Research Article

Statistical Characterization of Damage of Different Surface P-Wave Velocity Sets under Dynamic Load and Study on Overall Radon Detection Consistency

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On the basis of reviewing the existing research status of cumulative damage of the rock mass and summarizing the existing engineering application fields of radon, this paper attempts to apply radon detection technology to the research field of rock damage mechanics so as to monitor the evolution process of cumulative damage of the rock mass. Based on the above research purposes, a test device for detecting cumulative damage of radioactive rocks by surface radon gas was designed, and the test results were obtained by integrating the system to implement the test scheme. Due to the limitation of the nonmetallic ultrasonic detector, a single blasting damage value of 25 detection points appears after a single blasting measurement, which is a surface longitudinal wave velocity characterization damage set, while the surface radon exhalation rate in the subsequent analysis process is an overall characterization value; that is, the existence of damage directly affects the whole body radon exhalation rate of the test block, and the data dimensions of the two are different. In order to solve this problem, we try to introduce three data evaluation methods, the average weighting method, grey prediction method, and K-means clustering algorithm, and compare the feasibility of these three methods. It is proved that there is a certain linear relationship between the radon exhalation rate and the cumulative damage, which further verifies the feasibility of using radon to detect cumulative damage. The results show that the cumulative damage of loaded radioactive rock test blocks can be reflected by surface radon detection technology, and finally, the correlation between the cumulative damage characteristics and the continuous change of the body radon exhalation rate is obtained. Based on the correlation, the body radon exhalation rate is introduced into the field of fractured rock mass damage characterization, which is mutually improved with common monitoring methods such as acoustic emission and microseismic monitoring, supplementing and enriching the means of rock mass damage evolution characterization, providing a theoretical basis for finely describing the whole process of fracture closure and initiation, and finally accurately ensuring the stability of surrounding rock under the action of deep underground engineering excavation disturbance.

1. Introduction

In underground engineering construction projects, such as mining of mineral resources, tunnel excavation, and utilization of underground spatial structure, the mining disturbance process will cause the stress and other environments of the underground fractured rock mass to change continuously, which will inevitably cause the deterioration of surrounding
rock mass, further affect the stability of surrounding rock mass, and seriously affect the surface and destroy the ecological environment [1–3]. With the increasing number of deep underground engineering projects, its special occurrence environment (such as high geostress, high ground temperature, high well depth, high osmotic pressure, strong compression, strong mining, and strong aging characteristics) not only deteriorates the surrounding rock but also aggravates the appearance of dynamic disasters, which restricts the construction of underground engineering to a great extent [4, 5].

The deterioration of surrounding rock is manifested in the initiation and expansion of cracks in natural defective rocks and then increases the original crack structure. In view of the above problems, it is urgent to carry out targeted measures to prevent the damaged area of surrounding rock from further increasing. In addition, in the specific engineering background, such as uranium mining, oil mining, and geothermal mining, it is necessary to further expand the deterioration area of surrounding rock, and it is often necessary to use hydraulic fracturing or blasting to increase cracks in natural defective rocks to achieve practical purposes [6–8]. Therefore, the study of surrounding rock control is extremely important to ensure the stability of deep underground engineering, which is embodied in the real-time characterization and inversion technology of the whole process of rock mass damage evolution to achieve the purpose of surrounding rock control [9–12].

Through literature retrieval [13, 14], scholars at home and abroad have explored the characterization methods of cracks in the whole process of damage evolution of different rock masses as comprehensively as possible. The specific monitoring methods include microseismic monitoring technology, acoustic emission monitoring technology, ultrasonic monitoring technology, electromagnetic radiation monitoring technology, CT inversion technology, digital speckle monitoring technology, and thermal infrared monitoring technology. The above monitoring conclusions are often based on qualitative or semiquantitative parameters, and the monitoring data still need reliable identification and analysis by observers [15]. At present, some scholars have introduced the radon measurement method into the field of coal mine detection. A large number of studies have shown that radon migration behavior in the emanative medium is an aging process related to internal and external factors such as temperature, pressure, water content, porosity, and permeability [16, 17]. Scholars at home and abroad have analyzed the above factors in detail and have made a good promotion in the identification of spontaneous combustion areas in coal mines. However, there is no monitoring method based on radon indicators in the characterization of damage evolution of loaded rocks [18].

Considering that damage evolution is closely related to dynamic load and the research on the blasting mechanism is mature recently, the periodic blasting method can not only break adjacent rock but also cause continuous damage to reserved rock mass, and its blasting damage crack evolution law has been systematically studied. Therefore, with the help of cyclic blasting load, this paper attempts to monitor the dynamic process of rock damage evolution by using the abnormal index of the radon exhalation rate so as to construct a new quantitative damage analysis method of the radon exhalation rate and provide a theoretical basis for the subsequent evaluation of surrounding rock stability.

2. Theoretical Basis

Because radon is radioactive, it can be detected even if its concentration is small. At the same time, it has the geophysical and chemical properties of inert gas; basically, it can be transported and accumulated in micropores or microcracks, so it is widely used in the field of detection [19–21].

