Investigation of the fractal characteristics of cumulative damage to tunnel surrounding rock under blasting vibration

SONG Xiaolong1, GAO Wenxue1, JI Jinming1, YE Mingban1, ZHANG Dengjie1

1 College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, 100124, China
Corresponding author: wxgao@bjut.edu.cn, GAO Wenxue
First author: 443014081@qq.com, SONG Xiaolong

Abstract. In this work, the cumulative damage effect of tunneling and blasting on the rock surrounding a tunnel is studied. Ground penetrating radar (GPR) is used to detect the damage of tunnel surrounding rock during blasting, and EEMD–HHT transform is used to process the obtained radar signals to obtain an intuitive representation of the damage. The relative relationship between fractal dimension and degree of damage is established to analyze the damage evolution of the tunnel surrounding rock quantitatively. The results show that the instantaneous amplitude parameter obtained by the EEMD–HHT transform could reflect the damage characteristics of the original signal and analyze the characteristics of damage evolution quantitatively. The effect of cyclic blasting causes a great direct disturbance to the area near the blast source and generates new fissures, which could aggravate the damage. The impact of blasting on areas located far from the blast source is mostly manifested as the expansion and penetration of existing cracks. The fractal dimension of the damage area is closely related to the damage evolution of the rock mass; the greater the change in fractal dimension, the more intense the damage expansion and evolution. This study quantitatively analyzes changes in the damage of tunnel surrounding rock through fractal dimensions, enriches the theoretical system of damage evolution in rock masses, and explores a new strategy to study blasting disturbances in tunnel surrounding rock.

1. Introduction
Tunnel blasting and excavation inevitably cause damage to the surrounding rock. Evidence from engineering practice has well demonstrated that continuous blasting causes cumulative damage to the surrounding rock [1]. The effect of blasting vibration on the rock mass is accompanied by the whole construction process, and assessment of this damage is directly related to engineering safety. Complex fractures and broken areas promoting discontinuity and unevenness are widespread in the rock mass. During blasting excavation, rock masses containing cracks generate new cracks under the influence of blasting vibrations, and new cracks may appear at the tip of older cracks, thereby causing penetration. Crack propagation reduces the engineering strength of the rock mass and causes it to lose its stability until failure. Therefore, controlling damage and supporting the surrounding rock by monitoring changes in rock mass damage are important to ensure safety during tunnel excavation. Ground penetrating radar (GPR) is widely used as a damage detection technology on account of its non-destructiveness and high-efficiency. Li Shucal [2] and others proposed a comprehensive four-stage full-process tunnel forecasting system for the quantitative advanced forecasting of tunnels. Teng Junyang [3] used geological radar to conduct on-site monitoring of the excavation damage zone, compared the results of this technology with the simulation results of 3DEC, and found good agreement. Guo Liang [4] verified the feasibility of geological radar detection of the loose zone of the surrounding rock by combining theoretical calculations with on-site
monitoring and provided reliable support and reference data for tunnel excavation, support, and construction. Geological radar can effectively identify broken and cracked areas in the rock mass during the detection of the surrounding rock, but the damage method requires further qualitative analysis and, thus, cannot truly reflect the damage characteristics of the rock mass. Thus, developing new theories and methods to describe and analyze the complex energy dissipation process of rock mass damage quantitatively is necessary.

In this work, several field blasting tests were carried out to study the cumulative damage effect of the blasting effect on the surrounding rock of a tunnel. GPR detection was used to scan the surrounding rock of the tunnel before and after blasting excavation, and the radar signal was processed by EEMD–HHT transform to extract the first-order instantaneous amplitude component as a damage feature. The area–perimeter method was used to measure the fractal feature of the damage obtained, which could lead to the determination of the rules of cumulative damage evolution in the surrounding rock under cyclic blasting. Quantitative analysis of the cumulative damage of the surrounding rock was then performed. The results of this work enrich the theoretical system of blasting damage and could direct the design of tunnel blasting parameters to help protect the stability of the surrounding rock.

