INTRODUCTION

Coalbed methane (CBM) is a kind of beneficial unconventional natural gas, but is also the main cause of underground excavation disasters. Hydraulic fracturing (HF) plays a very good role in stimulating the coal seam by increasing the permeability to enhance CBM recovery and prevent gas disasters. The key to increase the permeability of a coal seam by HF is to promote fracture initiation, propagation, and connection, and the formed fracture network is expected to provide sufficient accesses to the gas flow within the coal matrix. There are two main factors influencing the formation of fracture network: the geological condition (regional tectonic, hydrological conditions, in situ stress field, and
roof-floor properties) and the physical characteristics of coal and rock (strength, elastic modulus, Poisson’s ratio, and pore and cleat, etc.). However, it is tedious and complicated to acquire these parameters, and the accuracy is less reliable. As a consequence, it is necessary to find a brief and effective method to monitor fracture network growth of HF treatment in the coal seam.

Microseismic (MS) monitoring technique has been proposed to widely apply to the HF evaluation in geothermal resources, shale gas, tight gas, and oil reservoirs, following the recognition of microvibration caused by rock fracture. During the HF process, the MS events are identified to determine the crack direction and location and extent of the fracture network. MS monitoring technique was used to construct the fractal-induced fracture network distribution model in shale. It was found that HF fractures usually passed through rather than simply along the formation. And the MS activities mainly occurred in the direction perpendicular to the minimum principal stress and were partially influenced by the faults. MS monitoring technique is also used for HF evaluation in geothermal development. These studies fully demonstrate the effectiveness of MS monitoring technique in assessing HF fracture network growth.

MS monitoring technique has begun to be applied to the coal mines since 1984 in China, which is normally used for early warning and water inrush monitoring, as well as recently for gasification. Many researches have been conducted on MS monitoring in coal mines for several years, and a number of practical applications with a self-developed MS monitoring system have been performed. These researches have laid the foundation for the application of MS monitoring in coal mines. Meanwhile, MS has been studied depending on the theories and practices of dynamic disasters in coal mines. All these studies have rapidly developed the MS theory and the related technology and provided the feasibility of MS monitoring for HF in coal mines.

The first case of MS monitoring for HF in the coal seam, carried out on the ground surface, was reported that the fracture network induced by HF exhibit an asymmetric morphology. The length and width of the fracture network can be estimated by analyzing the MS locations. A number of application tests of MS monitoring for subsurface HF have been performed to estimate the stimulated area. And the characteristic of MS responses to the evolution of hydraulic pressure (HP) is significant, which can reveal the fracture occurrence mechanism. However, the mechanism of MS responses to HF is rarely expressed in the complicated subsurface field. In some laboratory experiments, the acoustic emissions might hardly predict where and when the fractures initiated and propagated due to the significant heterogeneity of the stratum. Furthermore, the hydraulic fractures growth tendency and the stimulated area are of significance in the thin and multicoal seam formations.

In the current study, to estimate the stimulated area, and to investigate the fracture growth and MS response in the coal seams, a field experiment was performed. The MS monitoring technique was applied to record the MS activity induced by HF throughout the experiment. HP history and MS response during HF process were analyzed to reveal the HF growth behavior in coal seams. Spatial distribution and energy of MS events were determined by data post-processing. After HF, the water content of coal seam was measured to investigate the practice water intrusion area. The MS locations were combined with the water content to delimit the stimulated area in coal seams. The present research will provide instructional significance for hydraulic fracturing treatments well as the evaluation of the stimulated area.

