Research Article

Research on Structural Evolution and Microseismic Response Characteristics of Overlying Strata during Repeated Mining of Steeply Inclined and Extra Thick Coal Seams

Xingping Lai, Yanbin Yang, and Leiming Zhang

School of Energy Resources, Xi’an University of Science and Technology, Xi’an 710054, China

Correspondence should be addressed to Yanbin Yang; y17203078030@163.com

Received 16 September 2021; Accepted 19 October 2021; Published 16 November 2021

Academic Editor: Hao Liu

Copyright © 2021 Xingping Lai et al. Exclusive Licensee GeoScienceWorld. Distributed under a Creative Commons Attribution License (CC BY 4.0).

Repeated mining is the main factor that leads to development, propagation, and eventual deformation of the overlying strata fissures in the steeply inclined and extra thick coal seams (SIETCS). The evolution of the overlying strata structure is closely related to microseismic events in a mine. As the mining depth increases, the evolution rules of the overlying strata structure become more complicated and can easily induce dynamic disaster accidents. To solve these problems, this paper established a physical similarity simulation model. Microseismic monitoring equipment was used to study the relationship between the evolution of the overlying strata structure and the energy-frequency of microseismic events. On the basis of the principle of quantitative seismology, the response relationship between the overlying strata structure and the microseisms at different mining stages was compared and analyzed from a quantitative perspective. The characteristics of cumulative apparent volume, energy index, and microseismic $b$ value were used to reveal the precursor characteristics of overburden instability and failure. The results showed that due to the occurrence characteristics of coal seam, the distribution characteristics of rock stratum stress, and the effects of mining disturbances, the energy accumulation-release period after instability failure of the overlying strata induced by shallow mining was longer than the energy accumulation-release period induced by deep mining. And the deep coal and rock mass had a periodic "balance-instability-rebalance-instability again" dynamic evolution process under the disturbance of repeated mining. In the working face mining, the slope of the accumulative apparent volume $\Sigma V_A$ curve suddenly increased, and the energy index EI gradually decreased at the late peak period, which indicated the deformation and failure of overburden. However, the $b$ value of the microseismic event presented the precursory characteristics of rock stratum fracture that gradually increased and then changed drastically.

1. Introduction

In recent years, with the continuous increase in coal mining depth and the complex of mining conditions, the coal production had been increased, but it incurred a series of potential safety hazards [1–3]. For SIETCS, due to the selected mining method and the special occurrence environment [4–6], the formation characteristics and dynamic evolution rules of the overlying strata structure on the working face were more complicated with the continuous increase in mining depth and mining intensity. The fracture structure of the overlying strata induced by deep mining in SIETCS was significantly different from the fracture induced by shallow mining. The risk of dynamic disasters was increased [7, 8], and the difficulty of prevention and control was markedly increased, which directly affects the safe mining of the working face and the stable and effective supply of energy. Therefore, it is urgent to further improve the techniques for prediction and prevention of dynamic disasters in mines.

A large number of scholars had carried out a lot of in-depth and systematic researches on the movement characteristics of the overlying strata. The techniques for prediction of dynamic disasters after the mining of SIETCS had achieved various beneficial achievements [9–11]. Relevant scholars had conducted a great deal of researches on the movement characteristics of the overlying strata after mining of...
SIETCS. Shi and Zhang [12] proposed that SIETCS were prone to form the “cross-layer arch” structure and presented the stable conditions of the arch structure. Shao et al. [13] analyzed the roof of SIETCS by the elastic thin plate theory and obtained the criterion for roof fracture, eventually verified the existence of the unloading arch structure in the overlying strata. Lai et al. [14] studied the mining stress conduction of multiple coal seams, which caused the rock pillars to compress the coal seam to induce rockburst and revealed the mechanism of rockbursts in the mining of SIETCS. Ju et al. [15] found that the structural instability in the cantilever beam of the overlying strata was the main reason for inducing the rockburst on the working face. At present, with the rapid development of digital technology, computer technology, geophysics, monitoring, and early warning of dynamic disasters in mine mining had become one of the hot research issues [16–19]. As a dynamic nondestructive evaluating technology, microseismic monitoring had been widely and maturely used in geotechnical engineering, tunnel excavation, and rock failure prediction [20–23]. Dou et al. [24] established a multi-information normalized early warning mechanical model for coal rock impact failure. A comprehensive monitoring and early warning model based on time-space architecture had been formed, which improves the pertinence and accuracy of monitoring and early warning of rockbursts in coal mines. Xia et al. [25] monitored the impact hazards during the extracting of island working face in the Qianju Coal Mine using the microseismic and geo-acoustic monitoring system and determined the corresponding early warning indicators, which improved the accuracy of the prediction and forecast of rockbursts. Liu et al. [26] established a hierarchical evaluation method for the impact hazards of the driving working face based on geo-acoustic monitoring and electromagnetic wave CT detection, which improved the prediction and evaluation of impact hazards during work face driving. Yuan [27] established the identification and early warning monitoring model of dynamic disaster risks in coal mine, which based on big data analysis and data mining. The above mentioned scholars had conducted very useful explorations and studies on the formation of overlying strata structure, the mechanism of instability and disaster, and the early warning techniques of coal rock failure process in the mining of SIETCS. However, there was little knowledge about the relationship between the evolution of the overlying strata structure and the microseismic activities of mines in the mining of SIETCS, especially the establishment of a quantitative relationship between the overlying strata structure and the microseismic response characteristics deserves to be deeply studied.