2. Damage detection and identification of surrounding rock

Widely distributed non-penetrating fractured rock masses are present in tunnel surrounding rock, which basically includes two types of initial damage: conventional cracks, also known as singular damage, and randomly distributed voids and micro-cracks in the rock mass, also known as distribution damage. Conventional cracks are larger than voids and micro-cracks and, thus, are the main macro damage of the rock mass. The initial damage inside the rock mass and the cumulative damage sustained after each blasting could be divided into these two types of damage. The essence of the damage evolution in surrounding rock is that the distributed damage developing into conventional cracks from micro to macro which is affected by the blasting load. Macro damage is the dominant factor in rock mass damage that directly affects the mechanical properties of the rock mass. Distributed damage expands and penetrates the rock mass under the influence of blasting seismic waves, thereby aggravating macro damage. It could be detected by GPR to identify the macro damage in the surrounding rock and study the corresponding evolution rules.

2.1. Ground penetrating radar detection

The damage area inside a rock mass generally appears as cracks and fracture zones, which form interfaces between different dielectric media. During the detection process, GPR emits a high-frequency electromagnetic wave into the rock mass. Electromagnetic waves are diffracted and reflected on the interface of these media and then received by the radar to form a radar signal. The waveform of the signals obtained by GPR is the convolution of the radar wavelet and reflection coefficient R, which is essentially affected by the relative dielectric constant of different media.

\[
R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}
\]

where \( \varepsilon_1 \) is the relative permittivity of the incident medium and \( \varepsilon_2 \) is the relative permittivity of the exit medium. This equation reveals that, when an electromagnetic wave enters a medium with a lower dielectric constant from a medium with a higher dielectric constant, the echo of the single-channel radar appears to be positive; otherwise the echo appears to be negative. The radar waveform can effectively reflect changes in the relative dielectric constant of the medium. Electromagnetic waves will experience air, rock, air, rock... and other medium areas with large differences in dielectric constant when there are crack areas in the rock mass, then the radar waveform will also violently oscillate which make it possible for identifying damage.

2.2. Damage detection tests of the surrounding rock

Several field blasting tests were conducted to explore the blasting damage effect of the surrounding rock in the tunnel, and GPR was used to detect the damage of the surrounding rock before and after blasting. The blasting test site is located in Yanqing District, Beijing, and belongs to the Beijing Winter Olympics
Snowmaking and Water Diversion System Project. The tunnel for blasting excavation is a spillway tunnel with an altitude of 1013.310 m, a total length of 113 m, a height of 6 m, and a width of 5 m. The full-section excavation method is adopted, the explosive load is 96 kg, the unit explosive consumption is 0.71 kg/m$^3$, and advance per round is about 2.5 m. A schematic of the GPR measurement diagram and blast hole are shown in Figs. 1 and 2, respectively. The detection area is divided into five subareas for fine analysis.

Figure 1. GPR measurement diagram.

Figure 2. Schematic diagram of a blast hole (unit: mm).

The GPR which model is LTD series could be used to detect the surrounding rock on the side wall during blasting excavation. The sampling frequency of the radar is 1024 MHz which equipped with a 400 MHz antenna, and the measurement method is measuring wheel. The effective measurement range of the radar under a central-frequency antenna is 40 m. In this research, the acquisition time window is set to 200 ns to ensure effective measurement within 10 m. GPR is used to scan the right wall before and after each blasting. Horizontal measurement is carried out during the detection process, and the measurement position is 1.5 m above the ground. The detection area starts 5 m from the tunnel face and approaches the tunnel entrance. The length of the measure line is 50 m; this line is divided into five areas numbered #1, #2, #3, #4, and #5 starting from the tunnel face and moving toward the tunnel entrance for accurate analysis. Figure 4 shows the original GPR signal obtained in the observation area. The original signal shows the strong reflections of electromagnetic waves. However, the figure also shows poor image recognition and serious interference. Thus, the original signal must be processed.