2 | EXPERIMENTAL STUDY

2.1 | Mechanism of MS location

The MS locations are the premise to determine the expansion of the fractures and represent the locations of the coal failure. MS distribution can not only describe the induced new fracture, but also analyze the growth trend of the fracture network. The distribution characteristics of the hypocenter can be regarded as the fracture network geometry that determines the HF range. Before the MS event is located, the time difference in waveform, namely travel time, needs to be picked up. The short-term averaging/long-term averaging (STA/LTA) method was implemented to detect the travel time. The basic principle is to first calculate the energy ratio of STA and LTA, and appraise the energy ratio increase. Once the ratio exceeds the threshold value, the time should be appraised as the original time, and the end time should be acquired when the ratio damp again to the threshold value. The travel time is obtained as the difference between the original time and the end time. The energy ratio can be calculated by the equation below.

\[
\frac{\text{STS}}{\text{LTA}}(i) = \frac{t_s \sum_{j=i-t_s} f(j)}{t_l \sum_{j=i-t_l} f(j)} \geq \lambda
\]

where \(i\) is sampling time, \(t_s\) is the length of short-time window, \(t_l\) is the length of long-time window, \(f(j)\) is the characteristic function which represents the amplitude of waveform in this paper, and \(\lambda\) is the threshold value.

After determining the travel time of the appropriate channels, the MS location can be calculated by applicable algorithm. Many localization algorithms, such as USBM, Inglada, Geiger, Thurber, and Simplex method, have been studied by scholars. The Simplex method is widely used for its reliability and strong convergence. The principle of the method is as follows.
Firstly, four vertices are created in three-dimensional space to form the initial tetrahedron. Secondly, the target function \( f(x, y, z, t, v) \) is calculated with respect to the four conditions of each vertex as the source. The vertex of maximum residual \( \gamma \) is eliminated, and the initial tetrahedron is stretched, contracted, and symmetrized. Repeat this process and stop until the target function value satisfies the iterative termination condition. Finally, the point of smallest residual is selected as the source in the tetrahedron. The target function \( f(x, y, z, t, v) \) above can be written as: \(^{36}\)

\[
\sum_{k=1}^{n} \gamma_k^2 = \sum_{k=1}^{n} \left( t_k - \frac{\sqrt{(x_k - x_0')^2 + (y_k - y_0')^2 + (z_k - z_0')^2}}{v_k} - t_0' \right)^2
\]

where \( k (k = 1, 2, 3, \ldots, n) \) is the number of geophones, \( \gamma_k \) is the residual of the arrival time of the geophone, \( t_k \) is the arrival time, \( v_k \) is the MS propagation velocity from the hypocenter to the corresponding geophone, \( (x_k, y_k, z_k) \) is the geophone position coordinate, \( (x_0', y_0', z_0') \) and \( t_0' \) are the hypothetical hypocenter coordinate and the original time of MS response, respectively, in the iterative process.

### 2.2 Field situation

As a key technology to increase the reservoir permeability, HF has become an indispensable technology in some underground coal mines in southwestern China. The Shihao coal mine in Chongqing, China has complicated geological conditions with twelve coal seams and two typical geologic structures: one is the Yang Cha Tan anticline with the axes of N35°~55°E, and the other is the Da Shu Mu syncline with the axes of N30°~55°E.

The HF experiment was set in the #12 gas drainage roadway in No. 3 District of Shihao Coal Mine (Figure 1A). There is a vertical distance of 54 m, 44 m, and 37 m from the #12 gas drainage roadway to the M6, M7, and M8 coal seam, respectively. The geotechnical logging records in this area are shown in Figure 1B. Both the roof and the floor of the M6 coal seam are sandy mudstone. The top and bottom plates of the M7 coal seam are limestone and sandy mudstone, respectively, and their strength is lower than that of sandstone. Both the top and bottom plates of the M8 coal seam are thin mudstone layers. There is a thick layer of 6.88 m of fine sandstone beneath the floor of the M8 coal seam. The fine sandstone layer has the strongest strength among the strata illustrated in Figure 1B.

HP is supposed to be affected by the geological environment associated with several parameters. To previously predict the pump pressure, the fracturing initiation pressure of the target coal seams was calculated and showed in the right column in Table 1.

### 2.3 MS detection scheme

The HF borehole drilling site has a subsurface depth of 350 m. As shown in Figure 2A, the T9 fracturing borehole was mainly implemented for the M6 coal seam. Similarly, the W9 was mainly for the coal seam M7 and M8. M6 was first to be stimulated, and both M7 and M8 were second.

