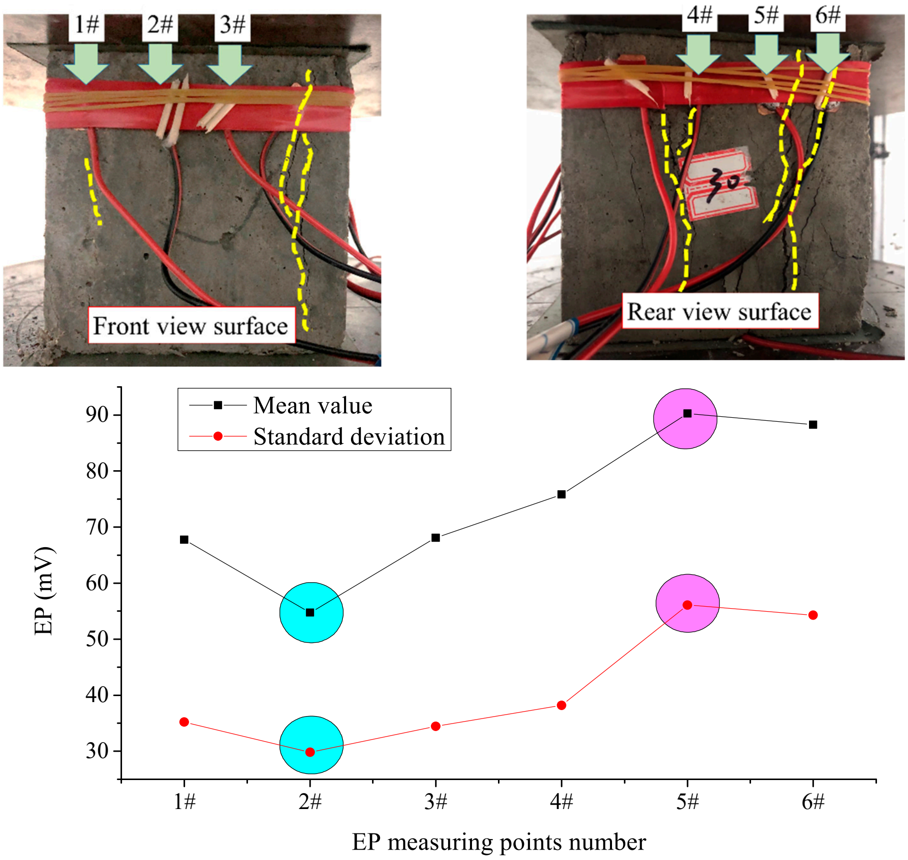


Figure 10. Statistics of mean and standard deviation of the EP signal at different measuring points of the concrete specimen.

4. Field Test and Application Results of the EP Monitoring Device during Mining Activities

4.1. Survey of the Mining Coal Seam in the Field

In coal mining activities, as the coal body is mined, a suspended area (i.e., "goaf") is formed in the original position, resulting in a change in the stress distribution of the coal seam, which imposes an "additional loading stress" on the coal body, similar to Section 3.2 [28]. At the same time, the coal mining process uses the machine to cut the coal body, so that the coal body is broken and gas is pushed out, which further disturbs the stability of the coal seam. Under the action of mining stress, the deformation and fracture of the coal body develop to a certain extent and even have the hazard of dynamic disasters such as coal and gas outburst and roof collapse [29].

In order to further verify the application effect of the EP monitoring device for mining in the field, this paper used the EP monitoring system in Section 2.3 to test the EP signals in the mining coal seam of Xuehu Coal Mine in Shangqiu City, Henan Province, China. The test address was the return air roadway (belonging to the coal roadway) of the 25050 fully mechanized mining face in the NO. 25 Mining Area, where the EP measuring points were arranged. The NO. 25050 Ming Area has a strike length of 1200 m, an inclination length of 160 m, an average inclination angle of 11°, an average coal thickness of 2.3 m, and a height of 720–750 m from the ground. It is located in the outburst threat area, with a large gas content, and the absolute gas emission volume of the excavation is 3.0–1.0 $\times$ 10^3 m^3/min. There are many small faults and magmatic rocks intrusion locally, which have an important impact on the stress distribution of the mining coal seam and the gas migration. Moreover, it has high pressure and serious slats, and it is easy to form stress anomalous areas locally, resulting in a broken roof, development of cracks, and gas enrichment, which has the danger of inducing coal and rock dynamic disasters. It is necessary to strengthen the monitoring of coal and rock dynamic hazards in the mining face. The arrangement of EP measuring points in the field coal mining face is shown in Figure 11.

