Research Article

Study on Coal Gangue Identification Based on Vibration and Its Adaptability to Coal-Caving Process Parameters

Lirong Wan,1 Jiantao Wang,1 Dejian Ma,1 Zhaoji Li,1 Zhenguo Lu,2 and Zhaosheng Meng3

1 College of Mechanical and Electronic Engineering, Shandong University of Science and Technology, Qingdao 266590, China
2 College of Transportation, Shandong University of Science and Technology, Qingdao 266590, China
3 State Key Laboratory of Mining Disaster Prevention and Control Cofounded By Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Zhaosheng Meng; skdmzs@163.com

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The broken top coal and gangue in the fully mechanized cave mining will be released from the rear of the hydraulic support in the form of bulk. In this process, the medium properties through the coal opening can be judged by monitoring the vibration signal on the tail beam. Based on the coupling method of the discrete element method (DEM) and the finite element method (FEM) in LS-DYNA, this article simulates the whole process of coal caving, establishes the finite element model of the tail beam of hydraulic support and the discrete element model of coal gangue particles, and analyzes the influence of coal caving step distance, mining and caving ratio, and pitching angle of the mining field on the application effect of the vibration identification method. The coal caving step distance has a great influence on the recognition effect, and some bottom coal should be appropriately sacrificed to reduce the gangue content. The application effect of the vibration identification method is good under different mining and caving ratios. Downward mining can cause gangue to be released in advance, making the recognizable signal lag behind the change of gangue content, while upward mining will lose a part of the coal, but the application of vibration recognition is better than downward mining.

1. Introduction

Coal is an important energy pillar in China, accounting for more than half of the national energy consumption, and China’s coal consumption accounted for 50.72% of the world’s total in 2017 [1, 2]. The thick coal seam refers to the coal seam whose thickness is greater than 3.5 m. China has rich reserves of the thick coal seam. Fully mechanized cave mining technology has been widely used in many mining areas due to its high yield and high efficiency [3, 4]. How to control the closing of the coal opening is one of the key links in the process of top coal cave mining. The earlier closing of the coal opening will make part of the coal not to be released thus leading to wastage, and the later closing will make the gangue to be excessively released, thereby reducing the quality of the coal and increasing the cost of late coal preparation. At present, the closing time in coal mines still depends mainly on the manual observation and hearing. However, this method is easily affected by the experience of the operators, and the operating environment is also dangerous, which is not in line with the developmental trend of unmanned coal mines in the future.

Because of the current situation of low automation of the coal caving process, many scholars have carried out research studies on the coal gangue identification. Zhang et al. [5] proposed that the difference in natural gamma rays between coal and gangue can be used to identify the gangue content in a coal gangue mixture. Wang et al. [6] proposed image recognition intelligent coal caving technology, to improve the automation level of the coal caving process. Hou et al. [7]
established a coal gangue sorting system based on the artificial neural network and image feature extraction by using the difference in surface texture and the gray level of coal and gangue. Wang and Zhang [8] proposed a method to obtain volume data and to further calculate the density by using three-dimensional laser scanning technology, which effectively solved the problem of separating coal and gangue. Guo et al. [9] proposed an identification method based on the difference in dielectric properties of coal gangue and obtained the relationship curve of the dielectric constant of coal and gangue with frequency and voltage.

In summary, while the current top coal caving working face is still dominated by manual control, scholars have also explored various intelligent coal caving control technologies. However, the harsh environment of the top coal caving field, such as noise, dust, and low visibility, seriously affects the application effect of many coal gangue identification technologies [10–12].

The basic principle of the vibration-based coal gangue identification method is to use the obvious difference in the physical properties of coal and gangue, resulting in different vibration signals of the tail beam after being impacted by coal and gangue. This method can effectively resist the influence of various noises and dust, and since its characteristics are based on the vibration sensors, it also makes the installation of equipment more convenient, so it has a good application prospect. However, at present, the research on coal gangue identification based on vibration mainly focuses on the impact process of a small number of rock particles and signal processing [13–15]. There are a few studies on the coal gangue identification effect in the whole process of coal caving, while no study has yet focused on how the application effect of the vibration identification method is affected by the numerous process parameters of the coal release process and environmental conditions.