Eleven geophones were evenly arranged on both sides of the fracturing borehole along the gas drainage roadway, and the distance of the adjacent geophones was 10 m, as shown in Figure 2A. The geophone was solidly connected with the roadside. To ensure the logical solutions can be calculated ultimately, a portion of the geophone was placed on one side of the tunnel and the other was placed on the top of the tunnel. The three-dimensional coordinates of these geophones were...
determined in Table 2. The MS monitoring system consisted of three parts, as shown in Figure 2B, including the geophones used to detect the vibration, the substation to receive the signal, and the computer for data acquisition and analysis.

When the HF stress is greater than the internal strength of the coal seam, tensile or shear failure will be exhibited. MS activity occurs in the form of elastic waves when the coal is fractured. After the geophones detecting the wave signal, the vibrational mechanical energy is transformed into electricity, which is converted into the digital signal by substation. Finally, the signal is obtained and shown in the computer.

2.4 Water content measurement

The measurement of water content can provide a preference for MS monitoring to effectively evaluate the stimulated area. The reaction between water and coal should be considered during the stimulation process, with the fact that water can change the physical property of coal. On the one hand, the region invaded by water will be corroded after HF, and coal or rock will be destroyed with fracture generation; on the other hand, water can replace or expel gas to some extent, decreasing the gas content and eliminating gas outburst risk. Moreover, it is easy to extract CBM from the region where water can inject into due to the existence of flow channels. Thus, the water content in each coal seam was measured before and after HF process. It is convenient to measure the water content of the three target coal seams with hundreds of gas drainage boreholes in the #12 gas drainage roadway. Fifty boreholes were chosen, filled in Figure 3A, from different directions and distances to measure the water content using the gravimetric method with the water content meter (Figure 3B).

3 RESULTS AND DISCUSSION

3.1 MS responses to HP evolution

The origin time of MS responses was corresponded with the duration of HF, and their relation characteristics at different stages were studied. By plotting the MS energy into the
longitudinal coordinate, the fracture effectiveness during the HF process could be investigated.

During the HF process, 220 valid MS events were obtained. Among them, 106 events occurred in the T9 borehole, and the other 114 events were recorded in the W9 borehole. The origin time of these MS responses is shown in Figure 3. The red curve represents the changes of water injection pressure with time, and the blue bars represent the origin time and energy of the MS events.

As shown in Figure 3A, the first stimulation process lasted for 450 minutes and the second for 90 minutes, with a break for 110 minutes. Initially, HP increased from 0 MPa to 9.69 MPa, and the duration of the process was 70 minutes. As the HP value increased, the coal seam might be pressurized to be destroyed. Two forceful MS events were obviously detected within the first 70 minutes, which indicated that two large scale cracks had been initiated. Then, the HP was maintained at 9.69 MPa until the HP increased by 0.27 MPa at 125 minutes. A MS event with an energy of 107.6 J was detected at the same time. After this point, the HP value kept constant for a long time. The HP suddenly slumped after 376 minutes, the reason for which was that water-related cracks were created and provided sufficient volume for the incoming water. After the volume was full of water, HP increased again and was maintained at 10.79 MPa until the pump was turned off for the first time. When the stimulation started again, a higher HP was required to connect the fractures to the water (at 564 minutes); however, the MS energy at this point was lower, and few MS events were detected when HP re-increased to 13.25 MPa.

During the stimulation for the both M7 and M8 coal seams, it took 6 minutes to raise the HP from 0 MPa to 14.16 MPa, and the pressure did not generally change until the finish of the HF process. Coincidentally, a number of MS events with high energy were detected within the first hour of the HF process (labeled in Figure 4B). When the 217th minute was arrived, HP rose by 0.16 MPa, and plenty of MS events were found around it.