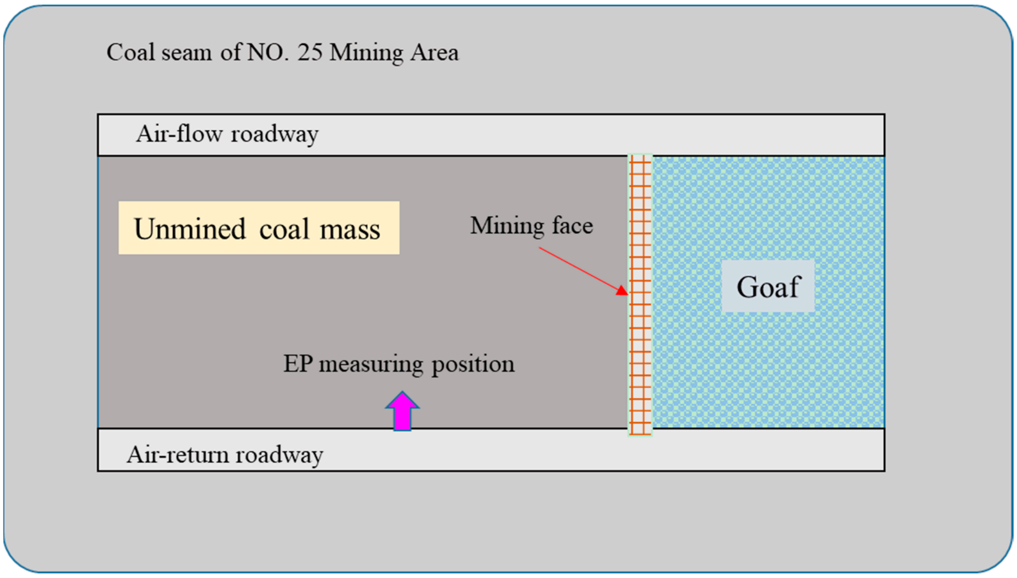


Figure 11. Schematic diagram of EP measuring layout in the coal seam of the NO. 25 Mining Area.

4.2. Response Characteristics of EP Signals in the Coal Mining Process

4.2.1. "Mining-Maintenance" Process and EP Response in the Coal Seam

Generally, coal mining activities are carried out intermittently. In Xuehu Coal Mine, the coal mining activities are carried out continuously for 20 h on the mining face each day, followed by a four-hour pause for equipment maintenance during the coal mining process. After the completion of maintenance, coal mining activities continue to carry out circularly.

Taking 27–30 August as an example, the response characteristics of the EP signals during maintenance and coal mining were analyzed, shown in Figure 12. (1) The maintenance stage was carried out from 9:00 to 14:00 on 28 August, during which the EP signals quickly entered a quiet period from a relatively fluctuating state and remained stable. Additionally, the EP signals quickly left the relatively quiet state after entering the next coal mining cycle and fluctuated significantly. (2) The mining process entered the maintenance stage again from 9:00 to 14:00 on 29 August, and the EP signals showed a trend of "fluctuation–calm–fluctuation" again. (3) From 9:00 to 14:00 on 30 August, the mining process entered the maintenance stage again, and the EP signals of the measuring point were not as calm as the previous maintenance stage, and the EP signals fluctuated greatly.