DEM as a powerful tool to study particle movement has been widely studied by Zheng et al. [16]. Ketterhagen et al. [17] used DEM to analyze the hopper powder flow, and DEM simulation results and design charts are very consistent. Coetzee et al. [18] proposed a calibration process of the DEM method to calibrate the parameter value of broken rock particles with a size of 40 mm. Su and Ali Akcin [19] used DEM to propose a numerical model that can predict the tool force in the process of rock cutting, and the results of this model have a strong correlation with the results of theoretical and experimental studies. Hang et al. [20] used the DEM method to study the micromotion and macrodisturbance behavior of the soil under the combined action of two subsoils.

Mastering the variation law of the application effect of the vibration-based coal gangue identification method under various working conditions can better guide the formulation of the coal caving process in the future. Therefore, based on the coupling technology of DEM and FEM in LS-DYNA, this article established a three-dimensional numerical model of the top coal caving in fully mechanized cave mining. The difference of vibration signals of the tail beam in different stages of coal caving is studied, and the influence of coal caving step distance, mining and caving ratio, and the pitching angle of the mining field on the application effect of the vibration identification method is discussed. This article analyzes how to control the coal caving process to better obtain a better recognition effect from the perspective of vibration-based coal gangue identification technology. The conclusion can provide guidance for better application of the vibration identification method by adjusting the coal caving process.

2. Model and Methods

2.1. Model Description. In this article, a numerical model is established as shown in Figure 1. The left side of the figure is the complete model, and the baffle on the top is the boundary of the coal gangue particles flowing around, and there is an opening at the bottom of the baffle to simulate the coal opening. A funnel is arranged below the coal opening to load the particles released from the coal opening. The short side width of the funnel is 500 mm, which is slightly larger than the maximum diameter of the particles, and it is convenient to count the gangue content in the top coal released. The model simplifies the hydraulic support, and the complete hydraulic support is shown in the figure. Considering the calculation time and the motion state of the components in the coal caving process, only the canopy, shield beam, and tail beam are left. At the same time, the canopy and shield beam are simplified as flat plates. The degrees of freedom of baffles, canopy, and shield beams are fully constrained, and gravity is applied to the model, $g = 9.81 \text{ m/s}^2$.  

2.2. Discrete Element Model of Coal Gangue Particles. The DEM is proposed by Cundall in the 1970s [21]; it is a numerical simulation method for solving discontinuous media problems. In LS-DYNA, the interaction between particles is defined by the keyword *CONTROL_DISCRETE_ELEMENT, including the normal damping coefficient, tangential damping coefficient, sliding friction coefficient, and rolling friction coefficient between particles. The influence of the normal damping coefficient and tangential damping coefficient on particle motion is very important. When two particles collide, a damping coefficient of 0 is a completely elastic collision. When the damping coefficient is 1, the two particles are no longer separated after the collision, and the normal and tangential damping coefficients are set to 0.5. The CAP parameter in this keyword can control whether it is dry or wet particles. If CAP = 0, it is dry particles. Coal gangue particles can be regarded as an ideal loose medium. There is no adhesion between the particles in this kind of a medium. Therefore, this parameter is set to 0.

The interaction between particles is processed by the algorithm based on the penalty function [22]. Figure 2 shows the normal contact force and tangential force between particles [23].

Some basic assumptions are needed to establish the numerical model of the coal gangue particles during coal caving and they are as follows:
The support is only affected by the coal gangue particles from above.

The boundary of the broken top coal above the support is located in half of the top beam.