The sharp MS events were usually detected within the first hour of the HF process (Figure 4). The energy of the sharp MS event in T9 borehole stimulation was $1.458 \times 10^5$ J, while that in W9 borehole stimulation was $2.706 \times 10^5$ J. The energy magnitude of the two sharp MS events were 2 to 4 orders higher than that of the other events, which indicated that a larger fracture had been produced. Generally, a pressure decreases when sharp MS events occur in laboratory scale, similar to the acoustic emissions; however, no pressure decrease occurs when the high-energy MS events took place (Figure 4), and the difference of them could be explained by the theory of “wet” and “dry” events produced in the HF process. The wet events caused by the direct pressurization of fluid could push a Mohr circle to the left until it touched a failure envelope, and a shear event was produced. The dry events triggered by mechanical stress changes did not directly involve the fluid pressure. Thus, most of the MS events were dry events, especially for the W9 borehole which had no pressure spike.

In addition, it was found that the HP of W9 was higher than that of T9, and the HP difference might be associated with the gas pressure and depth. The gas pressure of the M7 and M8 coal seam is higher than that of the M6 coal seam. In order to stimulate the coal seam, the injected water should not only overcome the in situ stress and the strength of the coal, but also overcome the gas pressure. The gas pressure and the buried depth are positively correlated with the acquired HP values.

However, both the HP of T9 and W9 were lower than the calculated pressure (Table 1). Traditionally, the HF process has an obvious water pressure peak called the fracturing
initiation pressure. The theory in hard-rock reservoirs is based on the tensile strength rule as
\[ P_f = 3\sigma_h - \sigma_H - \alpha P_0 + S_t, \]
where \( P_f \) is HP, \( \sigma_H \) and \( \sigma_h \) are the maximum and minimum horizontal principal stress respectively, \( P_0 \) is the pore pressure, \( \alpha \) is the pore pressure coefficient, and \( S_t \) is the tensile strength of rock. When the left side of the equation is larger than the right side, coal or rock will split as the fracture initiates, and the HP value reaches to the maximum and falls down as soon as fracture initiates. Although the peak value did not appear during the HF process in the soft coal seam, the coal or rock was still fractured due to the fitful MS activities. It seems that the theory of HF in hard-rock reservoirs is no longer suitable for soft coal seams. The recorded MS activities during fluid injection were attributed to the shear events on pre-existing natural fractures and coal cleats. The increased injection pressure caused the natural fractures to slip, resulting in MS responses. Furthermore, HF can influence the in situ stress field and lead to the stress concentration to cause regional damage.

From another perspective, water weakening might also cause coal or rock damage. Water weakening is identified as a kind of the chemical and physical process that weakens the minerals. The injected water can corrode some substance in coal or rock mass, such as bauxite, montmorillonite, and other water sensitive minerals. The physical and chemical effects of water will reduce the strength of coal and rock mass. In other words, water weakening can change the strength to a certain extent, which is generally a constant for the specific stratum. Yin et al. had proposed a function of the water weakening effect as
\[ g(\zeta) = (1-R)(1-\zeta)^2 + R \]  
where \( \zeta \) is the water content, \( g(\zeta) \) is a monotonically decreasing function, and \( R \) is the strength coefficient when saturated water. Thus, the actual strength could be marked as \( S_tg(\zeta) \). Based on this, we can try to change the classical stress equation into
\[ P_f = 3\sigma_h - \sigma_H - \alpha P_0 + S_tg(\zeta) \]  
This Equation (4) can reflect the water weakening in coal or rock. The procedure about water weakening may be consistent with the “matrix penetrating frac-fluid” which has been reported by Erle C. Donaldson. Therefore, MS events were sometimes found when HP had never changed.