2.1. Radon Characteristics. Radon (Rn) is a chemical element, which often exists in the form of radon. Radon is the only radioactive inert gas that human beings come into contact with. Under normal conditions, radon is colorless and odorless, is soluble in water, has a half-life of 3.82 days, and has strong migration ability.

2.2. Application Category at Present. In the field of engineering geology, the radioactive radon survey has been widely used in geological prospecting and geological mapping, as well as in detecting hidden structures, finding bedrock groundwater and geothermal areas, and predicting earthquakes and volcanic eruptions. In the field of coal mine safety, radioactive radon gas has been widely used in the fire source location of coal seam spontaneous combustion areas. What is more, in the field of comprehensive detection, radioactive radon gas has been widely used in surface detection of overlying stratum mining fractures and their water content [22, 23].

2.3. Technological Base. Through a literature search, it is found that up to now, there has not been any relevant research on detecting the dynamic expansion and cumulative damage of radioactive rock fissures under cyclic blasting load. Therefore, the research group has carried out relevant pioneering basic research and exploration, mainly based on the following three principles:

(1) Under normal temperature and pressure, radon gas can escape from radioactive rock and migrate through the original microcracks and damaged areas in the rock mass

(2) The destruction and damage evolution of radioactive rock can obviously increase the migration speed and distance of radioactive radon, and the radon concentration is different with different damage degree measurements

(3) Through surface detection of the variation law of the radioactive radon exhalation rate of radioactive rock under cyclic blasting dynamic load, the damage law of radioactive rock under cyclic blasting load can be reversed
3. Test Scheme Design

The sustained periodic blasting action (cyclic blasting load) changed the original stress conditions in the rock mass, stimulated the penetration and development of cracks in the rock mass, and caused the cumulative damage of the rock mass, which easily increased the generation of radioactive radon gas, and this provided a theoretical basis for detecting the cumulative damage by radioactive radon gas.

3.1. Scheme Feasibility. Through a literature search, it is found that radon detection in the small-scale environment has made important achievements, and some scholars have made beneficial attempts in the field environment. In the indoor medium-scale environment, considering that the size of the research object exceeds the diffusion length of radon, the long-distance migration mechanism of radon is demonstrated, and the radon precipitation law in the process of damage evolution is studied, which provides a theoretical basis for further popularization and application in the large-scale field.

Because the sample size conceived is the mesoscale, and the indoor sample size responding to the requirements is relatively large, and it is bound to limit the disturbance device applied to it, considering the feasibility of simple replication of indoor blasting. In addition, in order to fully describe the whole process of damage evolution and avoid the direct damage of the sample, the sample is dynamically disturbed by calculating the small dose charge. Therefore, applying continuous periodic blasting (cyclic blasting load) through the self-made indoor mesoscale test device changes the original stress conditions inside the rock mass, stimulates the penetration and development of cracks inside the rock mass, and leads to the cumulative damage of the rock mass, which can easily increase the generation of radioactive radon gas, and this also provides a theoretical basis for detecting cumulative damage by radioactive radon gas.

3.2. Self-Made Experimental Device. After repeated investigation and demonstration by the research group, the independently designed test device for detecting accumulated damage of radioactive rocks with surface radon gas is mainly composed of the three-dimensional similar simulation test device, cyclic blasting load application device, accumulated damage degree measurement device, and radioactive radon gas detection device, and the system design is carried out through three-dimensional mechanical design software SOLIDWORKS, and different functional systems are shown in Figures 1(a)-1(d). In addition, due to the low radioactivity level of natural rocks and the high radioactivity level of radioactive ores, both of them cannot be directly used in indoor detection tests. In order to visually depict the characteristics of the radon exhalation law in the whole process of damaged and evolved rocks, according to the similarity theory, the follow-up tests were completed by preparing radioactive rocks.

3.3. Test Flow Design. In this paper, a self-developed surface radon detection device for cumulative damage of radioactive rock was applied to the three-dimensional similar physical simulation test to study the correlation between the cumulative damage evolution of radioactive rock and the change of radioactive radon concentration under cyclic blasting load.

Specific implementation steps of the test process of the comprehensive test device are as follows:

1. Obtaining prototype parameters involving physical, mechanical, and radioactive parameters of original rock
2. Selecting similar materials and determining the mixture ratio of various influencing parameters
3. Preparing radioactive rocks based on the above principles and conclusions
4. Carrying a comprehensive test system and carrying out installation and debugging
5. Carrying out blasting load, detecting the longitudinal wave velocity of each point, and converting it into the damage value of each point
6. Measuring radon in a closed way and detecting the radon exhalation rate on both exposed sides
7. Repeating step (5) until the test is completely damaged
8. Analyzing the relationship between the cumulative damage and the radon exhalation rate

Detailed implementation details are not repeated in this paper. In order to vividly represent the test process, the overall flow chart shown in Figure 2 is drawn.

4. Acquisition of Test Data

Following the test steps of detecting blasting damage of radioactive rock by radon gas on the surface, this paper carries out cyclic blasting dynamic load, collects the ultrasonic longitudinal wave velocity values of all measuring points before and after a single blasting, calculates the damage value of each measuring point, and comprehensively analyzes the evolution law of blasting cumulative damage of radioactive rock. Because of the huge amount of data, all the data are not listed, but all the data can be found in the literature [24].