To study the response relationship between the overlying strata structure and microseismic events in the mining of SIETCS, this paper used the physical similarity simulation test of SIETCS as the research basis. According to the actual mining conditions, the caving characteristics of the overlying strata after coal seam exploiting were simulated, and SOS microseismic monitoring equipment was used to monitor and analyze the overlying rock collapse. The paper studies the characteristics of movement failure characteristics and energy evolution characteristics of overlying strata in repeated mining of SIETCS. Based on the principle of quantitative seismology, the paper established a quantitative relationship between the evolution of the overlying strata structure and the microseismic characteristics. Cumulative apparent volume and the energy index were used to compare and analyze the response relationship between overlying strata structure and microseismic in different mining stages. The paper reveals the precursor characteristics of instability and failure of overlying strata by studying the variation rules of the microseismic $b$ value during the process of deformation and failure of overlying strata at different extraction levels, which guided the prevention and control of dynamic disasters in SIETCS as a basis for predicting instability and failure of overlying strata.

2. Engineering Background

Wudong Coal Mine was located in the northeast of Urumqi. The minefield was about 10.8 km long from east to west and 0.7–2.7 km wide from north to south, with an area of about 20.3 km$^2$. The north mining area of the Wudong Coal Mine was located on the north flank of the Badaowan syncline. The basic structure was a monoclinical structure inclined to the north. The stratum strike was 67° northeast and 157° southeast, with an average dip angle of 45° and an average ground elevation of about 800 m. The main coal seam in the north mining area was the 43# and 45# coal seams. The 43# coal seam had a main roof thickness of 10–20 m and an immediate roof thickness of 3–5 m. The roof had a large thickness and high strength, with few fissures, and was hard and not likely to cave. Due to the particularity of the coal seam occurrence, the horizontal sublevel caving was used as the coal mining method for the north area, and the sublevel height was 15–25 m on average. The increase in the horizontal sublevel height helps increase the output of the working face on the one hand, but on the other hand, it also increases the risk of large-scale caving of the surrounding rock. The layout of fully mechanized horizontal sublevel caving mining in SIETCS in the Wudong Coal Mine is shown in Figure 1.

In the north mining area, the coal seam of 43# was mined at +575 level. After the working face was mined, the roof remains intact and difficult to collapse, which poses a potential threat to the safety of the working face. By reviewing the historical mining level, it was found that with the increase of the sublevel and the increase of the mining depth in the north mining area, the fully mechanized advanced sublevel caving mining caused the gob space to increase rapidly in scale, and the area of the exposed roof overhang also increases accordingly. At the same time, the special occurrence environment of coal and rock mass makes the migration rules of coal gangue mixture, multiple structures of roofs, floors, and surface soil overburden more complicated above the working face. It was impossible to accurately grasp the formation characteristics and dynamic evolution of roof structure with the change of mining depth. This severely restricts the safe and efficient production of coal mines.
3. Evolution Test of Overlying Strata Structure during Mining of SIETCS

3.1. Test Plan Design. This similarity simulation test was taken the geological characteristics and mining layout characteristics of SIETCS in the north mining area as the prototype. The main research object was the caving characteristics of the roof rock stratum of the 43# coal seam. Based on the test platform of the plane strain model, a model test of overlying strata migration was designed. The geometric similarity constant of the test was determined according to the test objective. The field investigation result (prototype: model) is \( C_I = 200 \). This model test used a plane strain model frame with an external dimension \( (\text{length} \times \text{width} \times \text{height}) = 3.0 \times 0.2 \times 2.0 \text{ m} \) and model setup dimension \( (\text{length} \times \text{width} \times \text{height}) = 3.0 \times 0.2 \times 1.75 \text{ m} \). Other similarity constants were determined according to similarity theory [28–30]. The dimensional analysis is as follows: stress similarity constant \( C_\sigma = 300 \); bulk density similarity constant \( C_\gamma = 1.5 \); time similarity constant \( C_t = 14.14 \); and strength, elastic modulus, and adhesion force similarity constant \( C_R = C_E = C_C = 1 \); Poisson’s ratio and internal friction angle similarity constant were 1.

3.2. Monitoring Equipment Layout and Mining Design. Monitoring equipment was arranged for test after the model (see Figure 2(a)) and dried for 5-7 days. In this test, SOS microseismic monitoring equipment was utilized to identify the rock fracture signal during the advancement of the working face. It could record the changes of microseismic signals
inside the rock formation when the overburden was broken and the working face was compressed, so as to better analyze the breaking energy evolution law of the underlying rock under the influence of mining on the working face. The layout of the monitoring equipment is shown in Figure 2(b). 5 microseismic sensors were installed around the model with installation numbers (counterclockwise) 1#~5#. This similar simulation test was conducted based on the actual mining environment of the coal seam, an unloading arch was formed above the working face [1]. The upper and lower arch feet were located in the coal and rock mass above the gob and the roof rock of the lower slice. The arch structure was distributed asymmetrically. This was because the over-hanging roof fracture in the dipping direction of the coal seam has significant zoning characteristics. The upper middle part of the roof fractured first, which result that the vault of the arched structure was on the upper side. The arch structure had a certain supporting capacity and temporarily protects the working face that was being extracted.