### 3.2 Spatiotemporal mechanism of MS occurrence

The results of MS event locations are shown in Figure 5. The red points represent the locations of the MS sources, and the blue points represent the water outlet positions of the HF borehole. The 3D coordinates are associated with the local coordinate system, where the coordinates of the T9 HF borehole are (North, East, Altitude) = (446.8 m, 700 m, 288.8 m). Both M7 and M8 coal seams were stimulated by the W9 HF borehole at the geodetic coordinates of (North, East, Altitude) = (454.3 m, 700 m, 278.5 m). As
shown in Figure 5, the MS events of T9 mainly occurred in the space of the altitude difference of 150 m and within the plane of 200 m × 200 m (Figure 5A). These events of W9 mainly occurred in the space of the altitude difference of 130 m and within the plane of 200 m × 200 m (Figure 5B). However, the positions of the two HF boreholes were not at the center of the distribution of the MS sources. The MS events distributed around the HF boreholes, and the events mainly occurred in the M6 coal seam floor, while the MS sources mainly located in the roof of M7 and M8 coal seams.

The MS energy is essentially the released strain energy of the fractured coal and rock. According to Tang et al.\textsuperscript{43} the logarithm of MS energy was used to describe the magnitude of the MS response. The energy distribution is shown in Figure 6. This indicated that the most forceful MS event was located in the northeast of the T9 borehole at a distance of 51.2 m, and the other larger-energy (13910 J) MS events occurred around that largest one (Figure 6A). When the W9 borehole was stimulated, the most forceful MS event occurred in the southwest part of the W9 borehole at a distance of 17.8 m, and the MS responses in the north and south were more active than that in the east and west (Figure 6B). It can be found that MS events did not occur from the near to the distant but disorderly when compared MS location with the time scale. The result demonstrated that coal and rock were fractured before or even without water intruding into. The reason might be that the in situ stress field had been influenced by HP evolution\textsuperscript{44} and led to the stress concentration. On the one hand, the reservoir has prominent anisotropy (Figure 1), resulting in various strength of coal or rock. And those low-strength coal or rock would be damaged primarily before pressurized water reached. On the other hand, micro natural fractures and coal or rock cleats pre-existed in the reservoir. When HF disturbed the in situ stress around the borehole, the mechanical balance was broken.\textsuperscript{45} The micro

**FIGURE 5** 3D locations of the MS events, (A) MS events of T9, (B) MS events of W9

**FIGURE 6** MS locations and energy responded successively. The greater scatter, the greater energy of MS, the color from green to blue indicates the sequence of MS events. (A) M6 was stimulated by T9 borehole, (B) both M7 and M8 were stimulated by W9 borehole
natural fractures and coal or rock cleats might slip to produce MS activities.

Figure 7 showed that a large number of MS events occurred on the roof and floor, indicating that both the coal seam and the roof-floor had been destroyed during the HF process. In particular, the MS events above the M8 coal seam were obviously more than those below, probably due to the thick (6.88 m) siltstone stratum beneath the M8 coal seam. This siltstone, to some extent, obstructed water flow from the overlying strata to damage the under layers. In contrast, the roof of the M8 coal seam was comprised of mudstone, sandy mudstone, and limestone. Not only the mudstone, but also the limestone is readily weathered as the result of full joints and natural fractures. Once these joints and natural fractures are sunk by water, they will slip to lead to the damage of the strata. In other words, the strata between the M8 coal seam and the M6 coal seam, even the roof of the M6 coal seam, are easily damaged by the HF treatment. The results of HF not only produced more fractures in the coal seam but also made the layers nearby fractured. The results greatly facilitate the gas extraction in the later period and effectively reduce the strength of the strata for the later recovery.

The rose map of Figure 8A reflected the projection of MS events onto different planes when HF was performed in the T9 borehole. The figure showed the following: (a) From the horizontal projection of the plane, overall, the MS events tended on average to be due west, south, north, and east. MS sources in the N-S direction were generally further than that in the E-W. The farthest MS event was at 130 m away from T9 north 30° by west. (b) Viewed from the side, the MS sources were mainly distributed in the E-W direction below T9 and in the N-S direction of T9. In other words, referring to Figure 2, the MS response occurred substantially in the floor of the M6 coal seam along the bottom gas roadway. The MS distribution near the M6 coal seam was mainly orthogonal to the bottom gas roadway, even with a farthest distance of 120 m. (c) When the radius was reduced to less than 40 m, this trend was no longer obvious. In addition, there were few MS events in the roof of the M6 coal seam.