4.1. Damage Data Acquisition. Before and after a single blasting, there are 25 measuring points at the key points (the key points are selected based on the position of explosives and arranged at intervals of 4 cm in turn). The initial longitudinal wave velocity of the test block and the longitudinal wave velocity of the test block after a single blasting are measured by using a nonmetal ultrasonic detector, which is converted into the cumulative damage degree of a single blasting [14]. Formula (1) is as follows:

\[ S_n = 1 - \left( \frac{V_n}{V_0} \right)^2 \]
In formula (1), \( S_n \) is the cumulative damage degree of measuring points after multiple blasting; \( V_0 \) is the longitudinal wave velocity at the measuring point of the test block before blasting, \( \text{m} \cdot \text{s}^{-1} \); and \( V_n \) is the longitudinal wave velocity at the measuring point of the test block after the \( n \)th blasting, \( \text{m} \cdot \text{s}^{-1} \).

Relevant research conclusions show that when the velocity \( v \) of the longitudinal wave decreases by 10%, the damage factor \( d \) defined by the acoustic wave is equal to 0.19; that is, the characteristic damage is formed at this moment [25]. The final crack propagation state of the test object is shown in Figure 3.

4.2. Radon Data Acquisition. In order to effectively avoid the measurement error, it is proposed to adopt the closed cavity method, so the abovementioned self-made blasting container is used as the radioactive radon collection device, and considering that the upper surface is the blasting vulnerable surface (there will be some damage, and the increase of the surface area will lead to the distortion of radon emission), in order to analyze the penetration process of internal damage, after a single blasting, the relevant surface is wrapped with aluminum foil paper, and the symmetrical sides around it are exposed, and the RAD7 radon meter is used to measure the accumulated radon concentration before and after blasting, and the fitting inclined line \( K \) is directly obtained by using supporting software. Formula (2) is as follows:

\[
J_n = \frac{k_n \cdot V}{S}.
\]  

In formula (2), \( J_n \) is the radon exhalation rate of the test block after multiple blasting, \( \text{Bq} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \); \( k_n \) is the inclined line of accumulated radon concentration of multiple blasting blocks, \( \text{Bq} \cdot \text{m}^{-2} \cdot \text{s}^{-1} \); \( S \) is the exposed area of the test block, \( \text{m}^2 \); and \( V \) is the effective volume of the radioactive radon collection device except for the test block, \( \text{m}^3 \).

According to the principle of radon measurement by the closed chamber method, the abovementioned self-made blasting container is used as the radon collection device. After a single blasting load is applied, the broken objects in the internal test block and the fine sand as boundary conditions in the blasting process are cleaned. At the same time, considering that the upper surface where the blast hole is located is the blasting vulnerable surface (there will be some damage, and the increase of the surface area will lead to the distortion of radon emission), in order to analyze the internal damage evolution and the penetration process of macrocracks, aluminum foil paper is used to wrap the upper surface and bottom surface of the test block, and a set of symmetrical surfaces around the test block after a single
Blasting and only the other set of symmetrical surfaces are exposed. The accumulated radon concentration before and after a single blasting was measured by the RAD7 continuous radon measuring instrument. Before the measurement, it was necessary to purify the RAD7 continuous radon measuring instrument for 30 min to remove the residual radon content and reduce the humidity until the measured value of the internal radon concentration was close to the air background value. The fitting inclined line was directly obtained by using the supporting software CAPTURE, and the radon exhalation rate before and after cyclic blasting was calculated.

4.3. Inconsistent Analysis of Data Dimensions. Due to the limitation of the nonmetallic ultrasonic detector, a single blasting damage value of 25 detection points appears after a single blasting measurement, which is a surface longitudinal wave velocity characterization damage set, while the surface radon exhalation rate in the subsequent analysis process is an overall characterization value. Then, the existence of damage directly affects the overall surface radon exhalation rate of the test block, and the two data dimensions are different. How to establish the relationship between the damage value of multiple detection points and the radon exhalation rate of a single surface has become a difficult problem! In order to solve this problem, we try to introduce different data evaluation methods to reduce the dimension of damage data, which will be explained in detail later.

5. Analysis of Test Results

5.1. Regression Analysis of Cumulative Damage of Longitudinal Wave Velocity at Fixed Measuring Points. According to the related literature, the cumulative damage evolution curve of rock mass fatigue has three obvious stages and presents an inverted S shape. The following is regression fitting for cumulative damage caused by blasting, using the cubic polynomial and exponential fitting, and taking the better fitting result from each measuring point.

The cubic polynomial used is expressed as follows:

\[
D = A_0 + A_1n + A_2n^2 + A_3n^3. \quad (3)
\]

In formula (3), \(D\) is the blasting damage value of the test block; \(n\) is the blasting times; and \(A_0, A_1, A_2,\) and \(A_3\) are undetermined coefficients. See Table 1 for specific data.

The exponential expression used is as follows:

\[
D = A_0e^{A_1n}. \quad (4)
\]

In formula (4), \(D\) is the blasting damage value of the test block; \(n\) is the blasting times; and \(A_0\) and \(A_1\) are undetermined coefficients. See Table 2 for specific data.

