

Article

Optimization of Blasting Parameters Considering Both Vibration Reduction and Profile Control: A Case Study in a Mountain Hard Rock Tunnel

Junjie Zhou ^{1,*}, Shan Gao ², Pingkuang Luo ¹, Jiale Fan ¹ and Congcong Zhao ^{1,*} 

¹ School of Resources and Safety Engineering, Central South University, Changsha 410083, China

² Guangxi Xinfazhan Communication Group Co., Ltd., Nanning 530029, China

* Correspondence: zhoujj@csu.edu.cn (J.Z.); congcongzhao@csu.edu.cn (C.Z.)

Abstract: The number of excavated tunnels is increasing day by day, and the corresponding engineering scale is also getting increasing. Safe, efficient, and economically beneficial tunnel construction methods are indispensable in the process of crossing mountains and steep ridges in the southwest region. However, behind the improvement of transportation infrastructure in Southwest China is the support provided by the rapid development of blasting industry engineering technology in China. In the process of tunnel construction using the drilling and blasting method, in addition to blasting vibration disasters the phenomenon of overbreak and underbreak caused by blasting construction is a prominent problem. This phenomenon not only affects the safety and stability of the tunnel excavation but also seriously increases the construction cost. Based on a short mountain hard rock tunnel project in southwest China, this paper studies the effect of blasting construction on the blasting vibration of adjacent structures and the influence of tunnel contour forming quality. Through the monitoring and analysis of in situ blasting vibration, the Sadowski formula is used to study the attenuation law of blasting vibration velocity in different tunnel sites, which provides a theoretical basis for tunnel blasting vibration control. This article compares the use of overbreak and underbreak value with the traditional method to determine the degree of overbreak and underbreak. It introduces the analysis of contour section fractal dimension value and uses fractal theory in the Python image processing module to accurately and quantitatively describe the problems of tunnel overbreak and underbreak. The feasibility and accuracy of this method have been verified, by combining the total station and 3D laser scanner results of overbreak and underbreak measurements of the Brenner Base Tunnel and a short hard rock tunnel in a mountainous area of southwestern China. The blasting scheme was optimized from the aspects of cut hole form, detonator interval time, and peripheral hole charge structure, and the rationality of the optimized scheme was verified according to the on-site blasting experiments. It has a profound influence on strengthening the protection of adjacent tunnel structures and improving the economic benefit of mountain highway projects.

Keywords: tunnel blasting; vibration control; overbreak and underbreak; image processing; fractal theory; optimization of blasting scheme



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1. Introduction

As an economical and efficient rock fragmentation method, the drilling and blasting method is widely used in fields such as mines, tunnels, and hydraulic engineering. Although it has brought enormous engineering value to human society, it often causes different secondary disasters during the blasting process, such as blasting vibration disasters, blasting air shock waves and noise disasters, blasting flying object hazards, blasting dust hazards, and blasting harmful gas hazards [1]. Usually, during the excavation process, explosives generate highly destructive detonation energy, which exists in different forms. Except for most of the energy acting on rock fragmentation, displacement, and throwing, the remaining energy includes the energy of the shock wave generated and the energy

of the gas. The shock wave energy mainly presents as radial and tangential stress wave energy when transmitted to the rock mass, and the vibration caused by blasting is the result of these waves acting on rock strata. This type of stress wave causes a negative effect of attenuation as the distance from the blasting source increases within a certain range of blasting construction [2,3]. Therefore, this is the most common and major hazard that occurs during blasting—blasting vibration disasters.