2.3. Ground penetrating radar data processing

Because of GPR uses a wideband receive method, the signal inevitably contains a large amount of clutter and interference. Post-processing of the initial signal is necessary [7] to obtain the true radar reflection characteristics of the rock mass. Figure 4 shows a large amount of clutter and poor contrast. Post-processing of GPR signals is carried out via two methods. One is to use its own software processing the signal, which includes background removal, deconvolution, gain control, Kirchhoff migration, and data filtering, among others. This method is easy to operate but the selection of parameters for signal processing
highly depends on the operator’s experience and low efficiency may be obtained when processing large amounts of data. Several scholars have attempted to use other mathematical calculation software programs to process and analyze the original GPR data via different data processing methods. In these works, wavelet analysis [8], HHT transform, and other signal analysis methods were employed to reduce interference. HHT transform is a highly adaptable time-frequency localization analytical method [9] with good effects on the processing and analysis of non-stationary signals with obvious mutations. HHT transform includes two components: EMD decomposition and Hilbert transform. Of these, EMD decomposition is the key component. The original signal could be decomposed into several groups of simple, uncorrelated, non-sinusoidal IMF components (i.e., intrinsic modal functions) through EMD decomposition and then gradually scaled according to the fluctuation degree for further analysis and research. However, EMD decomposition has a modal aliasing effect and the decomposition of signals containing singular events is poor; thus, its application in signal processing is limited. Researchers have found that adding small-amplitude white noise to the data could effectively prevent the diffusion of low-frequency mode components [10]. Huang proposed EEMD decomposition (i.e., overall evaluation empirical mode decomposition) on the basis of this concept. Modal aliasing and endpoint effects are alleviated, and the average values of the white noise sequences in the time domain cancel each other out, thereby obtaining the real component of the signal.

After EEMD decomposition, a series of IMF components are obtained, and each component is Hilbert-transformed to construct the analytical signal $z(t) \cdot H[c(t)]$ in Equation 2 shows the IMF component after Hilbert transformation.

$$z(t) = c(t) + jH[c(t)] = a(t)e^{j\omega(t)}$$  \hspace{1cm} (2)

The polar coordinate form of the analytical signal could reflect the physical meaning of the Hilbert transform to obtain the best approximation of the signal by adjusting the amplitude of the sine curve [11]. All of them are functions of time, and the instantaneous amplitude $a(t)$ and frequency $\omega(t)$ functions could be obtained.

$$a(t) = \sqrt{c^2(t) + H^2[c(t)]}$$ \hspace{1cm} (3)

$$\omega(t) = \frac{d\Phi(t)}{dt}$$ \hspace{1cm} (4)

**Figure 4.** First-order IMF component.  
**Figure 5.** First-order instantaneous amplitude.  
**Figure 6.** First-order instantaneous frequency component.

After the EEMD–HHT transform of the radar signal, the IMF component, the instantaneous amplitude component, and the instantaneous frequency component of the original signal could be obtained. Thanks to the high-order components are severely distorted, extract their first-order components for analysis. The first-order IMF component, instantaneous amplitude component, and the instantaneous frequency component are shown in Figs. 4, 5, and 6, respectively. Compared with the original signal, the first-order IMF component map filters out a large amount of clutter and interference, leaving only the strong reflection area of the signal, and the instantaneous amplitude can reflect the better of damage area. The first-order instantaneous frequency graph is unsuitable for specific analyses because of drastic changes.

In summary, compared with that of multiple instantaneous components obtained by EEMD–HHT transform, the significance of the instantaneous amplitude is greater because that the radar echo experiences large amplitude oscillations when the instantaneous amplitude changes rapidly. It indicates that electromagnetic
waves pass through different media with different relative dielectric constants, and the first-order instantaneous amplitude has a good effect. The first-order instantaneous amplitude is used in this paper to identify the crack in the surrounding rock. In fact, when an electromagnetic wave passes through the crack-affected area in a tight rock mass, the instantaneous amplitude component is changed drastically. The bright area in Fig. 5 is the area affected by cracks in the detection plane, and the dark blue area indicates the intact rock mass. Image recognition software can be used to identify areas of different colors, and the size of the crack-affected area could be determined in the GPR detection plane, which is very important for subsequent calculations of rock mass damage.