The measuring points 3, 8, and 13 are in the same plane as the charge hole, and the shock wave at the measuring point 13 is the largest, so all the points around it present the “inverted S” law of the cubic polynomial, and the nonlinear characteristics are very obvious. The evolution curve is not a three-stage form of “inverted S” but a single steep increase form, so it has a good effect to fit it by the exponential formula. These blasting points are small in scale and far away from the blasting source, and the damage value of the rock mass has not reached the critical value of fracture
failure. The damage degree of the rock mass is low, and it is still in the stage of fatigue crack propagation, so it can be said that this stage is in the first half of the “inverted S” three-stage type, and its curve also has this effect, which is consistent with the actual situation [26].

5.2. Determination of the Symmetrical Distribution Law of Single Damage at Different Measuring Points. Due to limited space, this paper only shows the data distribution of the damage value at each measuring point after blasting once, as shown in Figure 4. In order to describe the damage distribution law more vividly, the distribution positions of ultrasonic wave velocity detection points on the surface of the test block are plotted, as shown in Figure 5.

Through Figures 4 and 5, an obvious rule can be found, which is described as follows:

(1) Based on the transverse observation angle, the damage values calculated by each measuring point are symmetrically arranged in the transverse angle relative to the measuring points in the third line.

(2) Based on the vertical observation angle, the damage values calculated by each measuring point are also symmetrically arranged in the vertical angle relative to the measuring points in the third line.

5.3. Analysis of the Cumulative Damage Evolution Law of the Single Measuring Point in the Whole Process. Based on the above analysis, this paper focuses on the analysis of the damage value change curve after the 13th full-process blasting in the third row, which is shown in Figure 6. It can be seen vividly that the single blasting has played a certain role in deteriorating radioactive rocks. In addition, in order to further analyze the cumulative damage evolution law of the whole process, the cumulative damage evolution law of each

Table 1: Cubic regression fitting coefficient.

| Measuring point number | \(A_0\)   | \(A_1\)   | \(A_2\)   | \(A_3\)   | \(R^2\) |
|------------------------|----------|----------|----------|----------|--------|
| 4                      | 0.0061   | -0.0027  | 0.0003   | 0.00002  | 0.9576 |
| 6                      | -0.0007  | 0.0127   | -0.0012  | 0.00005  | 0.9891 |
| 7                      | 0.0021   | 0.014    | -0.0016  | 0.00007  | 0.9687 |
| 8                      | 0.0102   | 0.0113   | -0.0013  | 0.00006  | 0.9817 |
| 9                      | 0.0041   | 0.015    | -0.0018  | 0.00008  | 0.9616 |
| 10                     | -0.0058  | 0.021    | -0.0027  | 0.0001   | 0.9756 |
| 11                     | -0.0009  | 0.0176   | -0.0023  | 0.0001   | 0.9719 |
| 12                     | -0.0078  | 0.0187   | -0.0023  | 0.0001   | 0.9657 |
| 13                     | 0.0218   | 0.0096   | -0.0013  | 0.00007  | 0.9358 |
| 14                     | -0.0047  | 0.017    | -0.0019  | 0.00008  | 0.9847 |
| 15                     | -0.0045  | 0.015    | -0.0016  | 0.00007  | 0.9634 |
| 17                     | 0.0035   | 0.0153   | -0.0017  | 0.00007  | 0.982  |
| 18                     | 0.021    | 0.009    | -0.0009  | 0.00004  | 0.958  |
| 19                     | 0.0126   | 0.0112   | -0.0013  | 0.00006  | 0.9822 |
| 20                     | 0.0104   | 0.011    | -0.0015  | 0.00007  | 0.9418 |

Table 2: Exponential regression fitting coefficient.

| Measuring point number | \(A_0\)   | \(A_1\)   | \(R^2\) |
|------------------------|----------|----------|--------|
| 1                      | 0.0017   | 0.2841   | 0.9467 |
| 2                      | 0.0021   | 0.2534   | 0.9528 |
| 3                      | 0.0178   | 0.0925   | 0.9325 |
| 5                      | 0.0006   | 0.3657   | 0.9572 |
| 16                     | 0.005    | 0.1879   | 0.9583 |
| 21                     | 0.0011   | 0.3141   | 0.9643 |
| 22                     | 0.0005   | 0.3606   | 0.9777 |
| 23                     | 0.0004   | 0.3678   | 0.9628 |
| 24                     | 0.0006   | 0.3254   | 0.961  |

Figure 4: Damage value of each measuring point in the first blasting. (a) Different columns. (b) Different lines.
measuring point in line 3 with blasting times is still selected, as shown in Figure 7 [27].

6. Statistical Characterization of Damage of Different Surface P-Wave Velocity Sets

6.1. Data Processing Based on the Average Weighting Method

6.1.1. Brief Introduction of the Method. The weighted average method is the basic method of the comprehensive index, which has two forms: addition rule and multiplication rule.

6.1.2. Analysis of Advantages and Disadvantages. Its advantages are simple calculation and convenient processing. The disadvantage is that the error is large and the persuasion is small.