The EP signals of the coal body change with the coal mining activities, which is mainly caused by the change in the coal body stress distribution due to coal cutting by the coal mining machine [30]. Theoretically, the stress state and structure of the coal seam in front of the working face are relatively stable during the maintenance stage, so the EP signals should be in a relatively stable state, and the fluctuation of the EP signals during coal mining is more significant. During the coal mining process, the coal mining face is constantly moving forward, while the EP measuring points are fixed, so the distance between the EP measuring points and the coal mining face is constantly decreasing. With the continuous decrease in this distance, the coal body at the EP measuring points is increasingly affected by the coal mining activities, so the EP intensity shows an overall increasing trend. On 29 August, the EP measuring point was about 10 m away from the coal mining face. The coal near the measuring point was greatly affected by the pressure relief effect of the coal mining face, and the coal at the measuring point had a large deviatoric stress difference, resulting in severe damage and fracture. Therefore, even in the maintenance stage, the damage state of the coal body at the EP measuring points was still in a slow evolution and development process, and the EP signals had a relative fluctuating response.

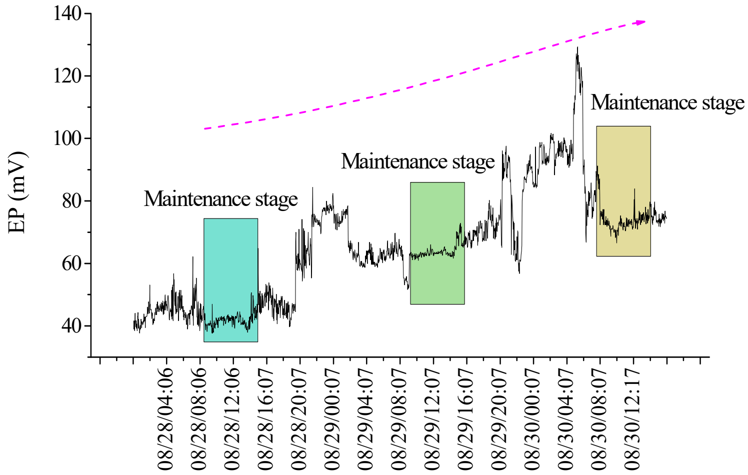


Figure 12. Influence on EP response during mining activities by maintenance.

4.2.2. Mining Stress Anomaly and EP Response

The geological structures of an underground coal seam are complex, which are often rich in small faults, collapse columns, water-bearing layers, gas abundance zones, and so on, resulting in the distribution of stress anomalies in coal and rock mass during mining [31]. When the mining stress is abnormal, the damage to the coal body is more severe under the same mining influence, and it is easy to induce dynamic damage phenomena of the coal body.

On 21 August, the mining stress of the coal body was abnormal. Correspondingly, at 18:30 on 21 August, the EP intensity suddenly increased, with an increase of 1.5–6.2 times for the original value. The mean and standard deviation for the daily EP signals of coal body were counted, as shown in Figure 13. Before 21 August, the EP intensity and standard deviation increased rapidly, and after the occurrence of stress anomaly, the EP intensity continued to increase and the standard deviation decreased after reaching the peak, which meant that the EP intensity and standard deviation showed the abnormal response characteristics with types of "↗" and "∧", respectively. The above test results showed that when the stress abnormality occurred, the stress distribution of the coal body near the measurement point changed from a relatively balanced state to an unstable state, and the damage was more severe, resulting in an increase in the EP strength and the increase in the dispersion of the EP signals, and the heterogeneity of the coal body damage evolution was enhanced [32]. As the stress distribution of the coal body gradually transitioned from "abnormal" to "new equilibrium" state, the loading state of the coal body was more stable, and even though the EP signals continued to increase, the dispersion of EP signals decreased, resulting in a decrease in the EP standard deviation.

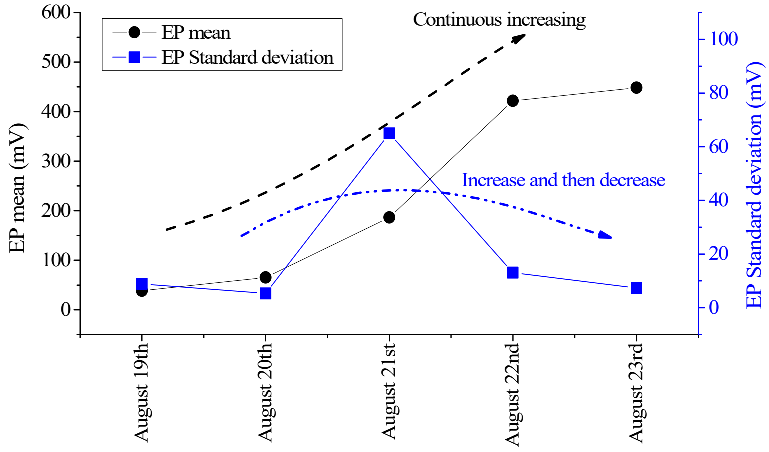


Figure 13. Response results of EP signals before and after stress abnormality occurrence.