2.4. Damage evaluation and analysis

Different viewpoints and principles corresponding to the characterization of rock material damage and the definition of damage variables have been widely discussed in damage mechanics. In general, damage variables are defined in the form of micro or macro measurements. The damage variable \( D \) is a thermodynamic internal variable and characterized using indirect description methods. \( D \) is most commonly defined in terms of the elastic modulus:

\[
D = 1 - \frac{E_d}{E}
\]  

\( E \) in Equation 5 is the elastic modulus of the undamaged rock and \( E_d \) is the elastic modulus of the rock in the damaged state. Although the description of damage variables based on the change in elastic modulus has been widely used in rock damage mechanics analysis and research, it cannot give timely results on account of its relatively cumbersome process and is, thus, limited in practical application. The propagation speed of sound waves in rocks is closely related to the elastic properties of this medium [12]. Rock with damage has weaker elastic properties than rock without damage, which is reflected by changes in wave speed. Therefore, changes in wave speed are widely used in field detection to determine the rock damage variable. The damage variable is described in Equation 6, where \( v_p \) is the lossless rock longitudinal wave velocity and \( \overline{v}_p \) is the damaged rock longitudinal wave velocity.

\[
D = 1 - \frac{\overline{v}_p}{v_p}
\]  

Similar to sound wave detection, GPR detection also identifies cracks and broken areas in the rock mass by analyzing changes in the reflection characteristics of high-frequency electromagnetic waves in the damage area. From a microscopic point of view, the failure of a rock mass unit refers to the formation of a penetrating fracture surface within the unit, and the ability of the rock to continue to bear the load is lost. Thus, the overall failure of the rock mass structure could be obtained from the connection of the fracture surface of each rock mass unit. The overall structure loses the function of normal work. The expansion and penetration of the crack area is the main determinant of the surrounding rock damage. The rock damage variable could be determined by the change in crack density of the rock: \( D = f(C_s^*) \). KUS [13] believed that the crack density corresponds to the ratio of the rock volume in the crack-affected zone to the total volume of the rock, and the crack-affected zone could be regarded as the space occupied by cracks within the rock mass. GPR detection is generally considered to be a planar measurement. In fact, the scanning range of GPR is a narrow and long space with a thickness of \( \Delta s \). The distance is \( l \) and \( l \gg \Delta s \); thus, it is regarded as a plane. The equivalent crack density \( C_s^* \) can be used as an evaluation index in GPR detection.

\[
C_s^* = \frac{S_d \cdot \Delta s}{S_{all} \cdot \Delta s} = \frac{S_d}{S_{all}}
\]  

In Equation 7, \( S_d \) refers to the area of the crack-affected zone in the GPR detecting range and \( S_{all} \) is
the total area of the detection zone. The crack-affected zone could be approximately described by the equivalent crack density $C_d^e$, which is easily measured.

Therefore, the evolution characteristics of the fracture area determine the degree of deterioration of the bearing capacity of the rock mass, and $S_d$ could be used as an evaluation index of the rock mass damage.

The instantaneous amplitude component is obtained by the EEMD–HHT transform of the GPR signal of the surrounding rock during blasting excavation, which could be used to illustrate the damage of the rock mass. The observation area is 50 m wide and 10 m deep. The top of the image shows the surface of the surrounding rock, and the left side reflects the position of the tunnel face before the first blasting. Five blasting cycles are performed during the detection proper, and the surrounding rock damage is shown in Figs. 7–10.

Figures 7–10 show that the area of cracks in the surrounding rock gradually increases under the influence of cyclic blasting. The observation area shows two obvious damage areas, the sizes of which increase with the number of blasting cycles. Cracks also clearly show extension. The damage near the blast source expands, but damage is not observed at points beyond the damage area, which is located 40 m from the tunnel face. Several damage areas experience the process of increasing first and then decreasing. However, because only qualitative analysis of the damage evolution can be achieved from the damage image, developing new theories and methods to identify and evaluate the damage evolution of rock masses is necessary.

Figures 7–10 reveal another obvious phenomenon; this phenomenon also appears in subsequent observations. In Figs. 7–9, an obvious vertical crack area could be found at the left side of the image. This area expands under the influence of multiple blasts. However, after five cycles of blasting, the crack area shows obvious signs of reduction, as illustrated in Fig. 10. Two reasons may explain this phenomenon.