Due to the redistribution of the original rock stress under the effect of mining disturbance, the microseismic characteristics of the overlying strata showed (Figure 3(b)) that the locations of microseismic events were widely distributed. Before the roof fracture occurred, the microseismic events were mainly concentrated at the lower slice roof. As the mining level advanced, the area where the microseismic events were densely distributed increased. With the coal caving, the scope of the gob gradually increased, the roof lost support and under the action of its own weight and the load of the overlying strata. The roof stretched along the normal direction of the bedding surface (as shown in Figure 3(a)). Due to the special occurrence environment of the coal seam, an unloading arch was formed above the working face [1]. The upper and lower arch feet were located in the coal and rock mass above the gob and the roof rock of the lower slice. The arch structure was distributed asymmetrically. This was because the over-hanging roof fracture in the dipping direction of the coal seam has significant zoning characteristics. The upper middle part of the roof fractured first, which result that the vault of the arched structure was on the upper side. The arch structure had a certain supporting capacity and temporarily protects the working face that was being extracted.

4. Analysis of Test Results of Structural Evolution Overlying Strata

In the test, the model was extracted strictly in accordance with the design plan. Based on the characteristics of the microseismic events, it was found that the roof collapse pattern shows markedly periodicity and imbalance with the increase in the sublevel. This was due to the special environment of SIE TCS and the mining method selected.

4.1. Movement Failure Characteristics of Overlying Strata

4.1.1. Shallow Mining Stage. In the early stage of extracting, the roof of the working face was stable and did not move significantly. With the coal caving, the scope of the gob gradually increased, the roof lost support and under the action of its own weight and the load of the overlying strata. The roof stretched along the normal direction of the bedding surface (as shown in Figure 3(a)). Due to the special occurrence environment of the coal seam, an unloading arch was formed above the working face [1]. The upper and lower arch feet were located in the coal and rock mass above the gob and the roof rock of the lower slice. The arch structure was distributed asymmetrically. This was because the over-hanging roof fracture in the dipping direction of the coal seam has significant zoning characteristics. The upper middle part of the roof fractured first, which result that the vault of the arched structure was on the upper side. The arch structure had a certain supporting capacity and temporarily protects the working face that was being extracted.

As the mining depth continued to increase, the immediate roof were mined and caved with the mining of the working face. The fallen coal and rock mass filled the new mining area, restraining the separation of the rock strata under the...
roof along the normal direction of the bedding. As the caving height of the rock strata increased, the cantilever of the main roof above the working face bent, fractured, and caved, squeezed with the caved gangue to form a hinged structure. It could prevent the collapsed gangue from sliding down and could form an arch structure above the current extracting working face to protect it to a certain extent. The hinged structure formed above the working face was similar to the “masonry beam” structure of the overlying strata of the nearly horizontal, gently inclined stope. In other words, there were coal wall support areas and separation zones in the coal and rock mass around working face. A large free space was formed in the gob on the upper part of the roof, which provided larger space for the continuous collapse of the upper and middle rock strata of the roof and the upper coal body. Collapse was propagating upwards, and the arch structure formed within the coal and rock mass was developing upwards. Until the roof fractured at the end of extracting at the +645 level, which resulted in surface collapse (Figure 4(a)). In this process, the shallow arch structure was transited to the hinge structure formed by the deep mining of coal and rock mass. This was not only the transition of the collapse pattern of the rock stratum but also the transition of the extracting depth of the working face.

After mining the +645 level (as shown in Figure 4(b)), the roof fractured caused the ground to lose support and successively fractured. The vibration caused by the fracture of overlying strata spread to the roof and floor, thus resulted in “V-shaped” microseismic events corresponding to the ground surface. The energy released by the ground surface collapse caused by the fracture of the roof at +645 level was transferred to the horizontal working surface.

4.1.2. Deep Mining Stage. As the mining depth increased, the failure mechanism of overlying strata was also shifting and it will develop from the static failure of the shallow roof structure to the squeezing dynamic failure of the in-depth overlying strata. The rebalanced deep coal and rock mass had a periodic dynamic evolution process of “balance-instability-rebalance-instability again” under the repeated disturbance of the extraction level.

In the shallow mining stage, the collapse height of overlying strata continued to increase, and the gangue in the gob slipped to backfill the new mining area. Thus, it inhibits the separation the upper rock strata from the roof along the plane line and results in an increase in the length of the cantilever beam, thus inhibiting the separation of the upper rock strata of the roof along the normal direction of the level, resulting in an increase in the length of the roof cantilever. After entering deep mining stage, the main roof had a high strength and good integrity, and the fractured main roof formed a hinged rock beam structure with the integral roof and the recompacted gob. The hinge rock beam structure, on the one hand, bears the weight of the gangue above the working face and the lateral squeezing force of the roof and protects the lower horizontal working face. However, on the other hand, it increased the unsupported roof distance of the gob, and the instability failure of the hinge rock beam structure would cause huge loss to the working face. Thus, the stability of the structure plays a key role in the safe mining of the working face.