Therefore, when the mining stress is abnormal, the EP signals have a rapid and greatly enhanced abnormal response characteristic. The increase in EP strength is the most intuitive reflection of the mining stress anomalies, while the EP standard deviation is more able to identify the continuous "anomalous" and "new equilibrium" state of the mining stress distribution. The EP monitoring results have significant anomalous response characteristics to the coal mining stress anomaly and can monitor the stress state and damage process inside the coal and rock body.

4.2.3. Coal Cannon Phenomenon and EP Response

Coal is damaged and deformed under the action of mining activities, and the elastic energy is continuously accumulated. When the accumulation of elastic energy reaches the critical condition, due to roof fracture, rock vibration, and so on, the coal body occurs in a small range of sudden fracture and emits a loud sound [32]. It is called the "coal cannon" phenomenon, belonging to a classical type of coal dynamic failure. When the energy released by the coal cannon is large, especially when the continuous high-energy coal cannon phenomenon occurs and cannot be effectively controlled, it will pose a threat to the safety of personnel and equipment in the mining space, which is one of the early warning signs of coal and rock dynamic disaster hazards.

As shown in Figure 14, a continuous high-energy coal cannon phenomenon occurred on 20 September, resulting in a significant crack with 1.2 m length and 0.5 m width on the floor of the roadway with a large destructive force. Before the occurrence of the coal cannon, the EP intensity was already at a high level up to 159.7 mV and showed a certain increasing trend. At 21:30 on 18 September, the EP response began to reveal precursory information, showing a significant abnormal response characteristic of "plunge-stabilization-swell-stabilization-decrease", and rapidly decreased after 9:00 on 19 September. Compared with the moment when the coal cannon occurred, the precursory information of the EP signals was about 2 days earlier and lasted about 1 day. When the coal cannon occurred, the EP intensity was close to the peak, and then the EP signals fluctuated violently during the continuous occurrence of the coal cannon. After the occurrence of the coal cannon, the EP intensity decreased rapidly again and remained relatively stable afterwards.

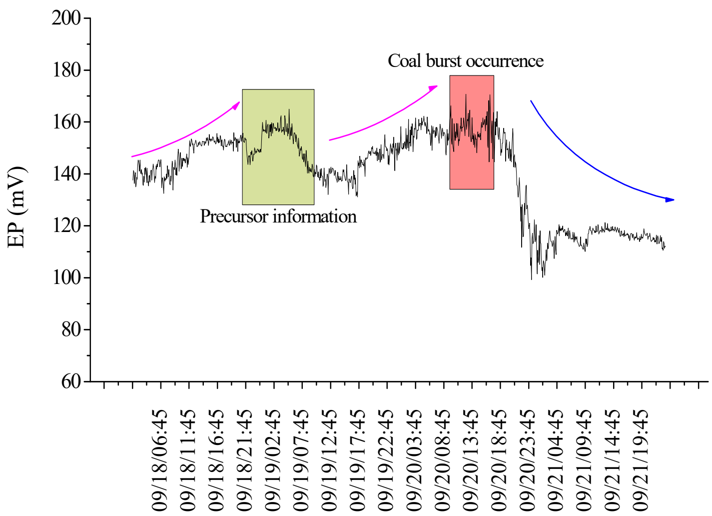


Figure 14. EP measuring results around the coal burst occurrence.