1. The rock mass undergoes a certain internal stress redistribution under the influence of its own weight, which is a dynamic process. The crack area is compacted for a short time under the influence of this effect. It is shown on the image as a decrease in the area of the damaged area in some observation area.

2. Figures 7 and 8 show that another larger crack area begins to appear in the area near the elongated crack as cyclic blasting progresses, and the damage expansion is quite obvious. These two areas are located close
to each other, leading to a certain top-end diffraction during the detection of high-frequency electromagnetic waves, the radar signal of the fixed and small damage area submerged.

3. Fractal characteristics of blasting damage in surrounding rock
Fractal theory was first proposed by Mandelbrot in 1980s and used to describe the characteristics of irregular structures that cannot be described by traditional geometry. Numerous experimental observations show that the macro damage of a material is formed by the concentration of small fracture groups, and small fractures are evolved and aggregated by smaller cracks. This self-similarity will inevitably cause rock damage to show fractal features [14]. Xie Heping discovered that the fractured rock mass also has fractal characteristics and introduced a fractal theory comparison system to the geotechnical mechanics method. Years of development have enabled the use of fractal dimensions as a nonlinear representation and achieved good results. The box dimension has been used extensively in this context. The box dimension reflects the relationship between the micro-scale and the macro-morphology. For the rock mass damage area, the micro-scale represents the distribution damage that has not yet penetrated and expanded the micro-cracks, and the macro-morphology affects the stability of the surrounding rock that the larger crack is the main cause, so the box dimension of the damaged area cannot fully reflect the characteristics of rock damage.

In fact, fractal dimensions have different definitions and calculation methods, and no definition and calculation method are applicable to all fractals. Therefore, different fractal dimension calculation methods should be selected according to their ability to analyze different fractals. Different methods use different measures or scales to characterize fractals. In this paper, the fractal island dimension is used as an index to evaluate crack propagation in the rock mass.

3.1. Perimeter fractal dimension and relative damage variable
The damage images of the rock mass resemble independent irregular boundary figures. The ratio of the perimeter of the regular pattern to the square root of the area is only related to its geometric shape, not to its size. However, for a fractal island with a fractal boundary, the boundary length is related to the measurement scale. When the measurement size is infinitesimal, the length of the fractal boundary is infinite and the area enclosed by the fractal boundary tends to be finite. Fractal island dimensions may be used to calculate the irregular damage area; this dimension calculation method is also called the area–perimeter method. The degree of filling of the fractal island perimeter in the plane could be determined on the basis of the perimeter, and the calculated fractal dimension is called the perimeter fractal dimension. The perimeter fractal dimension of the elongated island measured by the proposed method will be higher, which means the perimeter fractal dimension is sensitive to the shape of the penetrating cracks. The larger the perimeter fractal dimension, the greater the number of penetrating cracks and the greater the damage in the observation area. The mathematical expression of the perimeter fractal dimension is:

\[ P = kA^D \]  \hspace{1cm} (10)

where \( A \) is the area of the fractal island, \( P \) is the perimeter of the fractal island, and \( k \) is the scale constant. The perimeter and area of each island are measured separately, and the slope, which is equal to the average fractal dimension of the islands, could be obtained from the log-log plot of the perimeter and area. For a single fractal island, the perimeter fractal dimension \( D \) is:

\[ D = 2 \frac{\log P}{\log A} \]  \hspace{1cm} (11)

Fractal dimensions cannot easily establish a direct mathematical connection with damage. The relative damage degree \( \alpha \) is introduced to indicate the degree of impact of blasting disturbance on damage and illustrate the relationship between the intuitive physical meaning of fractal dimensions and rock damage accurately:

\[ \alpha = \frac{\Delta D}{D_0} = \frac{D_n - D_0}{D_0} \]  \hspace{1cm} (12)

In Equation 12, \( D_0 \) is the perimeter fractal dimension of rock mass damage during the initial detection.
and $D_n$ is the perimeter fractal dimension of rock mass damage after $n$ cycles of blasting.

$\omega$ can represent the change in fractal dimension of the damage area, and quantitative analysis of the surrounding rock damage could be carried out through $S_d$ and $\omega$.