At the end of extracting at the +550 level, the roof did not fracture, which posed a serious threat to the security of the working face. The gangue in the gob squeezed the roof cantilever beam under the influence of the weight of overlying strata, temporarily formed a hinged rock beam structure above the working face (Figure 5(a)). Microseismic events mostly occurred here because of the mutual compression and friction between the gangue and the roof (Figure 5(b)).
The similarity simulation test results show that in the similarity simulation test, the rock strata were simply divided into hard rock strata and soft rock strata according to the different physical and mechanical parameters of the rock strata. The skeleton of the rock mass structure belongs to the hard rock strata of overlying strata. The overlying strata mined could be divided into several groups. Each group had a hard rock stratum as the bottom layer, and the soft rock layer above it could be regarded as the cushion layer connecting the two groups of hard rock strata. As the rock strata had different physical and mechanical parameters, they had slight differences in bearing capacity and compressive strength. As the sublevel caving method was used for the SIETCS, the roof was affected by repeated disturbances. With the increase in mining depth, the structure formed after the fracture of the overlying strata would shift from the shallow arch structure to the deep hinge rock beam structure. Different fracture modes of the overlying strata led to dynamic adjustment of the stope stress and changes in energy-frequency of microseismic events, which might pose a serious threat to security of the working face. With a good mastery of the structural evolution of overlying strata, which studied the relationship between the migration characteristics of overlying strata and the law of microseismic response, it could achieve the goal of safe production in mines by application of the microseismic monitoring analysis.

4.2. Energy Evolution Characteristics of Overlying Strata. In the mining process of SIETCS, the structure formed after the overlying strata undergo instability failure also presents different characteristics with the increase in the mining depth. In the test, the fracture and collapse of the roof structure caused the accumulation and release of energy inside the rock stratum. Microseismic monitoring instruments were used to monitor the accumulation and release of energy during the activity process of overlying strata. Based on the statistics of the energy and frequency of the microseismic events, the characteristics of the microseismic events in coal seam 43# were plotted, as shown in Figure 6. The evolution law of the overlying strata structure was quantitatively analyzed from the energy point of view.

Based on an analysis of the energy-frequency law of microseismic events in the extraction stage, it was found that the shallow mining caused redistribution of the overlying strata stress and the energy-frequency of the microseismic events of the overlying strata increased slowly. Meanwhile, the energy accumulation and release had a long cycle. The microseismic events were primarily caused by the separation and fracture of the roof. The frequency of microseismic events at the +707 level reached its peak for the first time, which was mainly caused by the vibration arising from the initial collapse of the roof. The energy of microseismic events showed a trend of slowly increasing. Due to the gradual increase in the energy release of the overlying strata fracture, the overall trend fluctuated slightly. At the +645 level, the microseismic energy and frequency began to increase significantly, and the fluctuation range of the microseismic energy increased.

The energy-frequency of microseismic events in the deep mining stage was significantly higher than that in the shallow mining stage. As a result, the risk of dynamic disasters increased in the deep mining stage. In the stage of deep mining, the microseismic energy fluctuated considerably, and the energy peaked for the first time at the +620 level. There were because the collapse of the roof at this level extends to the surface, which resulted in large-scale migration of the overlying strata. The roof did not fracture at the +575 level; the energy accumulation reached the maximum at this time. As the collapse height of the overlying strata extended upwards, the frequency of fracture microseismic events of the roof at the +525 level reached the maximum. But, the energy-frequency of overlying strata at the next level showed a downward trend. The energy accumulation and release cycle of the overlying strata in the deep mining stage were...
shorter than that in the shallow extraction stage. The energy 
events ($10^2-10^4$) that posed a greater threat to the working 
face during extraction accounted for 35.6% and were mainly 
concentrated in the deep mining stage.

Based on an analysis of instability failure and energy 
evolution characteristics of overlying strata, it was found 
that in the mining of SIETCS, the failure mechanism of 
overlying strata changes as the mining depth increases. 
In deep mining, the roof was affected by repeated mining. 
With the increase in mining depth, the collapse width of 
the roof gradually increases, and a dynamic propagation 
structure was forming. In other words, the hinged rock 
beam structure of the deep roof exists for a long time. 
This was because the chain reaction caused by repeated 
mining prevents the surrounding rock system from reach-
ing an equilibrium state, and the surrounding rock system 
mining prevents the surrounding rock system from reach-
ing in instability failure.

The similarity simulation test showed that the working 
face of SIETCS was mainly threatened by the multistructure 
of the roof and floor above it, coal gangue mixture in the 
gob, and the overburden of surface soil. The instability of 
the structure above the working face jeopardizes the safe 
production of the mine. To analyze the formation character-
stics and dynamic evolution law of the overlying strata 
structure, SOS microseismic equipment was used in the sim-
ilarity simulation test to monitor the microseismic event 
characteristics. Due to the complexity of the migration law 
of the overlying strata structure, a single microseismic 
event does not necessarily form a quantitative rela-
tionship with mining activities, and many seismological 
parameters could not be derived from a single microseismic 
event. It might be seen from the monitoring data of micro-
seismic events in the overlying strata during the mining 
stage that the spatial distribution of microseismic events 
was relatively scattered. The seemingly chaotic data actually 
reflects some regular changes. Statistical analysis is a good 
method and tool. Therefore, the seismological and statistical 
theories were utilized to analyze the microseismic events in a 
certain time and space, so as to obtain the evolution law of 
overlying strata structure and microseismic events with time 
and space.