In a similar manner, according to Figure 8B, when both the M7 and M8 coal seams were stimulated, the MS distribution of W9 at 40 m from the center was dense and exhibited no obvious tendency. When considering the MS distribution of W9 at over 40 m from the center, the MS distribution would tend to be aligned along the N-S direction. Moreover, many events in the north were at over 100 m distance from W9. The density of MS in the roof of the M8 coal seam was slightly larger than that in the floor. The farthest distance of the source from W9 on the horizontal plane was 130 m.

It was worth noting that the MS tendency did not follow the classical stress controlling theory that cracks always give priority to the direction perpendicular to the minimum principal stress ($\sigma_h$). In this case, the azimuth of $\sigma_h$ was measured to be 209.3°. However, there were few MS activities acted in the direction perpendicular to $\sigma_h$. As a result of that, the fracture propagation was largely influenced by the geological environment, such as geological structure, depth of stratum, and the different strengths between coal and rock and their anisotropy. Thereby, those geophysics methods, for example MS monitoring technology, were urgently to be further studied and applied to HF in underground coal mines. Although there is relative effective exhibition in this study, more researches should be implemented for MS monitoring contributing to HF in underground coal mines.

![Figure 7](image7.png)

**Figure 7** MS distribution related to the coal seam

## 4 | **STIMULATED AREA IN THE COAL SEAM**

Stimulated area is the area covered by the induced fracture network in coal seam after HF. The investigation of the stimulated area is mainly to check whether there is a non-stimulated area. MS monitoring was associated with water
content measurement to obtain a more reliable and effective stimulated area and to guide the construction of field application.

It is believed that coal fracturing produces microseism, and the more MS events occur, the more developed the fracture network is. MS density, referred to the number of MS events per unit area, was proposed to determine the stimulated area. Using the bivariate kernel density estimation method, the MS density was calculated and estimated to draw the density cloud map (Figure 9A, C, E). Considering the limited influence distance of microseism, the curves in Figure 9A, C, E were drawn according to the MS density and the influence distance of microseism. And the stimulated area in coal seams judged by MS monitoring can be seen approximately. In addition, water content of coal seam can directly reflect the intrusion area of fracturing water. The area of water intrusion is considered to be sufficiently stimulated, because where water can enter, gas can also exit. If water content exceeds natural water content, it is considered to be intruded with fracturing water. The intrusion areas of water were illustrated (Figure 9B, D, F) compared with natural water content.

It was obvious that the stimulate areas judged by MS density or water content were asymmetrical. On the view of MS density, the stimulated areas of the three target coal seams showed an obvious north-south trend (Figure 9A, C, E). On the view of water content, the stimulated areas on the east side of the HF borehole were generally larger than that on the west side (Figure 9B, D, F). It was also find that most MS events in the coal seams tended to be located in the east side of the HF borehole. The stimulated area width in the east-west direction of MS was as wide as that of water. However, there was little water injected into the north-south direction. Therefore, in accordance with the classification of Maxwell, most MS events on the east side of the HF borehole were called wet events, and most MS events on the north and south side were called dry events. It demonstrated that the MS events cluster on the east side might be caused by hydraulic mechanism, and the MS cluster on the north and south side might be caused by the mechanism of stress transfer and concentration.

The water intrusion area of M8 coal seam was larger than that of the other two coal seams (Figure 9B, D, F). The reason is that there is a thick fine sandstone beneath M8 coal.