6.1.3. Process Description. The average value of blasting cumulative damage at 25 measuring points is calculated and normalized as the weight, and the total cumulative damage value of the test block after each blasting can be obtained by multiplying the cumulative damage at each point after each blasting by the weight. The results are shown in Table 3.

Through Figures 6 and 7, an obvious rule can be found, which is described as follows:

(1) The application of blasting dynamic load will easily cause unrecoverable disturbance to radioactive rock in a way similar to the spherical wave, resulting in the damage deterioration effect. The greater the damage near the third row and the third column
(blast hole position), the smaller the damage at other positions along with the distance.

(2) In a certain area, the boundary with the same distance appears to have a relatively consistent damage value, which can further verify the symmetrical distribution characteristics of blasting damage.

(3) The evolution process of cumulative damage caused by blasting dynamic load is an obvious three stages. The concrete analysis is that in the initial stage of blasting, the rock mass near the blast hole is directly disturbed, and the damage increases slowly. In the middle stage of blasting, the disturbance area expands, but the same explosive blasting dynamic load is equivalent to equal amplitude loading and unloading, which promotes the damage to fluctuate in a small range. In the later stage of blasting, the damage increases rapidly until the rock mass breaks rapidly.

In order to demonstrate the correlation between the cumulative damage and the radon exhalation rate obtained by the average weighting method, firstly, the graphs between the total cumulative damage and radon exhalation rate of the test block and the blasting times are drawn, as shown in Figure 8.

According to the above chart, with the help of the average weighting algorithm, there are certainly multiple relationships between the radon exhalation rate and the cumulative damage of the rock mass, and the test error value is close to 1, which shows that it is very consistent with this function curve.

6.2. Data Processing Based on the Grey Prediction Model

6.2.1. Brief Introduction of the Method. Grey prediction is a prediction made by the grey system. It is a method to predict the system with uncertain factors. Grey prediction can identify the differences of development trends among system factors, that is, carry out correlation analysis, generate and process the original data to find the laws of system changes, generate data sequences with strong regularity, and then establish corresponding differential equation models to predict the future development trends of things. It uses a series of quantitative values observed at equal time intervals to construct a grey prediction model and predicts the characteristic quantity at a certain time in the future or the time to reach a certain characteristic quantity. The grey prediction model is characterized by using grey mathematics to deal with uncertainties, which can quantify indicators, can make full use of known information to seek system rules, and can also deal with a small amount of data.

6.2.2. Analysis of Advantages and Disadvantages. The advantage is that it does not need a lot of data, but only a few groups of data can solve the problems of less historical data and low integrity and reliability of sequence. With convenient operation and high modeling accuracy, it is an effective tool to deal with small sample prediction problems. The disadvantage is that it is only suitable for short- and medium-term forecasting and exponential growth forecasting. Without considering the internal mechanism of the system, sometimes there will be big mistakes.

6.2.3. Process Description. By establishing the GM(1, 1) grey prediction model, the cumulative damage of each point is calculated, and then the sensitivity of the given 25 measuring points to the radon exhalation rate of the test block is determined by comparing the posterior difference ratio C.

Step 1. Establish the time series of the accumulated damage value of each measuring point as follows:

$$x^{(0)}(n) = \left(x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(n)\right).$$  (5)
Step 2. Accumulate the original data \(x^{(0)}\) once to get
\[
x^{(1)} = \left( x^{(1)}(1), x^{(1)}(2), \ldots, x^{(1)}(n) \right),
\]
\[
x^{(1)}(k + 1) = x^{(0)}(k + 1) + x^{(1)}(k).
\]

Step 3. A data matrix \(B\) and a data vector \(Y\) are constructed by
\[
B = \begin{bmatrix}
-\frac{1}{2} (x^{(1)}(1) + x^{(1)}(2)) & 1 \\
-\frac{1}{2} (x^{(1)}(2) + x^{(1)}(3)) & 1 \\
\vdots & \vdots \\
-\frac{1}{2} (x^{(1)}(n - 1) + x^{(1)}(n)) & 1
\end{bmatrix}
\]
\[
Y = \begin{bmatrix}
x^{(0)}(2) \\
x^{(0)}(3) \\
\vdots \\
x^{(0)}(1)
\end{bmatrix}
\]

Step 4. Calculate
\[
\bar{u} = \begin{bmatrix} \bar{a} \\ \bar{b} \end{bmatrix} = (B^T B)^{-1} B^T Y.
\]

Step 5. Establish the GM(1,1) grey forecasting model:
\[
\frac{dx^{(1)}}{dt} + \bar{a}x^{(1)} = \bar{b}.
\]

To solve, get
\[
\tilde{x}^{(1)}(k + 1) = \left( x^{(0)}(1) - \frac{\bar{b}}{\bar{a}} \right) e^{-\bar{a}k} + \frac{\bar{b}}{\bar{a}}.
\]

Step 6. According to the sequence prediction value \(\tilde{x}^{(1)}(k + 1)\), calculate the model reduction value \(\tilde{x}^{(0)}(k + 1)\):
\[
\tilde{x}^{(0)}(k) = \tilde{x}^{(1)}(k + 1) - \tilde{x}^{(1)}(k)
\]

Step 7. Calculate the following:

1. Residual value
\[
\varepsilon(k) = \left| \tilde{x}^{(0)}(k) - \tilde{x}^{(0)}(k) \right|.
\]

2. Residual variance
\[
S_2^2 = \frac{1}{n} \sum_{k=1}^{n} [\varepsilon(k) - \bar{\varepsilon}]^2.
\]

(3) Sequence variance
\[
S_1^2 = \frac{1}{n} \sum_{k=1}^{n} \left[ x^{(0)}(k) - \bar{x} \right]^2.
\]

(4) Posterior difference ratio
\[
C = \frac{S_1}{S_2}.
\]

Residual variance \(S_1\) indicates the discreteness of the prediction error, and sequence variance \(S_2\) indicates the discreteness of the cumulative damage at each point. Because the posterior difference ratio \(C\) reflects the degree of catastrophe of accumulated damage at each point to a certain extent and the occurrence of catastrophe often has a great relationship with the change of radon concentration, the sensitivity of each point to radon precipitation can be investigated by comparing the posterior difference of each index. The larger the posterior difference ratio \(C\) is, the greater the possibility of catastrophe is, and in this model, the more sensitive the measured point is to radon precipitation.

After preprocessing the data, the cumulative damage values of 25 measuring points after blasting 13 times were selected for analysis. Using MATLAB to calculate the posterior difference ratio of accumulated damage at each point, the sensitivity order of accumulated damage at each point to the radon exhalation rate can be obtained. Select the most sensitive value as the cumulative damage value. The results are shown in Table 4.

In order to demonstrate the correlation between the comprehensive cumulative damage and the radon exhalation rate, firstly, the curves between the total cumulative damage and radon exhalation rate of the test block and the blasting times are drawn, as shown in Figure 9.

According to the above chart, with the help of the grey prediction method, it can be seen that the relationship between the radon exhalation rate and the cumulative damage of the rock mass is very insignificant, and the correlation between them is poor. Therefore, the grey prediction method is not applicable to the above analysis method.

6.3. Data Processing Based on the K-Means Clustering Algorithm

6.3.1. Brief Introduction of the Method. The K-means clustering algorithm takes a certain distance from the data object to the prototype as the objective function and obtains the adjustment rules of iterative operation by using the method of the function extremum. In the beginning, \(K\) initial centers are selected, and the data object is updated to the cluster closest to the center. Update the center value of the class cluster by the iterative method until the objective function converges or reaches a certain condition.
6.3.3. Process Description. The K-means clustering algorithm firstly randomly selects $K$ objects as initial clustering centers. Then, the distance between each object and each seed cluster center is calculated, and each object is assigned to the nearest cluster center. The cluster centers and the objects assigned to them represent a cluster. Once all the objects are assigned, the cluster center of each cluster will be recalculated according to the existing objects in the cluster. This process will be repeated until a certain termination condition is met. The termination condition can be that no (or a minimum number of) objects are reassigned to different clusters, no (or a minimum number of) cluster centers change again, and the sum of squares of errors is locally minimum. Through the K-means clustering analysis algorithm and MATLAB, the total cumulative damage value of the test block after each blasting is calculated. The results are shown in Table 5.

In order to demonstrate the correlation between the total cumulative damage and the radon exhalation rate, firstly, the curves between the total cumulative damage and radon exhalation rate of the test block and the blasting times are drawn, as shown in Figure 10.

According to the above chart, with the help of the $K$-means clustering algorithm, there are certainly multiple relationships between the radon exhalation rate and the cumulative damage of the rock mass, and the test error value is also close to 1, which shows that it is also very consistent with this function curve.

6.4. Difference Analysis of Damage Statistical Characterization of Different Surface P-Wave Velocity Sets. In order to compare the difference of statistical characterization of surface longitudinal wave velocity set damage, based on three different theories and taking the surface longitudinal wave velocity set as the basic value, the total cumulative damage and radon exhalation rate obtained by different algorithms under cyclic blasting dynamic load were obtained. In order to demonstrate the correlation between the total cumulative damage and the radon exhalation rate, a graph between the total cumulative damage and the radon exhalation rate is drawn, as shown in Figure 11.

According to the above chart, it can be seen that the cumulative damage obtained by the average weighting method and K-means clustering analysis algorithm meets the linear relationship, while the cumulative damage data obtained by the grey prediction method fluctuates, which obviously does not meet the conditions. Based on the above analysis, there is a certain linear relationship between the radon exhalation rate and the cumulative damage of the rock mass, which provides a theoretical basis for the subsequent presentation of the characterization index of the radon exhalation rate. In addition, there are still large errors in the radon survey process and the related mechanism between them is not clear, which requires specific analysis and in-depth study. In the relatively small range of cumulative damage (the initial stage of blasting), the damage of uranium rock caused by the blasting stress wave increases in a small range, from scratch, forming microcracks, which leads to a weak correlation between the radon exhalation rate and the comprehensive cumulative damage. In the middle stage of blasting, the cyclic blasting load changes the radon exhalation rate and comprehensive cumulative damage in a stable range, and the correlation between them is more obvious at this stage. At the end of blasting, until the uranium rock is completely damaged by blasting, it is also a process in which the cumulative damage increases sharply again, resulting in a poor correlation between them.