### 3.2. Fractal features of blasting damage

The observation area is divided into five subareas with equal detection widths and labeled #1, #2, #3, #4, and #5 for fine analysis; the relative positions of these subareas are shown in Fig. 1. The detection range of each subarea is 10 m × 10 m. The damage area and perimeter fractal dimension in each subarea are calculated, and images of the blasting damage are shown in Figs. 11–16. Data of the damage characteristics are shown in Table 1.

The figures demonstrate that the damage of the five subareas increases distinctly after one blasting. $S_d$ increases more in subareas #1 and #4 than in subareas #2, #3, and #5, and $\omega$ increases more in subareas #1, #2, and #4 than in subareas #3 and #5. Subareas #1 and #4 shown initial damage before blasting; thus, these subareas will experience crack expansion under the blasting load.

Subarea #1, which is affected the most by the blasting vibration, is located closest to the blast source. The damage area and $\omega$ of this subarea increase significantly compared with the damage and characteristic data, and a large number of new crack areas appear. The increase in the damage area of subarea #2 is relatively small but its $\omega$ remarkably increases, thereby indicating that the fractal dimension of the damage area in this subarea increases significantly after one blasting. The figure illustrates a large number of penetrating cracks after the explosion in subarea #2. Because the perimeter fractal dimension of this subarea is highly sensitive to penetrating cracks, its fractal dimension increases remarkably. Changes in subareas #3 and #5 are small, which means these two areas are only slightly disturbed by the blasting effect.

Subarea #4 experiences multiple cyclic blasting loads, and the expansion of the damage area in the subarea is obvious. These findings indicate that quantitative analyses of the damage evolution characteristics of the surrounding rocks could be carried out using $S_d$ and $\omega$.

![Figure 11. Instantaneous amplitude of subarea #1 before blasting.](image1)

![Figure 12. Instantaneous amplitude of subarea #2 before blasting.](image2)

![Figure 13. Instantaneous amplitude of subarea #4 before blasting.](image3)

![Figure 14. Instantaneous amplitude of subarea #1 after one blasting.](image4)

![Figure 15. Instantaneous amplitude of subarea #1 after one blasting.](image5)

![Figure 16. Instantaneous amplitude of subarea #1 after one blasting.](image6)
Table 1. Characteristic data of damage before and after one blasting

| Subarea | Damage Area (m²) | Fractal Dimension | Relative Damage Degree | Damage Area (m²) | Fractal Dimension | Relative Damage Degree |
|---------|------------------|-------------------|------------------------|------------------|-------------------|------------------------|
| 1#      | 2.48             | 0.69              | 0                      | 5.08             | 0.74              | 0.24                   |
| 2#      | 0.01             | 0.53              | 0                      | 0.86             | 0.69              | 0.30                   |
| 3#      | 0.00             | 0.68              | 0                      | 0.20             | 0.68              | 0.02                   |
| 4#      | 1.07             | 0.62              | 0                      | 1.84             | 0.74              | 0.17                   |
| 5#      | 0.05             | 0.57              | 0                      | 0.41             | 0.60              | 0.04                   |

3.3. Cumulative damage effect of surrounding rock under cyclic blasting

GPR detection data before and after five blasting processes are processed to calculate $S_d$ and $\omega$ to study the cumulative damage effect of surrounding rocks under multiple cyclic blasting loads, and the evolution of blasting damage in the five subareas are summarized in Table 2:
The $\omega$ of subareas #3 and #5 does not change much, which means these areas are weak-damage areas. The subareas with high $\omega$ are #1, #2, and #4.

Table 2. Characteristic data of damage after two and five blastings

| Subarea | Damage Area (m²) | Relative Damage Degree | Damage Area (m²) | Relative Damage Degree |
|---------|------------------|------------------------|------------------|------------------------|
| #1      | 3.15             | 0.24                   | 4.45             | 0.20                   |
| #2      | 0.23             | 0.30                   | 1.11             | 0.25                   |
| #3      | 0.11             | 0.02                   | 0.17             | 0.01                   |
| #4      | 1.45             | 0.17                   | 3.86             | 0.27                   |
| #5      | 0.19             | 0.05                   | 1.11             | 0.06                   |