The broken top coal is loose, and the pressure from the surrounding particles in the process of coal caving is not huge, so the crushing of coal gangue particles is not considered.

The shape of the broken coal gangue particles is spherical.

LS-PrePost software is used for the creation of particles. In LS-PrePost, the boundary of the discrete element particles must consist of shell elements. After the boundary is specified, software generates loose particles randomly according to the radius range and gap entered. The radius range of the particles is 150 mm – 200 mm. There is a certain gap between the particles in the initial state, and the particles gradually form the compaction state under the action of gravity after the beginning of the simulation. The sliding friction coefficient of the normal damping coefficient between particles is 0.65, and the rolling friction coefficient is 0.1.

Because particles are regarded as rigid bodies in the DEM algorithm, MAT_ELASTIC is selected as the material of coal and gangue. The material model parameters of coal and gangue are shown in Table 1 [24], where \( \rho_0 \) is density, \( E \) is Young’s modulus, and PR is Poisson’s ratio.

Table 1: Material model parameters for coal and gangue.

<table>
<thead>
<tr>
<th>Materials</th>
<th>( \rho_0 ) (kg/m(^3))</th>
<th>( E ) (Pa)</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1400</td>
<td>2.3 \times 10^9</td>
<td>0.25</td>
</tr>
<tr>
<td>Gangue</td>
<td>2590</td>
<td>1.35 \times 10^10</td>
<td>0.123</td>
</tr>
</tbody>
</table>

The broken top coal and gangue before coal caving will form a clear boundary between coal and gangue, which can generally be described by a parabola, as shown in Figure 3. The shapes of the coal gangue boundary are related to the coal caving step distance, top coal thickness, and three-dimensional size of the support. According to Wang’s research [25], the numerical model of the coal gangue interface settings is shown in Figure 4.

2.3. Finite Element Model of the Tail Beam of Hydraulic Support. The hydraulic support used in this article is ZF4800-17-32 top coal-caving hydraulic support. The maximum and minimum work height of the support is 3.2 m and 1.7 m, respectively, and the working resistance is 4800 kN. The structural composition and finite element model of the support are shown in Figure 5. The tail beam and the shield beam are parallel before the coal caving, and the coal gangue particles are accumulated above the hydraulic support. After the coal caving begins, the tail beam swings downward and forms the coal opening. The coal gangue particles flow out along the coal opening and are transported to the scraper conveyor below. In previous studies, we found that the vibration signal on the tail beam is significantly stronger than that on the shield beam because the state of the tail beam was closer to the cantilever beam structure. Due to a large number of discrete element particles in the numerical model, it is found that the calculation time is not acceptable after trying to use the complete hydraulic support model. Therefore, only the tail beam structure is retained, and the rigid plate is used to replace the canopy and the shield beam, as a part of the flow boundary of coal gangue particles. The degrees of freedom of the position...
shown in Figure 6 are all constrained to simulate the fixed mode of the tail beam in the hydraulic support.

2.4. Coupling Algorithm. There are two ways to deal with the contact between the discrete element and the finite element in LS-DYNA. One is using \(*\) CONTACT_AUTOMATIC_NODE_TO_SURFACE. Although static friction and dynamic friction coefficient can be defined in this classical way, it is impossible to apply rolling friction, and the friction force acts on the center position of the discrete element particles. The other is using \(*\) DEFIN_E_DE_TO_SURFACE_COUPLING. This method is a special keyword defined in the LS-DYNA. It defined the contact characteristics between particles and structures through friction coefficient, rolling friction coefficient, and damping coefficient. It takes the outer surface of the particles as the physical boundary, and the force acts on the periphery of the particles rather than the center of mass, so it is closer to the real situation. Therefore, this article chooses this method to define the contact between the coal gangue particles and the tail beam. The friction coefficient between coal and gangue and each part of hydraulic support is 0.3, the rolling friction coefficient is 0.1, and the damping coefficient is 0.6.