In order to reduce the negative effects of blasting vibration and optimize the process of blasting from design to construction, scientifically and reasonably, it is necessary to study the theoretical mechanisms of vibration generation, propagation, and related disasters. However, accurate prediction and judgment of the vibration effects generated by blasting, as well as the development of reasonable criteria to measure blasting vibration, are currently hot research topics in the field of blasting. Ren et al. [4] proposed a construction method that combines drilling and blasting with mechanical excavation to effectively control the safety vibration threshold of Qingdao Metro tunnel construction in view of the geological conditions of the soft-upper and hard-lower composite strata. Liu et al. [5] found that the tunnel spacing and reasonable segmented charging parameters are crucial for the stability of the tunnel surrounding rock when studying the blasting vibration control problem of the Daxuanling small-distance tunnel and established a prediction model of the vibration attenuation law of each blasting tunnel section by means of regression analysis. Relying on on-site monitoring and measurement of Damaoshan small-clear distance tunnel blasting, Lin et al. [6] studied the attenuation formula of blasting vibration velocity under different surrounding rock conditions and revised the critical value of the tunnel blasting safe vibration velocity to 20 cm/s. Hu et al. [7] optimized the blasting scheme based on the drainage guide tunnel construction of a dam restoration project in Jiangxi Province. Through vibration monitoring and relevant theoretical formula analysis, the safety problem of blasting vibration in the dam has been fully solved. Ling et al. [8] considered different levels of surrounding rock and monitoring locations as research variables that affect the attenuation law of tunnel blasting vibration and found that the peak value of radial blasting vibration at the arch waist of the blasting side is largest. Therefore, similar engineering blasting vibration control can be used as a control standard to guide excavation work. Marilena et al. [9] proposed a new empirical “site criterion formula” to evaluate the propagation attenuation of vibration induced by rock engineering blasting in rock mass. The rationality and accuracy of the criterion formula were verified by collecting blasting vibration data from 12 engineering cases. Xia et al. [10] took the Damaoshan Highway tunnel project as an example to comprehensively study the impact of tunnel blasting excavation on the surrounding rock and lining system of adjacent tunnels and proposed a tunnel damage control method based on PPV threshold control via on-site experiments. Van Kien Dang et al. [11] argue that the empirical formula derived from single-parameter Peak Particle Velocity (PPV) does not take into account the changes between rock parameters and in situ conditional parameters. Therefore, rock parameters such as the Rock Mass Rating (RMR) and dynamic Young’s modulus are introduced into the establishment of a multivariable PPV generalized regression model.

In the process of tunnel construction using the drilling and blasting method, not only the blasting vibration disaster but also the phenomenon of overbreak and underbreak caused by blasting construction are very prominent problems. Xiao et al. [12] analyzed the impact of different blasting charge parameters on the safety and stability of a water diversion tunnel through multi-dimensional monitoring methods such as a blasting vibration test, a wave velocity test, 3D laser scanning, and microseismic measurement. It not only reflects the disturbance of blasting excavation on the rock mass but also reflects the differences in the impact of changes in blasting parameters on overbreak and underbreak. In view of the problem of tunnel overbreak and underbreak, the prolonged exposure time of the working face increases the risk of instability in the surrounding rock. Although supplementary blasting is adopted in engineering to solve the problem, it will lead to complex safety hazards and prolong the construction period [13]. Overbreak and under-

break caused by tunnel blasting is also a long-term and urgent research issue in the field of tunnel engineering.

Most engineers and technicians have conducted extensive research on overbreak and underbreak in tunnels. Ozgur and Sigh both noticed the impact of borehole deviation on overbreak and underbreak. Specifically, the look-out angle is the angle between the practical (drilled) and the theoretical tunnel profile. If the contour holes are drilled parallel to the theoretical line of the tunnel, it will cause the thickness of the damage zone of the tunnel face to be uncontrollable [14,15]. The thickness of the damage zone is closely related to overbreak and underbreak. The actual post fracture behavior of the tunnel's surrounding rock is also considered to be somewhere in between two extremities represented by the elastic perfectly plastic and elastic brittle models [16]. In view of the poor geological tunnel with karst development, Zeng et al. [17] mainly considered the influence of the interrelationships between blasting technical parameters on the blasting effect and quality and carried out reasonable excavation design of blasting parameters for the Maanshan No. 1 tunnel to ensure the quality of the tunnel section profile and the stability of surrounding rock. Yin et al. [18] explored the influence of peripheral hole control technology for the long-short hole contours around the tunnel on the damage to surrounding rock, creating conditions for subsequent engineering calculations of the blasting loose zone and the range of surrounding rock damage. Overbreak and underbreak occur in the damage zone of the tunnel. Meanwhile, there is settlement or convergence in the damage zone. Tamer et al. [19] constructed a numerical model to study the relationship between the convergence value of the tunnel and the thickness of the damage zone, in response to the problem of an uneven and irregular damage zone in soft and hard rock strata tunnels. Hao et al. [20] conducted on-site excavation and blasting experiments on the Panlongshan horizontal layered rock tunnel, considering the influence of different cyclic footage on tunnel contour shaping and linear overbreak. The experiment result shows that the smaller the cyclic footage, the less tunnel overbreak occurs. Guo et al. [21] believed that the internal factors causing poor quality of tunnel overbreak and underbreak were geological structure, rock type, and properties. Therefore, scientific and reasonable control of explosive dosage and millisecond delay blasting technology are key means to effectively control overbreak and underbreak. Facing the problem of overbreak and underbreak caused by the blasting of the horizontal sand-mudstone tunnel in Duanjiaping, Lv et al. [22] applied a new bidirectional shaped charge structure to the peripheral holes, which significantly improved the linear effect of the horizontal rock layer and provided an effective means for the control of overbreak and underbreak of the horizontal rock layer.