Before the occurrence of the coal cannon, the strain energy continued to accumulate by a large amount, leading to an increase in the elastic deformation and plastic damage of the coal body and a subsequent increase in EP strength [30]. This induced the abnormal response characteristics of the EP signals during the inoculation process of the coal cannon, which showed the precursory information of sustained increasing and violent fluctuation, and the EP intensity was close to the peak level when the coal cannon occurred. After the occurrence of the coal cannon, the mining stress level decreased rapidly with the release of energy, which was similar to the residual stress state in the uniaxial compression experiment (shown in Figure 11). At this time, the hazard of the coal and rock dynamic disaster was significantly reduced, and the EP intensity decreased rapidly and remained at a relatively stable level.

4.3. Application Prospect of the EP Monitoring Method in Forecasting of Coal and Rock Dynamic Disaster Hazards

According to the above analysis, the EP signals can be generated in the mining process of coal seam, and the response characteristics of EP signals are closely related to the stress state and damage evolution process of coal and rock mass. The EP signals have the response characteristics of the strength rising to a high value for coal and rock dynamic disaster hazards (i.e., mining stress anomaly or coal cannon phenomenon), which can reflect the loading and damaging state of specimen, and reveal the hazard degree of the coal and rock dynamic disasters [9,10]. Therefore, through monitoring the EP signals inside the coal seam during mining activities, it is possible to identify the abnormal response characteristics, monitor and forecast the coal and rock dynamic hazards, which are prevented and controlled by taking targeted measures. This provides a new engineering application method for fine forecasting and precise control of coal and rock dynamic disasters at the coal mining sites.

Compared with the previous conventional monitoring methods, such as the stress monitoring method, electromagnetic radiation method, and microseismic method, the EP monitoring has its own unique advantages [33–35]. Taking electromagnetic radiation as an example, it is a non-contact monitoring method. It monitors the electromagnetic radiation signal generated during the process of coal deformation and fracture, but it is easily disturbed by the electromagnetic induction phenomenon caused by the start, stop, and operation of large-scale electromechanical equipment, such as a shearer and scraper. This is unavoidable during the daily mining work. As a comparison, the EP monitoring needs to contact the electrode with the coal, and the electrode should avoid direct contact with electromechanical equipment, the metal anchor net, and wet coal, which effectively avoids the interference of the electromagnetic induction phenomenon. Similarly, the acoustic emission signal is easily disturbed by the noise generated during the operation of large electromechanical equipment. Due to the wide frequency spectrum of the acoustic emission signal generated in the mining activities, there is no widely adaptive filtering method to eliminate it. Usually, the acoustic emission sensor is arranged on the bolt to receive the acoustic emission signal generated inside the coal body.

For the EP monitoring method, on the one hand, the EP monitoring has the advantages of accurate response and strong anti-interference. The EP signals are not only sensitive to the large-scale fracture event of the coal body, but also respond to the deformation of the coal body (i.e., the strain field), which can reveal the evolution process of the coal body damage and failure from a deep level [30]. The EP signals are obtained by direct contact tests between the electrode and the coal body, and coal is one of the typical poor conductors, which is less disturbed by the work of electromechanical equipment. On the other hand, the process of EP monitoring is simple, requiring only the construction of ordinary boreholes with a small workload and negligible impact on production, which is similar to "non-destructive monitoring". The EP monitoring system can push the electrodes to the specified borehole depth through the pushing device, which can test the EP signals of the same borehole with different borehole depths in real time and continuously at high frequency, and realize the location monitoring of the EP spatial distribution law [10].

In this paper, the mine EP monitoring device was independently developed, which was tested and applied during mining activities. Consequently, some preliminary achievements and progress were made. However, the study on the EP monitoring technology and system of coal and rock gas dynamic disasters still needs to be carried out in depth. The authors' research group has independently developed EP monitoring instruments, matching facilities, and analysis software for coal seam mining on site. The next step is to monitor the coal seam EP signals online. Through artificial intelligence theory and big data analysis method, sensitive indicators are set up to carry out intelligent monitoring and forecasting of coal and rock dynamic failure and its induced disasters. The study results are not only applicable to the coal mining face, but also play a monitoring role in the tunneling of coal and rock roadway. Considering the technical advantages and low cost of the EP monitoring, this technical method has broad engineering study prospects.