7. Application of the Radon Exhalation Rate Index

7.1. Determination of the Damage Index for Predicting the Radon Exhalation Rate in the Body. According to the experimental results, there is a positive correlation between the damage evolution of radioactive rock and the law of radon exhalation under cyclic blasting load, and through this
In the experiment, a large number of basic experimental data are obtained, and the correlation between the damage degree of radioactive rock and the radon exhalation rate is obtained. Therefore, based on the above experimental analysis results, this paper tries to put forward a prediction index \( K \) for describing the change of the radon exhalation rate in the process of damage evolution of radioactive rock under cyclic blasting load, and the expression of \( K \) is defined as follows:

\[
K = \frac{E - E_0}{E_0} \times 100\%	ag{17}
\]

In formula (17), \( K \) is the prediction index; \( E \) is the measured value of the radon exhalation rate; and \( E_0 \) is the initial value of the radon exhalation rate.

It can be seen from the formula that the larger the measured radon exhalation rate is, the larger the prediction index \( K \) is, which indicates that the damage evolution degree of radioactive rock under cyclic blasting load is greater. In this paper, it is assumed that the interference of other external factors affecting radon exhalation is excluded, and the prediction index \( K \) is used as a new index to judge the damage degree of radioactive rock under cyclic blasting load. Combined with a large number of experimental results in this paper and the relationship between the overall damage degree and the radon exhalation rate, it is preliminarily determined that when \( K \) is greater than 9.8\%, the rock mass reaches the damage limit position, and it can also be judged that the rock mass has a deterioration effect or even macrocracks. The specific verification work needs further study.

### 7.2. Application of the Radon Exhalation Rate in the Body

The existing damage characterization methods of the fractured rock mass often adopt several commonly used monitoring methods, such as acoustic emission, microseismic, and electromagnetic radiation monitoring, which often invert the damage evolution of the fractured rock mass by arranging sensors on the surface of monitored objects and picking up the changes of sensitive physical parameters during the process of fracture closure or expansion in the rock mass and make precursory discrimination on its strength failure characteristic value, but the monitoring results often cannot reflect the overall damage characteristics, as it is easy to cause discrimination failure and so on. In addition, thermal infrared monitoring and digital speckle technology are also applied to the field of fractured rock mass damage characterization. However, because they pay more attention to the surface of the object to be measured and the evolution process of rock mass damage is an internal and external process, the above monitoring will inevitably lead to a certain lag, so different monitoring and characterization methods have certain limitations. Considering the particularity and

| Blasting times | Body radon exhalation rate (Bq m\(^{-2}\) s\(^{-1}\)) | Total cumulative damage |
|----------------|---------------------------------|------------------------|
| 1              | 3.34094                         | 0.012929               |
| 2              | 4.098606                        | 0.018915               |
| 3              | 4.246144                        | 0.025072               |
| 4              | 4.311575                        | 0.029278               |
| 5              | 4.480138                        | 0.032549               |
| 6              | 4.670269                        | 0.034240               |
| 7              | 4.808381                        | 0.036297               |
| 8              | 4.826869                        | 0.036075               |
| 9              | 4.833031                        | 0.039680               |
| 10             | 5.148588                        | 0.045486               |
| 11             | 5.205319                        | 0.052563               |
| 12             | 5.252081                        | 0.060617               |
| 13             | 6.503975                        | 0.066294               |
complexity of the whole process of damage evolution of the fractured rock mass, its rock mass damage characterization means cannot be accurately obtained by a single method. Considering the strong fluidity and high sensitivity of radon gas in natural fractured media and the high consistency between the volume radon exhalation rate and the total cumulative damage, the volume radon exhalation rate is introduced into the field of damage characterization of the fractured rock mass, which is mutually improved with common monitoring methods such as acoustic emission and microseismic monitoring, supplementing and enriching the rock mass damage evolution characterization means and providing a theoretical basis for fine characterization of the whole process of fracture closure and initiation.

8. Conclusions

(1) Based on the similarity theory, the medium-scale radioactive rock was prepared, and the cyclic blasting load caused disturbance to it. With the help of

![Figure 10: Data processing based on the K-means clustering algorithm.](image1)

![Figure 11: Difference in statistical characterization of damage of different surface P-wave velocity sets.](image2)

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the nonmetallic ultrasonic detector, the longitudinal wave velocities of 25 detection points after multiple blasting were, respectively, detected, and a surface longitudinal wave velocity characterization damage set was obtained, while the surface radon exhalation rate in the subsequent analysis process was an overall characterization value, comparing the data analysis in the difference of the existence of damage that directly affected the overall surface radon exhalation rate of the test block, and the two data dimensions were different. By trying to introduce different data evaluation methods, the dimension of damage data is reduced, and the feasibility of different data evaluation methods is comprehensively compared.

(2) By comparing the damage evolution law of radioactive rock under cyclic blasting load, it is concluded that the damage of radioactive rock increases in a small range at the initial stage of blasting, which leads to a weak correlation between the radon exhalation rate and the comprehensive cumulative damage. In the middle stage of blasting, the radon exhalation rate caused by cyclic blasting load changes in a stable range, and the correlation is more obvious. At the end of blasting, the cumulative damage increased sharply again, resulting in a poor correlation between them.