3. Signal Analysis at Different Stages of the Whole Process of Coal Caving

3.1. Signals at Different Stages of Coal Caving. In order to quickly determine the time when the coal-caving state is coal gangue mixing, the tail beam in the numerical simulation is defined as the rigid body, and the numerical simulation time is 15 s. In this case, the simulation time will be greatly reduced. After determining the time of coal gangue mixing, the rigid-flexible transformation method in LS-DYNA is used in the original model, and the material transformation of the tail beam is realized by the keyword \(*\) DEFORMABLE_TO_RIGID_AUTOMATIC. Before reaching the set time, the tail beam is rigid, and after reaching the set time, the tail beam is automatically transformed into a flexible body.

The space occupied by the released top coal before they are released is called the released body. In order to observe the shape of the released body, we find out the number of the released coal gangue particles and delete them one by one in the initial model, and the hole is the shape of the released body. Figure 7 shows the shape of the released body at different times in the process of coal caving. From Figure 7, it can be seen that the shape of the released body is basically elliptical and conforms to the rule summarized by Wang through experiments and simulations [25]. Therefore, the setting of the numerical model is reliable.

During the development of the released body, the long axis and the short axis of the ellipse increase continuously, and the increase rate of the long axis is significantly higher than that of the short axis under the action of gravity. When the released body develops in the coal, then the release medium is pure coal; when the boundary of the released body is tangent to the coal gangue boundary, the gangue in the released body will be released. Figure 8 shows the shape of the coal gangue boundary at different times. After the beginning of the coal caving, the bottom of the coal gangue boundary began to shrink in the direction of the hydraulic support. The friction coefficient between the coal gangue and the steel plate is about 0.3, and the friction coefficient between the coal gangue is about 0.65. The flow velocity of the particles above the tail beam and the shield beam is faster than that on the right side of the coal caving port. At 13 s, there are both coal and gangue in the particles contacting the tail beam, and the coal accumulated at the bottom belongs to the part that cannot be released.

The images at 12 s, 13 s, 14 s, and 15 s were intercepted, respectively, and Image-Pro Plus software is used to calculate the gangue content of the particles left in the funnel. The gangue content was calculated by counting the number of coal and gangue pixels in the image. The statistical process is shown in Figure 9, and the red pixels are the statistical objects. Table 2 shows the statistical results. The gangue content less than 20% is acceptable in actual production.

In order to compare the difference in vibration signal of the tail beam between the coal-caving stage and coal gangue
mixing stage, three groups of the numerical simulation were carried out for the same coal-caving process. The tail beam in 3-5 s, 7-9 s, and 12-15 s is transformed into a flexible body, and the acceleration signal of a point on the tail beam was extracted. The time domain waveform of acceleration in each stage is shown in Figures 10-12. It can be seen from the waveform that the intensity of the acceleration signal generated by the first two stages of coal caving is basically similar, and the intensity of the acceleration is obviously improved in the coal gangue mixing stage, and the frequency of the signal is also improved to some extent.

3.2. Signal Processing and Feature Extraction. In order to show the differences among the three signals more intuitively, the maximum, minimum, and root mean square of the signals are extracted, respectively. The root mean square is defined as follows:

\[ X_{\text{rms}} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}, \]

where \( X_{\text{rms}} \) is the valid value, \( x_i \) is the value of the sampling point, and \( n \) is the number of sampling points.

The time-domain characteristics of the three signals are shown in Figure 13. It is obvious that, in the coal caving process, the three characteristics are significantly increased. In the coal gangue mixing stage, the gangue is continuously contacted with the tail beam and released; because the density of the gangue is significantly higher than that of the coal, it is more likely to transfer higher energy to the tail beam, so the acceleration signal will be stronger. In the first stage of the coal-caving process, the particles arched in a short time, resulting in less coal caving, so its eigenvalues are slightly less than the eigenvalues of the second stage of the coal-caving process.