5. Conclusions

(1) The host device, data analysis software, and monitoring system of the EP monitoring device for mining were independently developed. The EP monitoring host has the function of synchronous, continuous, and real-time monitoring for the EP signals at the different measuring points. Further, the data analysis software can record the EP data of different acquisition channels and different test periods. The coal seam EP monitoring system can monitor the EP signals of multiple measuring points in real time, analyzing the spatial distribution characteristics.

(2) Multiple sets of laboratory experiments were carried out with EP monitoring host. The EP monitoring host has high sensitivity and little error for the EP signals. It shows the reliable test results and can reflect the nonlinear distribution characteristics of the EP signals in space. The experimental results of coal and rock specimen loading failure show that the EP monitoring host can effectively measure the EP signals generated by the deformation and rupture process of the specimens. The response characteristics of EP signals can reveal the stress state and damage degree of a specimen, to forecast its instability and fracture.

(3) The field tests and applications were carried out in coal mining faces, and the relationship between EP response and the hazard of coal and rock dynamic disasters was analyzed. The results show that the EP signals fluctuate greatly during coal mining and remain relatively stable during the maintenance stage. When the mining stress is abnormal, the EP signal intensity and standard deviation show the abnormal response characteristics with types of "↗" and "∧", respectively. Before the occurrence of the coal cannon, the EP signals show precursory information of increased intensity and violent fluctuation and were close to the peak level when the coal cannon occurred. After that, the hazard of disaster decreases, and the EP intensity remains at a relatively stable level.

(4) The EP monitoring method has the technical advantages of sensitive response, strong anti-interference, and approximate non-destructiveness, which can reveal the loading and damaging state of coal mass and indicates the hazard degree of coal and rock dynamic disasters. By identifying the abnormal response characteristics of EP monitoring results, it is expected to provide a new engineering application method for fine forecasting and precise prevention of coal and rock dynamic disasters in coal mining sites.