5. Analysis of Characteristics of Structural 
Evolution and Microseismic Response of 
Overlying Strata

Based on the monitoring results of rock formation fracture 
and microseismic events during extracting in the similarity 
simulation test, the microseismic signals in SIETCS were 
analyzed to study the relationship between the apparent vol-
ume, energy index, microseismic event b value of microseis-
ic events, other parameter response characteristics and the 
evolution of the overlying strata structure.

5.1. Overlying Strata Structure and Microseismic Events. The 
defformation failure of the coal and rock mass had 4 stages 
during extracting of SIETCS [24]: crack closure (OA), elastic 
def ormation (AB), crack development (BC), and overlying 
strata failure (CD) are shown in Figure 7. In the fracture 
closure and elastic deformation stage (OB), there were no 
damages to the coal and rock mass; the BC stage could 
be divided into slow development of fractures, stable 
development, accelerated propagation, and rapid penetra-
tion. The corresponding stress levels were ($\sigma_0$, $\sigma_{b1}$, 
$\sigma_{b2}$), ($\sigma_{b3}$, $\sigma_{b4}$), and ($\sigma_{b5}$, $R_c$), respectively. At this stage, 
both the frequency and energy of mine earthquakes 
increase as the crack propagation speed increases. After 
the compressive strength of the rock formation was 
exceeded, the fractures in the coal and rock mass were 
connected, and macroscopic large fractures appear, result-
in instability failure.

Figure 6: Characteristics of microseismic energy-frequency in the whole process of extracting of the 43# coal seam.
5.2. Characteristics of Apparent Volume and Energy Index. Deep mining of SIETCS faces the problems of large mining space and wide moving range of overlying strata. The vibration caused by the fracture of the rock stratum above the working space of the working face was transmitted to the gob, which might generate a larger energy release. The safety of the working space at the working face was mainly determined by the stability of the upper rock mass. One of the most important purposes of mine microseismic monitoring was to predict and distinguish dangerous microseismic activity areas. Microseismic monitoring during the extraction process provided support for the study of the temporal and spatial strong activity laws of the mine microseismic events and the response characteristics of mining disturbances.

In seismology, apparent volume and energy index were two important parameters that describe the incubation process of an earthquake. They were often used to describe the variation laws of rock mass before an earthquake occurs. Apparent volume denotes the volume of the rock mass in the inelastic deformation zone of the seismic source, which could be calculated from the recorded waveform parameters. The cumulative apparent volume was commonly used to characterize the degree of rock deformation, which could be expressed by the following formula [31–34],

\[ V_A = \frac{\mu P^2}{E}, \]  

where \( V_A \) was the apparent volume, \( \mu \) was the shear modulus of the rock, \( E \) was the radiation microseismic energy, and \( P \) was the microseismic body deformation. The apparent volume depended on the deformation of the microseismic body and the radiant energy. As it was a scalar quantity, which could be easily expressed in the form of a cumulative quantity or contour map.

The energy index of a microseismic event was the ratio of the measured earthquake release energy produced by the event to the average microseismic energy of all events in the region [25], which could be expressed as

\[ EI = \frac{E}{E(P)} = \frac{E}{10^{d \lg P + c}} = 10^{-c} \frac{E}{P^d}, \]  

where \( EI \) was the energy index of the microseismic event, \( E(P) \) was the average microseismic energy of all microseismic events monitored in the analysis area, and \( c \) and \( d \) were both constants. The energy index represents the driving stress inside the rock mass. A larger energy index indicates greater driving stress of the seismic source at the time when the event occurs. Therefore, the precursor characteristics and laws of rock mass disasters could be obtained through the time-history variation curve of apparent volume and energy index.

Based on this similarity simulation test, the microseismic monitoring data at the +645 level and +620 level were selected. The recorded waveform data with a high signal-to-noise ratio was selected for positioning and energy analysis. Taking the apparent volume and energy index in the study area of the overlying strata as the analysis parameters, the precursor information of the occurrence of deformation and fracture of the overlying strata was obtained by quantitatively observing and analyzing the time-history variation curve of the apparent volume and energy index during the extraction process. See Figure 8 for details.

It could be seen from Figure 8(a) that the energy index EI fluctuated slightly at the initial stage of extracting at the +645 level and reached a small peak at point A. At this time, the cumulative apparent volume \( \sum V_A \) suddenly increased, indicating that microfissure in the rock formation was developing and the stress was increasing constantly. During the extraction process, \( \sum V_A \) of the AB section \( \sum V_A \) slowly increased while the number of microseismic events decreased, and EI almost did not change. At this time, it entered the “quiet period” of microseismic events (the temporary disappearance of microseismic events before the release of microseismic large energy). The rock stratum accumulated energy at this stage, and then, the EI reached
its peak, and the slope of the $\Sigma V_A$ curve suddenly increased, indicating that the overlying strata released higher energy at this time. The development of rock fissures accelerated significantly, which eventually led to the instability and failure of the overlying strata structure. Figure 8(b) shows that the cumulative apparent volume and energy index were significantly higher than that of the upper level extraction. The “quiet period” before the release of microseismic large energy significantly decreased. At the same time, the intensity of energy release from the overlying strata increased correspondingly. After reaching its peak, the energy index $EI$ showed a continuous downward trend, and the cumulative apparent volume $\Sigma V_A$ increased faster, indicating that the microseismic strain rate increased rapidly. The energy index $EI$ and the cumulative apparent volume $\Sigma V_A$ curve also show some cyclical characteristics, which had a certain correlation with the cyclical characteristics of mining activities.