The vibration signal of the tail beam is a random signal, which cannot be reproduced by a specific time function, so it needs to be analyzed by statistical methods. Empirical mode decomposition (EMD) was proposed by Norden E. Huang et al. in 1998. They believed that any complex signal was composed of different modes, and the superposition of these
modes formed a nonstationary signal. The EMD method is used to decompose the abovementioned three signals. Figure 14 shows the EMD results of the acceleration signals in the two-stage coal-caving process, and Figure 15 shows the EMD results of the acceleration signals in the coal gangue mixing stage. The original signal is decomposed into nine IMF components, which contain different frequency components from high to low. The first four IMF components have higher frequency and amplitude, indicating that possible important information is included in the first four IMF components.

In order to represent the difference between signals more intuitively, the decomposed components are further processed to extract feature parameters.

The mean of the absolute value is used to represent the average level of the signal. The expression is

$$\text{Mean} = \frac{\sum_{i=1}^{n} |x_i|}{n},$$  \hspace{1cm} (2)

where Mean is the mean of absolute value.

The peak value is used to represent the range of IMF component amplitude. The formula of the peak value is

$$\text{Peak} = \frac{1}{2} (\max(x_i) - \min(x_i)), \hspace{1cm} (3)$$

where Peak is the peak value.

The peak factor is used to represent the fluctuation of the signal, and its value is the ratio of the peak value to the mean value of the absolute value. The calculation formula is as follows:

$$\text{PeakFactor} = \frac{1/2(\max(x_i) - \min(x_i))}{1/N \sum_{i=1}^{N} |x_i|}, \hspace{1cm} (4)$$

where PeakFactor is the Peak factor.

The comparison of each eigenvalue of each IMF component of the three acceleration signals is shown in Figure 16. In general, the eigenvalue of the IMF component decreases with the decrease in frequency. For a single eigenvalue, the difference between the first two IMF components is the most stable, and the eigenvalue of the coal gangue mixing stage is significantly larger than that of the coal caving stage. With the decrease in the frequency of the component, the eigenvalue of the coal-caving stage is higher.
than that of the coal gangue mixing stage in some low-frequency components. Therefore, when the gangue is released, the eigenvalue of the high-frequency component of the vibration signal will be significantly enhanced.

In the numerical simulation, the gangue content of the final released coal gangue particles is less than 10%. By analyzing the time-domain characteristics of the acceleration on the tail beam and the eigenvalues of the IMF components after EMD decomposition, it is found that the vibration signal characteristics of the coal gangue mixing stage and the vibration signal characteristics of the coal caving stage have an obvious upward trend. Therefore, it can be considered that when the gangue content increases, the nature of the medium in the discharge body can be judged by monitoring the vibration signal on the tail beam.

4. Analysis of the Vibration Identification Effect under Different Coal Mining Technology and Environments

In the process of top coal-caving mining, there will be a variety of different conditions, such as different coal seam thickness and pitching angle in the mining field. In the previous study of coal gangue identification based on vibration, researchers focus on the influence of the change of the particle itself on the vibration signal and have not yet analyzed the influence of environmental factors in the whole coal-caving process. In order to better apply the method of coal gangue identification based on vibration in the future, it is necessary to analyze the environmental factors involved in the coal mining process. This section analyzes the coal-caving step distance, the mining and caving ratio, and the pitching angle in the mining field.

4.1. Effect of Coal-Caving Step Distance. The coal-caving step distance refers to the distance with which the fully mechanized mining work face moves forward between the two coal-caving processes. The coal-caving step distance is an important factor affecting the recovery rate and the gangue content of the working face. In order to analyze the feasibility of applying the vibration-based coal gangue identification method under different coal-caving step distances, the distance between the tail beam and the bottom of the coal gangue interface is adjusted to 2.8 m, 3.5 m, and 4 m, respectively. The coal gangue interface before coal caving is shown in Figure 17. We observed the coal-caving process in three cases, focusing on the contact time of gangue and tail beam. It should be emphasized that based on the work in Section 3, we have proved that when the particles contacted with the tail beam that contained some gangue particles, some characteristic values of the acceleration signal will change significantly. In order to reduce the repetitive work and to avoid excessive length, the vibration signal is no longer analyzed in this section, but the gangue content in the particles’ contact with the tail beam is directly observed. When the gangue particles occur, we believe that the characteristics of the vibration signal are enhanced.