Author Contributions: Conceptualization, E.W. and Z.L.; methodology, Y.N.; software, Y.N.; formal analysis, Y.N.; investigation, H.W.; resources, E.W. and Z.L.; writing—original draft preparation, Y.N.; writing—reviewing and editing, H.L., J.D., J.W. (Jingkun Wang), F.L. and W.S.; supervision, J.W. (Jiali Wang); project administration, M.W.; funding acquisition, E.W., Z.L. and T.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the National Science Foundation for Young Scientists of Jiangsu Province (BK20210504), National Natural Science Foundation of China, China (52104234, 51934007, 52074280), and the Fundamental Research Funds for the Central Universities (2021QN1104).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Zhou, H.; Bhattarai, R.; Li, Y.; Si, B.; Dong, X.; Wang, T.; Yao, Z. Towards sustainable coal industry: Turning coal bottom ash into wealth. *Sci. Total Environ.* **2021**, *804*, 149985. [CrossRef] [PubMed]
2. Batugin, A.; Kolikov, K.; Ivannikov, A.; Ignatov, Y.; Krasnoshtanov, D. Transformation of the geodynamic hazard manifestation forms in mining areas. *Int. Multidiscip. Sci. GeoConf. SGEM* **2019**, *19*, 717–724.
3. Khan, M.; He, X.; Farid, A.; Song, D.; Li, Z.; Tian, X.; Ni, M. A novel geophysical method for fractures mapping and risk zones identification in a coalmine, Northeast, China. *Energy Rep.* **2021**, *7*, 3785–3804. [CrossRef]
4. Wolf, K.-H.A.; van Bergen, F.; Ephraim, R.; Pagnier, H. Determination of the cleat angle distribution of the RECOPOL coal seams, using CT-scans and image analysis on drilling cuttings and coal blocks. *Int. J. Coal Geol.* **2008**, *73*, 259–272. [CrossRef]
5. Lu, J.; Zhang, D.; Huang, G.; Li, X.; Gao, H.; Yin, G. Effects of loading rate on the compound dynamic disaster in deep underground coal mine under true triaxial stress. *Int. J. Rock Mech. Min. Sci.* **2020**, *134*, 104453. [CrossRef]
6. Wang, C.; He, B.; Hou, X.; Li, J.; Liu, L. Stress–Energy Mechanism for Rock Failure Evolution Based on Damage Mechanics in Hard Rock. *Rock Mech. Rock Eng.* **2019**, *53*, 1021–1037. [CrossRef]
7. Kuchibhatla, S.V.; Karakoti, A.; Bera, D.; Seal, S. One dimensional nanostructured materials. *Prog. Mater. Sci.* **2007**, *52*, 699–913. [CrossRef]
8. Bordas, S.; Rabczuk, T.; Zi, G. Three-dimensional crack initiation, propagation, branching and junction in non-linear materials by an extended meshfree method without asymptotic enrichment. *Eng. Fract. Mech.* **2008**, *75*, 943–960. [CrossRef]
9. Li, Z.; Zhang, X.; Wei, Y.; Ali, M. Experimental Study of Electric Potential Response Characteristics of Different Lithological Samples Subject to Uniaxial Loading. *Rock Mech. Rock Eng.* **2020**, *54*, 397–408. [CrossRef]
10. Niu, Y.; Wang, E.; Li, Z.; Gao, F.; Zhang, Z.; Li, B.; Zhang, X. Identification of Coal and Gas Outburst-Hazardous Zones by Electric Potential Inversion During Mining Process in Deep Coal Seam. *Rock Mech. Rock Eng.* **2022**, *55*, 3439–3450. [CrossRef]
11. Li, Z.; Niu, Y.; Wang, E.; Liu, L.; Wang, H.; Wang, M.; Ali, M. Experimental Study on Electric Potential Response Characteristics of Gas-Bearing Coal During Deformation and Fracturing Process. *Processes* **2019**, *7*, 72. [CrossRef]
12. Eccles, D.; Sammonds, P.; Clint, O. Laboratory studies of electrical potential during rock failure. *Int. J. Rock Mech. Min. Sci.* **2005**, *42*, 933–949. [CrossRef]
13. Wang, E.; Li, Z.; Liu, Z.; Li, Y.; Song, X. Experimental study on surface potential effect of coal under load. *Chin. J. Geophys.* **2009**, *52*, 1318–1325. [CrossRef]
14. Niu, Y.; Wang, C.; Wang, E.; Li, Z. Experimental Study on the Damage Evolution of Gas-Bearing Coal and Its Electric Potential Response. *Rock Mech. Rock Eng.* **2019**, *52*, 4589–4604. [CrossRef]
15. Takeuchi, A.; Lau, B.W.S.; Freund, F.T. Current and surface potential induced by stress-activated positive holes in igneous rocks. *Phys. Chem. Earth* **2006**, *31*, 240–247. [CrossRef]
16. Revil, A.; Ehouarne, L.; Thyreault, E. Tomography of self-potential anomalies of electrochemical nature. *Geophys. Res. Lett.* **2001**, *28*, 4363–4366. [CrossRef]
17. Niu, Y.; Song, X.; Li, Z.; Wang, E.; Zhang, X.; Wang, M.; Dong, M. Study on EP response to compression-induced damage of coal-measure rock and the mechanism behind such response. *J. Geophys. Eng.* **2019**, *16*, 242–252. [CrossRef]
18. Li, D.; Wang, E.; Ju, Y.; Wang, D. Laboratory Investigations of a New Method Using Pressure Stimulated Currents to Monitor Concentrated Stress Variations in Coal. *Nonrenew. Resour.* **2020**, *30*, 707–724. [CrossRef]
19. Revil, A. On charge accumulation in heterogeneous porous rocks under the influence of an external electric field. *GEOPHYSICS* **2013**, *78*, D271–D291. [CrossRef]
20. Roubinet, D.; Irving, J. Discrete-dual-porosity model for electric current flow in fractured rock. *J. Geophys. Res. Solid Earth* **2014**, *119*, 767–786. [CrossRef]
21. Czabanski, R.; Horoba, K.; Wrobel, J.; Matonia, A.; Martinek, R.; Kupka, T.; Jezewski, M.; Kahankova, R.; Jezewski, J.; Leski, J. Detection of Atrial Fibrillation Episodes in Long-Term Heart Rhythm Signals Using a Support Vector Machine. *Sensors* **2020**, *20*, 765. [CrossRef] [PubMed]
22. Zhang, X.; Li, Z.; Wang, E.; Li, B.; Song, J.; Niu, Y. Experimental investigation of pressure stimulated currents and acoustic emis-sions from sandstone and gabbro samples subjected to multi-stage uniaxial loading. *Bull. Eng. Geol. Environ.* **2021**, *80*, 7683–7700. [CrossRef]
23. Djozan, D.; Farajzadeh, M.A.; Sorouraddin, S.M.; Baheri, T. Molecularly imprinted-solid phase extraction combined with sim-ultaneous derivatization and dispersive liquid–liquid microextraction for selective extraction and preconcentration of meth-amphetamine and ecstasy from urine samples followed by gas chromatography. *J. Chromatogr. A* **2012**, *1248*, 24–31.
24. Lei, R.; Shi, Y.; Ding, Y.; Nie, J.; Li, S.; Wang, F.; Zhai, H.; Chen, X.; Wang, Z.L. Sustainable high-voltage source based on triboelectric nanogenerator with a charge accumulation strategy. *Energy Environ. Sci.* **2020**, *13*, 2178–2190. [CrossRef]
25. Li, D.; Wang, E.; Kong, X.; Zhao, S.; Kong, Y.; Wang, X.; Wang, D.; Liu, Q. Mechanical properties and electromagnetic radiation characteristics of concrete specimens after exposed to elevated temperatures. *Constr. Build. Mater.* **2018**, *188*, 381–390.
26. Wang, X.; Wang, E.; Liu, X. Damage characterization of concrete under multi-step loading by integrated ultrasonic and acoustic emission techniques. *Constr. Build. Mater.* **2019**, *221*, 678–690. [CrossRef]
27. Shen, R.; Chen, T.; Li, T.; Li, H.; Fan, W.; Hou, Z.; Zhang, X. Study on the effect of the lower limit of cyclic stress on the mechanical properties and acoustic emission of sandstone under cyclic loading and unloading. *Theor. Appl. Fract. Mech.* **2020**, *108*, 102661. [CrossRef]