Figures 17–24 illustrate the surrounding rock damage under the influence of cyclic blasting in subareas #1 and #2, which are closer to the blast source than other subareas. The damage area in these subareas increases and $\omega$ is high, thereby indicating that blasting disturbance affects these two areas the most. The initial damage area of subarea #1 is relatively large, and damage develops extensively under the influence of one blasting vibration. However, after two blasting cycles, the damage area is relatively fixed and no further sign of extension could be observed. $\omega$ decreases with increasing number of blasting vibrations. Initial cracks rarely develop in subarea #2 at the beginning of blasting. However, a damage area appears immediately under the blasting load, and penetration tends to occur. Thus, even if the damage area is small, it must be paid attention. The most prominent feature of subareas #1 and #2 is the emergence of new damage areas, which indicates that the effect of blasting vibrations on the blasting area is relatively strong.

Figure 17. Instantaneous amplitude of subarea #1 before blasting. Figure 18. Instantaneous amplitude of subarea #1 after one blasting.
Figures 19–22 show the surrounding rock damage under the influence of cyclic blastings in subarea #4. This area is located far from the blast source. After five cycles of blasting, the distance from the tunnel face exceeds 50 m. Each blasting disturbance causes the crack-affected area to expand, the intensity of blasting, and damage develops extensively. This damage must be monitored and controlled during the subsequent blasting excavation and supported in time to prevent the formation of a continuous rupture surface and instable failure. The most prominent feature of this area is its lack of new damage, which indicates that the effect of cyclic blasting on the surrounding rock in far areas is mainly expansion and penetration of the existing cracks. When blasting seismic waves arrive at this area, their intensity is greatly reduced and the dense rock mass is not broken.
Combining the images of the blasting damage and the change trends of the damage-affected area $S_d$, fractal dimension $D$, and $\omega$, the variation curves of the fractal dimension and $\omega$ shown in Figs. 29–31, the evolution rules of the surrounding rock damage under the influence of cyclic blasting could be obtained. Cyclic blasting affects crack development and increases $S_d$, but the self-weight effect of the rock mass causes compaction of the crack and decreases in $S_d$. The larger the $S_d$, the more fractured the surrounding rock becomes and the greater the damage degree of the rock mass. Fractal dimension and $\omega$ can effectively evaluate the penetration and expansion characteristics of cracks in the surrounding rock, and these parameters are more objective and accurate than damage image descriptions and damage area analyses.

4. Conclusion
The disturbance and influence of blasting vibrations on the rock mass are generated along with the entire construction process, and assessment of the damage degree exerts direct effects on engineering safety. In
this paper, GPR is used to detect the surrounding rock of the tunnel during blasting excavation, and the radar signal is transformed by EEMD–HHT transform to obtain the instantaneous amplitude, which could reflect the crack area in the surrounding rock. The fractal dimension of the damage area is also calculated. The conclusions of this work are as follows.

(1) The instantaneous amplitude component, which is obtained from the radar signal through EEMD–HHT transform, could effectively reflect electromagnetic waves passing through weak structural planes or crack zones in the rock mass, thereby enabling the detection and identification of the damage area.

(2) The greater the number of blasting cycles experienced by the rock mass, the higher the degree of fragmentation sustained. Areas closer to the blast source are more strongly affected by the blasting vibration effect than areas farther from this source. The compacted surrounding rock generates new cracks. Areas farther from the tunnel face will not generate new cracks, and the existing cracks only expand under the blasting effect.

(3) The damage evolution of the rock mass is related to its initial damage. The larger the initial damage, the more severe the subsequent damage evolution.

(4) The perimeter fractal dimension of the damage area is calculated by the area–perimeter method, which has good identification effects for crack development and penetration and could quantitatively describe the evolution of damage. The fractal dimension increases, which means more penetrating cracks are present in the surrounding rock, the distribution cracks are transformed into macroscopic cracks, the degree of damage of the surrounding rock increases, and the damage area could effectively assess the degree of damage expansion. The greater the crack density, the more extensive the damage evolution of the surrounding rock and the more obvious the crack penetration. The results of this work provide a new theoretical basis for the safety monitoring and early warning of damage to the surrounding rocks of tunnels.

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