5.3. $b$ Value Characteristics of Microseismic Events. To further reveal the failure process of surrounding rock during mining at the working face, the magnitude and frequency (G-R relationship for short) commonly used in seismological research were employed to quantitatively describe the relationship between the magnitude and frequency of microseismic events in SIETCS.

The G-R relationship describes the relationship between the frequency of regional seismic activity and the magnitude of earthquakes and is one of the most important statistical relationships in seismology. It reflects the regional magnitude $M$, and the logarithm of the cumulative number of earthquakes $N$ has a linear relationship with the magnitude $M$, namely

$$\lg N = a - bM,$$

where $a$ and $b$ were empirical constants related to regional seismic activity. The value of $b$ was often an important parameter to measure the level of seismic activity. According to the microseismic data in the extraction process of the similarity simulation test, the corresponding G-R relationship was $\lg N = 3.812 - 0.534M$. 

![Figure 8: Relationship between cumulative apparent volume and energy index over time: (a) cumulative apparent volume and energy index at +645 level; (b) cumulative apparent volume and energy index at +620 level.](image-url)
At the same time, the $b$ value, as a commonly used parameter for analyzing the magnitude and frequency in seismology, was of great significance for studying the proportions of different scale cracks in the rock mass. The research results show that the relationship between the magnitude and frequency of earthquakes (mining earthquakes, rockbursts) induced by human mining activities and natural earthquakes follows the G-R relationship expression. G-R relationship and $b$ value could be used as an important index for studying rock fractures and induced seismicity. The paper used the least square method to calculate the value of $b$; the formula was as follows:

$$ b = \frac{\sum_{i=1}^{m} M_i \sum_{i=1}^{m} \log N_i - m \sum_{i=1}^{m} M_i \log N_i}{m \sum_{i=1}^{m} M_i^2 - (\sum_{i=1}^{m} M_i)^2}, $$

where $m$ was the total number of magnitude levels, $M_i$ denoted the magnitudes of the $i$-th magnitude level, and $N_i$ denoted the actual number of events of the $i$-th magnitude level. In view of the physical and practical significance of the $b$ value, we had conducted an in-depth study on it and applied it to earthquake prediction research because of judgment of dynamic disaster risks during the mining process.

In the calculation process of the $b$ value, based on extracting microseismic data of the similarity simulation test at +742 level - +550 level, the lower limit of the microseismic data was 0.2. The $\Delta M = 0.4$ was used for division. The calculation result of the $b$ value is shown in Figure 9.

It could be seen from Figure 9 that the $b$ value slightly decreases at the +726 level. But the first 5 levels maintain an increasing trend as a whole, indicating that the frequently occurring small-magnitude microseismic events at this stage led to an increase in internal fractures in the rock strata. At the +645 level, the rock stratum collapsed in a large area and caused surface subsidence. The microseismic $b$ value decreased suddenly at A in the figure. The energy release rate suddenly increased, indicating that the number of microseismic events of large magnitude within this extraction level had gradually increased. It could be induct energy release in a large number of cracks, rapid generation a large number of small cracks connecting each other into large cracks. At the lower level (+620 level), the microseismic $b$ value increased sharply and reached the maximum. Corresponding to the point B in the figure, the height of the fractured rock stratum continued to increase, and the depth and width of the fissures continued to increase. The rock stratum had a large area of collapse, indicating that all the internal fissures within the rock stratum had developed to the maximum extent, and the rock stratum would experience collapse on a large scale. In summary, during the entire extraction process, the microseismic $b$ value shows the characteristics of slowly increasing-drastically changing-tending to be stable, which also indicated the change process of development-formation-closure of the internal fractures in the rock stratum. At the same time, the precursor characteristic of rock stratum fractures that the $b$ value of the microseismic event gradually increases during the extraction process followed by drastic changes was found.

6. Conclusions

(1) In the mining process of SIETCS, with the increase of the horizontal sublevel and mining depth, the roof caving pattern developed from the static failure of...
the shallow part to the dynamic failure of the deep overlying strata. In the shallow mining stage, as the top coal caving gob gradually increased, the roof lost support and failed in tension along the normal direction of the bedding surface to form an arch structure under the action of its own weight and the load of the overlying strata. In the deep mining stage, the gangue in the gob slid down and filled the new mining area, which inhibited the separation of the upper rock strata of the roof along the normal direction of the bedding. Due to causing the roof structure to be alienated and the complete rock strata to form a hinged structure, the rebalanced deep coal and rock mass had a periodic dynamic evolution process of “balance-instability-rebalance-instability again” under the repeated disturbance of the extraction level.