Figure 18 shows the process of coal caving when the distance is 2.8 m. After the beginning of coal caving, the vertical part of the coal gangue boundary gradually moves to...
the coal-caving mouth. The gangue begins to be released between 6s and 8s. However, there is no gangue in the particles contacting with the tail beam at 10s. The gangue began to contact the tail beam at around 11s, and the gangue content was about 20.2%. It can be seen that when the coal caving step is small, the gangue will be released in advance from the side of the coal-caving mouth away from the hydraulic support, resulting in a high gangue content in the coal gangue particles released when the gangue is in contact with the tail beam. Therefore, when the vibration-based coal gangue identification method is used in the small step of coal caving, the identifiable signal will lag behind the change of the gangue content.

Figure 19 shows the process of coal caving with a distance of 3.5m. At about 12s, the gangue began to discharge, and at about 13.4s, the gangue began to contact the tail beam. The time interval from the beginning of gangue release to the beginning of gangue contact with the tail beam is far less than that of the distance of 2.8m. The gangue content is about 4.67% at 13.4s, which fully meets the requirements of mining.

Figure 20 shows the process of coal caving with a distance of 4m, due to the increase in the distance, the coal-caving time needs to be extended. At about 11s, the gangue began to discharge, and at about 12.8s, the gangue began to contact the tail beam. At this time, the gangue content was about 5.1%. Since the fluidity of the bottom is worse than that in the vertical direction, more coal will be cut off and will be accumulated at the bottom in the case of a large step distance. However, according to the requirement of gangue content, these coal particles accumulated at the bottom cannot be released, resulting in waste.

Due to the effect of gravity, the horizontal movement speed of the bottom particles is much smaller than that in the vertical direction. Through the analysis of the coal-caving process under three different coal-caving step distances, it is

![Figure 15: EMD results of vibration signals in coal gangue mixing stage.](image-url)
found that the particles that finally contacted with the tail beam are mainly from the gangue at the high position. Therefore, when the gangue mentioned above reaches the tail beam, the movement of the vertical coal gangue boundary has a great influence on the application effect of the vibration-based coal gangue identification method. When the step distance is small, the change of vibration signal on the tail beam seriously lags behind the change of the gangue content, and the application effect of the coal gangue identification method based on the vibration is poor. When the step distance increases properly, the change in the gangue content can be reflected in the vibration signal of the tail beam in time. However, when the step distance is too large, some coal will accumulate at the bottom and will cause loss. Therefore, in the future, when using vibration-based coal gangue identification, the caving step should be reasonably adjusted to achieve better identification results.

4.2. The Influence of Mining and Caving Ratio. In a certain direction, the thickness of the coal seam in the mining area often changes. For example, the thickness difference between the east and west of the coal seam in Jiulishan Mine is large,
and the maximum thickness is 7 m, which becomes thin from east to west. According to the change in coal seam thickness, it is necessary to determine a reasonable mining and caving ratio to achieve a high resource recovery rate to ensure the safety and stability of the production. In order to study the effect of using the vibration identification method under different mining and caving ratios, this section conducts a numerical simulation of the coal-caving process under three different mining and caving ratios. Figure 21 shows three different mining and caving ratios, which are 1:1, 1:1.43, and 1:2.67, respectively. The distance from the bottom of the coal gangue interface to the tail beam is the same.