28. Wold, M.; Connell, L.; Choi, S. The role of spatial variability in coal seam parameters on gas outburst behaviour during coal mining. *Int. J. Coal Geol.* **2008**, *75*, 1–14. [CrossRef]
29. Wang, K.; Du, F. Coal-gas compound dynamic disasters in China: A review. *Process Saf. Environ. Prot.* **2020**, *133*, 1–17. [CrossRef]
30. Niu, Y.; Li, Z.; Wang, E.; Shen, R.; Cheng, Z.; Gao, X.; Zhang, X.; Wang, H.; Ali, M. Study on characteristics of EP responsing to coal mining. *Eng. Fract. Mech.* **2020**, *224*, 106780. [CrossRef]
31. Waclawik, P.; Ptacek, J.; Grygar, R. Structural and stress analysis of mining practice in the Upper Silesian Coal Basin. *Acta Geodyn. Geomater.* **2013**, *10*, 170. [CrossRef]
32. Xue, Y.; Liu, J.; Ranjith, P.; Liang, X.; Wang, S. Investigation of the influence of gas fracturing on fracturing characteristics of coal mass and gas extraction efficiency based on a multi-physical field model. *J. Pet. Sci. Eng.* **2021**, *206*, 109018. [CrossRef]
33. Yu, L.; Ignatov, Y.; Ivannikov, A.; Khotchenkov, E.; Krasnoshtanov, D. *Common Features in the Manifestation of Natural and Induced Geodynamic Events in the Eastern Regions of Russia and China*; IOP Publishing: Bristol, UK, 2019; p. 012004.
34. Hu, S.; Wang, E.; Liu, X. Spatiotemporal multifractal characteristics of electromagnetic radiation in response to deep coal rock bursts. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 2089–2103. [CrossRef]
35. Batugin, A.; Wang, Z.; Su, Z.; Sidikovna, S.S. Combined support mechanism of rock bolts and anchor cables for adjacent roadways in the external staggered split-level panel layout. *Int. J. Coal Sci. Technol.* **2021**, *8*, 659–673. [CrossRef]