(2) In the mining process of SIETCS, the structure formed after the overlying strata undergo instability failure also presented different characteristics with the increase in the mining depth. Due to the occurrence characteristics of the coal seams, the stress distribution characteristics of the rock strata, and the influence of mining disturbances, in the shallow mining stage, the energy-frequency of microseismic events was slowly increased, and the energy of accumulation-release of cycle was long. In the deep mining stage, the energy-frequency of microseismic events was significantly higher, and the energy-frequency reached the maximum at the +575 level. The energy accumulation-release cycle of the overlying strata in the deep mining stage was shorter than that in the shallow mining stage.

(3) The slope of the cumulative apparent volume $\sum V_A$ curve of the working face suddenly increased and continued to maintain an upward trend during the extraction process. At the same time, the energy index $E_l$ gradually decreased in the late peak period, indicating that the overlying strata started to release energy and to cause deformation.

(4) There was a certain correlation between the fracture of the overlying strata and the $b$ value characteristics of microseisms. The increasing slowly drastically changing-tending to be stable characteristic of the microseismic $b$ value corresponds to the process of development-forming-closing of internal fissures within the overlying strata. At the same time, the precursor characteristic of rock stratum fractures that the $b$ value gradually increases followed by drastic changes was found during the extraction process.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

No conflict of interest exists in the submission of this manuscript.

Authors’ Contributions

The manuscript is approved by all authors for publication.

Acknowledgments

The study has been supported by the National Natural Science Foundation of China (Nos. 52004201 and 51904227), the Natural Science Foundation of Shaanxi Provincial Department of Education (20JK0765), and the Open Foundation of the State Key Laboratory of Green and Safe Coal Development in Western China (No. SKLCRKF1901). Support from these agencies is gratefully acknowledged.

References

[1] Y. H. Wu, L. S. Cheng, L. Q. Ma et al., “A transient two-phase flow model for production prediction of tight gas wells with fracturing fluid-induced formation damage,” Journal of Petroleum Science and Engineering, vol. 199, article 108351, 2021.

[2] Y. H. Wu, L. S. Cheng, J. Killough et al., “Integrated characterization of the fracture network in fractured shale gas Reservoirs–Stochastic fracture modeling, simulation and assisted history matching,” Journal of Petroleum Science and Engineering, vol. 205, article 108886, 2021.

[3] H. C. Xu, X. P. Lai, S. Zhang et al., “Multiscale intelligent inversion of water-conducting fractured zone in coal mine based on elastic modulus calibration rate response and its application - a case study of Ningdong mining area,” Lithosphere, vol. 2021, article 7657143, pp. 1–16, 2021.

[4] Y. R. Yang, X. P. Lai, T. Luo, K. K. Yuan, and F. Cui, “Study on the viscoelastic-viscoplastic model of layered siltstone using creep test and RBF neural network,” Open Geosciences, vol. 13, no. 1, pp. 72–84, 2021.

[5] X. P. Lai, J. J. Dai, and C. Li, “Analysis on hazard characteristics of overburden structure in steeply inclined coal seam,” Journal of China Coal Society, vol. 45, no. 1, pp. 122–130, 2020.

[6] X. P. Lai, Y. R. Yang, N. B. Wang, P. F. Shan, and D. S. Zhang, “Comprehensive analysis to temporal-spatial variation of dynamic instability of steeply inclined coal-rock mass,” Chinese Journal of Rock Mechanics and Engineering, vol. 37, no. 3, pp. 583–592, 2018.

[7] X. P. Lai, H. C. Xu, J. D. Fan et al., “Study on the mechanism and control of rock burst of coal pillar under complex conditions,” Geofluids, vol. 2020, Article ID 8847003, 19 pages, 2020.

[8] Y. B. Yang and F. Cui, “Thermal infrared characteristics of rock strata fracture in steeply inclined and extra thick coal seam,” Thermal Science, vol. 24, no. 6, Part B, pp. 3933–3940, 2020.

[9] X. Rao, L. Y. Xin, Y. X. He et al., “Numerical simulation of two-phase heat and mass transfer in fractured reservoirs based on projection-based embedded discrete fracture model (pEDFM),” Journal of Petroleum Science and Engineering, vol. 208, article 109323, 2022.

[10] H. Liu, X. Rao, and H. Xiong, “Evaluation of CO2 sequestration capacity in complex- boundary-shape shale gas reservoirs.
using projection-based embedded discrete fracture model (pEDFM),” *Fuel*, vol. 277, article 118201, 2020.

[11] H. Xiong, D. Devegowda, and L. L. Huang, “EOR solvent-oil interaction in clay-hosted pores: insights from molecular dynamics simulations,” *Fuel*, vol. 249, pp. 233–251, 2019.

[12] P. W. Shi and Y. Z. Zhang, “Structural analysis of arch of spanning strata of top coal caving in steep seam,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 25, no. 1, pp. 79–82, 2006.

[13] X. P. Shao, P. W. Shi, and G. C. He, “Analysis on unloaded arch structure of roof in mining steep seams using horizontal section top-coal caving,” *Journal of University of Science and Technology Beijing*, vol. 29, no. 5, pp. 447–451, 2007.

[14] X. P. Lai, Y. R. Yang, J. Q. Chen, R. Z. Ge, F. Cui, and P. F. Shan, “Control of dynamic hazards induced by mining stress distortion in extremely steep and thick coal seams,” *Journal of China Coal Society*, vol. 41, no. 7, pp. 1610–1616, 2016.