Figure 22 shows the coal caving process under the condition of mining and caving ratio of 1:1. The first time of gangue discharge is 9.3 s, and the time of gangue beginning to contact with the tail beam is 9.9 s. At this time, the gangue content of the coal gangue particles in the funnel is 2.9%. Figure 23 shows the coal caving process under the condition of mining and caving ratio of 1:1.43; the time of the first release of the gangue is 11.7 s, and the time when the gangue begins to contact the tail beam is 12.5 s. At this time, the gangue content of the coal gangue particles in the funnel is 1.9%. Figure 24 shows the coal-caving process under the condition of mining and caving ratio of 1:2.67, the time of the first release of the gangue is 15.1 s, and the time of the
Figure 19: The evolution of the coal-caving process at a 3.5 m distance.

Figure 20: The evolution of the coal-caving process at 4 m distance.
gangue beginning to contact with the tail beam is 28.4 s. At this time, the gangue content of the particles in the funnel is 4.8%. There are two main reasons for the huge interval. One is that, during the coal-caving process, the particles formed several arch structures near the coal-caving mouth, and the coal-caving process was suspended. Second, the increase of the coal seam thickness in the vertical direction makes the release body grow along the long axis direction and the amount of coal that can be released also increases.

From the simulation results, it can be seen that the change in mining and caving ratio has no obvious effect on the application effect of the vibration identification method. With the increase in mining and caving ratio, the time interval from the first time the gangue particles leave the coal opening to contact with the tail beam gradually increases, so the number of gangue particles released gradually increases, but the number of coal particles released also increases at the same time, so the overall gangue content can be controlled.
within the scope of meeting the production requirements, and the effect of vibration identification method is better.

4.3. The Influence of Pitching Angle of Mining Field. In some areas, due to the complex geological conditions, coal seam inclination is often encountered in the process of advancing the coal mining face. In this case, it is necessary to combine the method of upward mining and downward mining to complete the mining work. The influence of upward mining and downward mining on top coal-caving law is different. In this section, the discrete element numerical models at different angles are established to analyze the influence of the angle of upward and downward mining on the identification effect of the vibration-based coal gangue identification method.

Figure 25 shows the numerical models of the coal drawing process at different angles established in this section. $\alpha = -20^\circ, -10^\circ, 0^\circ, 10^\circ,$ and $20^\circ$. $\alpha$ are the angles between the ground and the forward direction, which stipulates that the upward mining is positive and the downward mining is negative.

Figure 26 shows the coal-caving process under the conditions of $-20^\circ$ and $-10^\circ$. Different from the horizontal mining, under the action of gravity, the lower part of the coal gangue boundary moves significantly faster to the coal opening. When the angle is $-10^\circ$, the first time of the gangue discharge is 7.2 s, and when the angle is $-20^\circ$, this time was advanced to 6 s. In contrast, in downward mining, the first time the gangue particles discharge from the coal-caving mouth under the horizontal mining with the same coal gangue interface is 11.7 s. It can be seen that the time of gangue discharge is greatly advanced under the condition of downward mining, and the larger the angle is, the earlier the time is. When the gangue is released, there is still a large number of coal particles at the top of the coal opening, which will keep the gangue particles from contacting the tail beam. When the gangue particles located at the top of the coal gangue boundary in the initial state start to contact with the tail beam, the gangue located at the top of the coal gangue boundary will also be released in large quantities. In the case of $-20^\circ$, the contact time between the gangue and the tail beam is 13.7 s, and the gangue content of the released coal gangue particles is 33.3%. When the angle is $-10^\circ$, the contact time between the gangue and the tail beam is 11.6 s, and the gangue content is 13.3%. By contrast, when $\alpha = 0$, the contact time between the gangue and tail beam is 12.5 s, and the gangue content is 1.9%. Therefore, when the working face is undermined, the signal will lag behind the change of gangue content.