**FIGURE 8** Rose map of the MS tendency, where “U” is the “up” forward to earth surface, “D” is the “down” forward to underground. (A) MS tendency of T9, (B) MS tendency of W9
FIGURE 9  Stimulated area judged by MS density and water content. (A) and (B) correspond to the M6 coal seam, (C) and (D) correspond to the M7 coal seam, (E) and (F) correspond to the M8 coal seam. (A, C, E) show the distribution density of MS events, the area of curve circle is the stimulated area judged by MS density. (B, D, F) show the distribution of water content, the curve in the graph represents natural water content (1.6%).
After the pump was turned off, there was no longer pump motivation to drive the water to inject into the strata. But water always leaked down until reached the thick fine sandstone layer which had low permeability. This thick fine sandstone layer prevented water further leaking down. Therefore, it conclusively led to higher water content and more area of water intrusion in the M8 coal seam.

In order to provide a basis for later gas extraction design, the area of possible effects of HF was divided into four grades, as shown in Figure 10A. The stimulated area rate was defined as the percentage of cloud map of MS density or water content in the region of each area grade. By calculating the stimulated area rate, the results were illustrated in Figure 10B, C, D. It was almost observed that the stimulated area rate of MS was generally greater than that of water, even in every area grade.

In the area grade of 50 m × 50 m of each coal seam, the stimulated area rate of MS has reached 100% (Figure 10B, C, D). With the expansion of the area grade, the stimulated area rate of MS decreased linearly, the stimulated area rate of water decreased exponentially. In addition, the stimulated area rate of water of the lower coal seam was always higher than that of the upper one. This phenomenon conformed to the natural law of water seepage downward. It could be found that there was a number of MS events located in the rock.
strata between M6 and M8 (Figure 7), which indicated the generation of vertical fractures. Water leaked or diffused from the upper layers to the lower layers through the macroscopic or mesoscopic vertical fractures connecting the strata. It demonstrated from another view that water flow channels could also provide the passage for the later CBM extraction. When water has been dry, CBM will flow through the previous channels. When comparing M6 and M7 with M8 coal seam in the area grade of 50 m × 50 m, it was found that the stimulated area rate of water increased by the depth of layer because of water seepage downward. The stimulated area rate of water of M6 and M7 should have been high as about 90% before water seepage.

In summary, the achievable stimulated area of 50 m × 50 m was suggested in terms with both MS monitoring and water content measuring. The stimulated area judged by only MS monitoring was usually larger than that of judged by water content measuring. The stimulated area rate of water increased by the depth of the coal seam. In this case, the fracturing water preferred to flow toward the east side of the HF borehole. A part of MS locations was consistent with the tendency of water flowing. There was hardly water injected into where another part of MS event located in.

5  |  CONCLUSIONS

The application of MS monitoring technique for HF investigation had been studied in Shihao coal mine, and the characteristics between HP and MS responses were fully analyzed. MS events distribution and the correlation between MS locations and fractures induced by HF were analyzed as well. The stimulated area was conclusively investigated compared with water content. The main conclusions were obtained as follows:

1. The MS response was found to be closely related to the changes of hydraulic pressure. Typically, a sharp MS event was detected in the first hour of the HF process, and numerous small MS events occurred at the same time. The energy of the sharp MS event was found to be at least orders of magnitude higher than the others, suggesting that a primary fracture had grown. MS events were detected from time to time even if the HP maintained a high constant and never changed.

2. The MS distribution followed certain rules in this experiment. When the radius was less than 40 m, the MS location showed a complicated distribution. When the radius was greater than 40 m, the MS activity tended to be along an obvious direction. A few MS events were found to be well over 100 m from the hydraulic borehole. Not only coal seams, but also the relatively thin layers nearby had been destroyed in the process of HF. Additionally, MS locations were found to be concentrated in the layers above the M8 coal seam which was attributed to lower position of the fairly thick layer.

3. MS monitoring technique could be efficiently used to assess the stimulated area of HF in subsurface coal mine. According to the MS monitoring results, and tested water content for comparison, the achievable stimulated area was finally determined to be 50 m × 50 m. Furthermore, the stimulated area rate was proposed to investigate the efficiency of HF. By comparing MS density and water content in the coal seams, the geometry of their distribution showed asymmetrical, and the stimulated area in terms of MS distribution was easily found to be broader than the water direct intrusion area.

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