[15] W. J. Ju, J. W. Zheng, D. Wei, L. W. Sun, and W. Z. Li, “Study on the causes and control technology about the coal bump in multi-layered mining roadway in steep-thick coal seams,” *Journal of Mining and Safety Engineering*, vol. 36, no. 2, pp. 280–289, 2019.

[16] H. Wu, D. Ma, A. J. S. Spear and, G. Y. Zhao, “Fracture response and mechanisms of brittle rock with different numbers of openings under uniaxial loading,” *Geomechanics and Engineering*, vol. 25, no. 6, pp. 481–493, 2021.

[17] P. Jia, M. Ma, C. Cao, L. S. Cheng, H. F. Yin, and Z. Li, “Capturing dynamic behavior of propped and unproped fractures during flowback and early-time production of shale gas wells using a novel flow-geomechanics coupled model,” *Journal of Petroleum Science and Engineering*, vol. 208, article 109412.

[18] Y. D. Jiang and Y. X. Zhao, “State of the art: investigation on mechanism, forecast and control of coal bumps in China,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 34, no. 11, pp. 2188–2204, 2015.

[19] L. H. Tan, T. Ren, L. M. Dou, X. H. Yang, M. Qiao, and H. D. Peng, “Analytical stress solution and mechanical properties for rock mass containing a hole with complex shape,” *Theoretical and Applied Fracture Mechanics*, vol. 114, article 103002, 2021.

[20] X. H. Tian, Z. L. Li, D. Z. Song et al., “Study on microseismic precursors and early warning methods of rock bursts in a working face,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 39, no. 12, pp. 2471–2482, 2020.

[21] L. H. Tan, T. Ren, L. M. Dou, X. Cai, X. H. Yang, and Q. L. Zhou, “Dynamic response and fracture evolution of marble specimens containing rectangular cavities subjected to dynamic loading,” *Bulletin of Engineering Geology and the Environment*, vol. 80, no. 10, pp. 7701–7716, 2021.

[22] Y. Zhang and S. G. Cao, “Control of water-flowing fracture development with solid backfill mining: designing a backfill body compression ratio for water resources protection,” *Mine Water and the Environment*, 2021.

[23] Y. Zhang, S. G. Cao, N. Zhang, and C. Z. Zhao, “The application of short-wall block backfill mining to preserve surface water resources in northwest China,” *Journal of Cleaner Production*, vol. 261, article 121232, 2020.

[24] L. M. Dou, Y. D. Jiang, A. Y. Can et al., “Monitoring and pre-warning of rockburst hazard with technology of stress field and wave field in underground coalmines,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 36, no. 4, pp. 803–811, 2017.

[25] Y. X. Xia, H. Lan, and X. Z. Wei, “Study of comprehensive evaluation technology for rock burst hazard based on microseismic and underground sound monitoring,” *Journal of China Coal Society*, vol. 36, no. 52, pp. 358–364, 2011.

[26] S. H. Liu, J. F. Pan, Y. X. Xia, Z. H. Qin, T. T. Du, and F. B. Chen, “Research on the risk hierarchical assessment of rock burst of heading face based on acoustic emission and electromagnetic wave CT system,” *Journal of China Coal Society*, vol. 43, no. 8, pp. 2107–2116, 2018.

[27] L. Yuan, “Research progress on risk identification, assessment, monitoring and early warning technologies of typical dynamic hazards in coal mines,” *Journal of China Coal Society*, vol. 45, no. 5, pp. 1557–1566, 2020.

[28] R. Q. Huang and D. Huang, “Evolution of rock cracks under unloading condition,” *Rock Mechanics and Rock Engineering*, vol. 47, no. 2, pp. 453–466, 2014.

[29] S. K. Roy, D. Srinagesh, D. Saikia, A. Singh, and M. R. Kumar, “Seismic anisotropy beneath the eastern Dhawar craton,” *Lithosphere*, vol. 4, no. 4, pp. 259–268, 2012.

[30] C. Zhang, G. H. Jin, C. Liu et al., “Prediction of rockbursts in a typical island working face of a coal mine through microseismic monitoring technology,” *Tunneling And Underground Space Technology*, vol. 113, article 103972, 2021.

[31] L. Z. Tang, L. H. Wang, J. Zhang, and X. B. Li, “Seismic apparent stress and deformation in a deep mine under large-scale mining and areal hazardous seismic prediction,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 6, pp. 1168–1178, 2011.

[32] H. L. Liu, Y. Zhao, P. H. Zhang, F. Y. Liu, and T. H. Yang, “Stopate structure evaluation based on the damage model driven by microseismic data and Mathews stability diagram method in Xidian Gold Mine,” *Geomatics, Natural Hazards and Risk*, vol. 12, no. 1, pp. 1616–1637, 2021.

[33] T. H. Ma, C. A. Tang, S. B. Tang et al., “Rockburst mechanism and prediction based on microseismic monitoring,” *International Journal Of Rock Mechanics And Mining Sciences*, vol. 110, pp. 177–188, 2018.

[34] R. X. Xue, Z. Z. Liang, N. W. Xu, and L. L. Dong, “Rockburst prediction and stability analysis of the access tunnel in the main powerhouse of a hydropower station based on microseismic monitoring,” *International Journal Of Rock Mechanics And Mining Sciences*, vol. 126, article 104174, 2020.