In tunnel excavation, the surrounding rock undergoes macroscopic damage under the influence of blasting; currently, the evaluation and correlation analysis of the macro-damage degree caused by the loading of the surrounding rock is a pivotal issue of concern in the research process of rock engineering. Blasting has been the most effective solution for tunnel excavation in hard rock. The accuracy of the blasting works is demonstrated by the similarity between the design and the actual excavation boundary. Hence, the overbreak and underbreak of the tunnel boundary are used to evaluate the tunnel excavation [19]. The overbreak-underbreak profile after blasting is equivalent to a special "fracture surface", and the existence of the rock fracture surface largely affects the deformation of the rock mass. Fractal theory, as a mathematical tool, is used to analyze complex space geometry, cracks, contours, etc. By calculating the fractal dimension of the research object, the quantitative relationship between the fractal dimension and the research object can be obtained [23]. For evaluating the smoothness of the tunnel contour, as an unsmooth geometry generated by a nonlinear system, "over-underbreak", in professional terms, is suitable for the study of fractal theory describing chaotic and disordered events. In the past, research on tunnel overbreak and underbreak only focused on a limited number of measurement points, while the introduction of fractal theory did not simply simulate its shape through the separation of points and lines but also through overall consideration. Xie et al. [24] described the rock fracture surface morphology using laser surface measurement technology and accurately

measured the fracture surface morphological characteristics without damage, which created conditions for the study of the relationship between rock fracture surface morphology and joint mechanics. Wei et al. [25] applied image processing technology to the measurement of tunnel overbreak and underbreak in a hydropower station in southwest China, and began to consider the evaluation of overbreak and underbreak from a qualitative perspective. It has significant reference significance for the evaluation of overbreak and underbreak in subsequent projects. Based on fractal and wavelet theory, Zhang et al. [26] used on-site measurement methods to estimate the fractal dimension of the overall profile, arch crown, and side wall overbreak–underbreak of nearly 100 tunnel sections. The relationship between the stability of surrounding rock and the fractal dimension of the cross-section profile has been identified. Therefore, the fractal dimension of the macroscopic fracture contour fracture trajectory is used to characterize the incompleteness and inhomogeneity of blasting rock engineering, which can provide new research ideas for quantitatively analyzing the flatness of the tunnel contour surface after smooth blasting.

In the design and construction of tunnel blasting using the drilling and blasting method, effective control measures such as reasonable interval delay time, maximum single shot explosive amount, thickness of the smooth blasting layer, blasting hole charging structure, cut hole type, and setting pre-split holes can slow down the generation and diffusion of blasting vibration disaster effects [27–33].