The caving process is shown in Figure 27 when the upward mining angles are $10^\circ$ and $20^\circ$, respectively. Unlike
Figure 24: The coal-caving process when the mining and caving ratio is 1:2.67.

Figure 25: State before coal caving at different pitching angles.
the downward mining, the bottom of the coal gangue interface moves toward the hydraulic support very slowly, and the particles far from the side of the hydraulic support near the coal opening flow out slowly under the action of mutual extrusion between the particles. The flow velocity of the coal particles above the shield beam and the tail beam became faster, and the gangue particles above quickly cut down with the flow of coal particles and begin to have contact with the tail beam, resulting in some coal particles that originally existed at the bottom to be trapped and these cannot be released in time. When the angle is 10°, the time at which the gangue particles arrive at the coal opening is 11.3 s, and the time of gangue particles contacting the tail beam is 12 s. At this time, the gangue content of the coal gangue particles is 3.9%. When the angle is 20°, the time at which the gangue particles arrive at the coal opening is 9.1 s, and the time of gangue particles contacting with the tail beam is 9.2 s. At this time, the gangue content of the coal gangue particles is negligible. It can be seen from the coal-caving process of upward mining that the time interval between the gangue particles arriving at the coal opening and the gangue particles’ contacting the tail beam is very short, and the larger the elevation angle is, the shorter the time interval is. The larger the elevation angle is, the earlier the gangue is discharged, and more coal is wasted due to the accumulation at the bottom.

In summary, the effect of the vibration identification method is not as good as that of horizontal mining in both upward and downward mining. The change of vibration signal in downward mining lags behind the change of gangue content, which is not suitable for the application. If at the cost of sacrificing part of the coal at the bottom not to be released, when the vibration identification method is used in the upward mining, the vibration signal will change in time.
with the release of gangue, and the gangue content in the released gangue particles will be very low.

5. Conclusions

In this article, the discrete element and finite element coupling method is used to study the process of coal caving by monitoring the vibration signal of the tail beam to determine whether there are gangue particles released from the coal opening. After verifying the feasibility of the method, the influence of coal-caving step distance, mining and caving ratio, and pitching angle of the mining field on the recognition effect is studied.

(1) In the process of coal caving, when the gangue contacts with the tail beam, the time-domain characteristics of the acceleration signal on the tail beam and some characteristics of the IMF component after EMD will be significantly higher than those in the pure coal-caving stage, indicating that the acceleration signal can be used as a basis for judging whether the gangue particles will be released.

(2) The coal-caving step distance has an important influence on the recognition effect. When the coal-caving step distance is small, the gangue particles will be released in advance from the side away from the hydraulic support of the coal opening, resulting in a large number of gangue particles being released when the gangue particles from the top contact with the tail beam, and the gangue content is unacceptable. When the coal-caving step is large, although when the gangue particles contact the tail beam, the gangue content in the released particles is qualified, some coal particles at the bottom will pile up and cannot be released, resulting in coal waste.

(3) The application effect of the vibration identification method in different mining and caving ratios is ideal. With the thickness of the coal seam, the time from the gangue particles arrival at the coal opening to the gangue particles’ contact with the tail beam increases gradually, and the discharge of the gangue also increases. However, because the number of coal particles also increases at the same time, the gangue content is always maintained in an acceptable range.

(4) The caving process of upward mining and downward mining is obviously affected by gravity. In the case of upward mining, the time from the gangue particles’ arrival at the coal opening to the gangue particles’ contact with the tail beam is very short. The application of the vibration identification method has a good effect, which can ensure that the mined coal has a low gangue content, but it will cause the coal particles at the bottom to be difficult to be discharged leading to wastage. Downward mining will greatly advance the time of gangue being released, and the top coal will continue to hinder the contact between gangue particles and the tail beam, resulting in the change of signal lagging behind the change of gangue content. The effect of the vibration identification method is not good.

The conclusions of the article can provide a certain reference for the popularization and application of the vibration-based coal gangue identification method.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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