(3) Try to introduce the radon survey method into the field of cumulative damage detection of radioactive rock under cyclic blasting load and innovate a simpler, easier, faster, and more reliable detection method. At the same time, considering the strong fluidity and high sensitivity of radon in natural fractured media and the high consistency between the volume radon exhalation rate and the total cumulative damage, the volume radon exhalation rate was introduced into the field of fractured rock mass damage characterization, which was mutually improved with common monitoring methods such as acoustic emission and microseismic monitoring, which supplemented and enriched the means of rock mass damage evolution characterization, provided a theoretical basis for finely describing the whole process of fracture closure and initiation, and finally accurately ensured the stability of surrounding rock under the excavation disturbance of deep underground engineering.

**Data Availability**

All data included in this study are available upon request by contact with the corresponding author.

**Conflicts of Interest**

The authors declared that they have no conflicts of interest in this work.

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**References**

[1] H. Xie, J. W. Zhao, H. W. Zhou, S. H. Ren, and R. X. Zhang, “Secondary utilizations and perspectives of mined underground space,” *Tunnelling and Underground Space Technology*, vol. 96, pp. 103129–103129, 2020.

[2] Y. Zhao, C. L. Wang, and J. Bi, “Analysis of fractured rock permeability evolution under unloading conditions by the model of elastoplastic contact between rough surfaces,” *Rock Mechanics and Rock Engineering*, vol. 12, pp. 5795–5808, 2020.

[3] Y. Zhao, C. L. Wang, M. Teng, and J. Bi, “Observation on microstructure and shear behavior of mortar due to thermal shock,” *Cement and Concrete Composites*, vol. 121, pp. 104–106, 2021.

[4] 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.

[5] 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.

[6] 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.

[7] 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.

[8] 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.

[9] P. Jia, M. Ming, C. Cao, L. S. Cheng, H. F. Yin, and Z. Li, “Capturing dynamic behavior of propped and unpropped 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, p. 109412, 2022.

[10] H. Wu, D. Ma, A. J. S. Spearing, 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.
[11] L. H. Tan, T. Ren, L. M. Dou, X. Yang, M. Qiao, and H. Peng, "Analytical stress solution and mechanical properties for rock mass containing a hole with complex shape," Theoretical and Applied Fracture Mechanics, vol. 114, p. 103002, 2021.

[12] L. H. Tan, T. Ren, L. M. Dou, X. Cai, X. Yang, and Q. 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.

[13] J. R. J. Davidson, J. Fairley, A. Nicol, D. Gravley, and U. Ring, "The origin of radon anomalies along normal faults in an active rift and geothermal area," Geosphere, vol. 12, no. 5, pp. 1656–1669, 2016.

[14] J. W. Feng, J. X. Qu, P. F. Zhang, and F. Qin, "Development characteristics and quantitative prediction of multiperiod fractures in superdeep thrust-fold belt," Lithosphere, vol. 2021, no. 1, article 8895823, 2021.

[15] Y. Zhou, X. Yu, Z. Q. Guo et al., "On acoustic emission characteristics, initiation crack intensity, and damage evolution of cement-paste backfill under uniaxial compression," Construction and Building Materials, vol. 269, article 121261, 2021.

[16] H. P. Song, H. Zhang, D. H. Fu, and Q. Zhang, "Experimental analysis and characterization of damage evolution in rock under cyclic loading," International Journal of Rock Mechanics & Mining Sciences, vol. 88, pp. 157–164, 2016.

[17] W. Zhang, D. S. Zhang, L. Ma, X. Wang, G. Fan, and M. Xu, "Development of a comprehensive test system for detecting mining-induced fractures in overlying strata on surface with radon and its application - a case study of Ningdong mining area," Lithosphere, vol. 2021, no. Special 4, article 7657143, 2021.

[18] S. J. Wei, K. Li, Y. F. Wu, and H. H. Li, "A review of instability mechanism and control technology of roadway surrounding rock under rock burst condition," China Safety Science Journal, vol. 26, no. 9, pp. 90–95, 2016.

[19] D. S. Zhang, W. Zhang, L. Q. Ma, X. F. Wang, and G. W. Fan, "Developments and prospects of detecting mining-induced fractures in overlying strata by radon," Journal of China University of Mining and Technology, vol. 45, no. 6, pp. 1082–1097, 2016.

[20] F. L. Jiang, W. C. Yang, S. Zhang et al., "Experimental study on damage and radon precipitation law for quasi-uranium ore under cyclic blasting load," Mining and Metallurgical Engineering, vol. 39, no. 1, pp. 15–20, 2019.

[21] J. Du, J. Chen, Y. Pu, D. Jiang, L. Chen, and Y. Zhang, "Risk assessment of dynamic disasters in deep coal mines based on multi-source, multi-parameter indexes, and engineering application," Process Safety and Environment Protection, vol. 155, pp. 575–586, 2021.

[22] X. P. Lai, Y. B. Yang, and L. M. Zhang, "Research on structural evolution and microseismic response characteristics of overlying strata during repeated mining of steeply inclined and extra thick coal seams," Lithosphere, vol. 2021, no. Special 4, article 8047321, 2021.