However, in addition to the low level of on-site equipment construction leading to blasting vibration disasters, it is frequently accompanied by serious damage to the surrounding rock and poor smooth blasting effect leading to serious problems of overbreak and underbreak, which will indirectly induce large deformation or even collapse of the tunnel [34]. Therefore, this paper takes a southwest short mountain hard rock tunnel as the engineering background. By combining theoretical formula analysis, on-site blasting experiments, and image processing with fractal theory, technical research was conducted on the blasting construction of the short mountain hard rock tunnel. The research mainly focuses on the following aspects: (1) The vibration response of blasting to a short mountain hard rock tunnel is studied via on-site blasting monitoring and Sadovsky's empirical formula, providing a theoretical basis for the vibration reduction of the tunnel. (2) Based on the Python image processing method of the Tunnel section overbreak and underbreak fractal method, combined with the overbreak–underbreak data collected from BBT (Brenner Base Tunnel) and a short mountain hard rock tunnel, the fractal characteristics of tunnel contour section are explored, providing an effective evaluation method for tunnel contour control. (3) In response to the problems existing in the original blasting scheme on site, control blasting related experimental research was conducted. The blasting scheme is optimized and designed from the aspects of cut hole form, detonator section, interval time, and peripheral hole charge structure. The rationality of the optimized scheme is verified via on-site blasting experiments.

2. Materials and Methods

2.1. Overview of the Tunnel Project

2.1.1. Tunnel Project Introduction

The target mountain tunnel is located in a village in Guangxi Province, China. It is a typical double-hole-separated tunnel (as Figure 1). The direction of the tunnel is about 250°, and the tunnel area is a karst depression landform with large relief, less mountain overburden, and large area exposed bedrock. The entrance section of the tunnel has a steep slope of 35°, while the exit section has a flat terrain with a slope of approximately 10°. The designed length of the tunnel is 254 m.

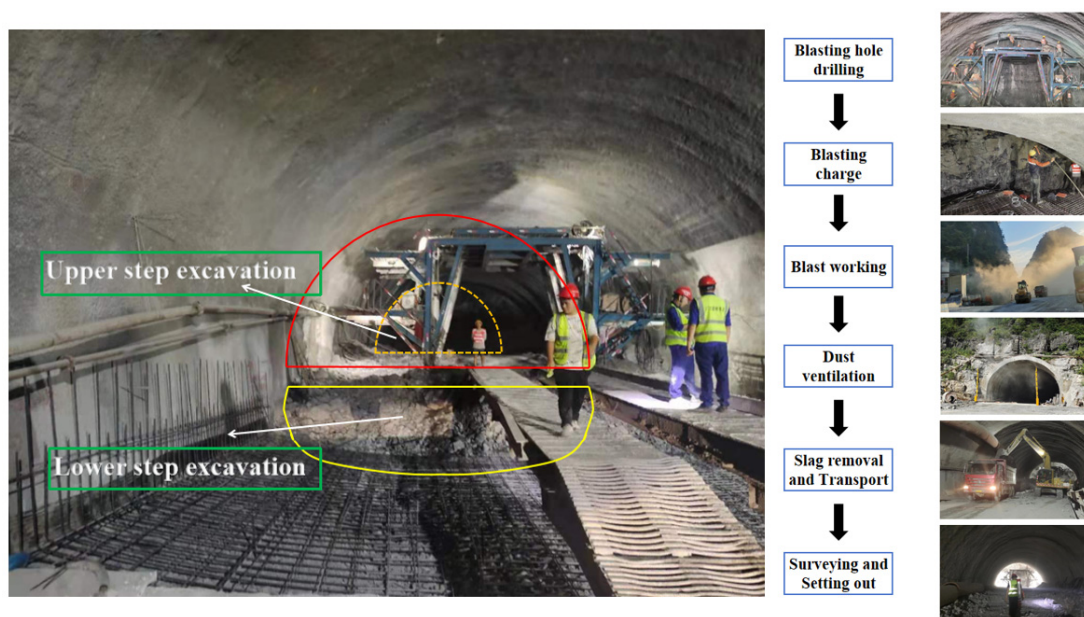


Figure 1. Blasting excavation and construction of up and lower steps on site.

2.1.2. Original Tunnel Excavation Design

The target tunnel is equipped with YT-28 air-leg rock drill for rock drilling and blasting. No. 2 rock emulsion explosive 300 g/ Φ 32 mm per roll with related ordinary millisecond detonator is applied to the tunnel. A total of 100 gun holes are laid in the design of the tunnel's upper step blasting excavation. Blasting excavation of the upper steps of the tunnel is shown in Figure 2. The detonator segment, detonation sequence, and charge amount of the detonator are shown in Table 1 for blasting excavation parameters.

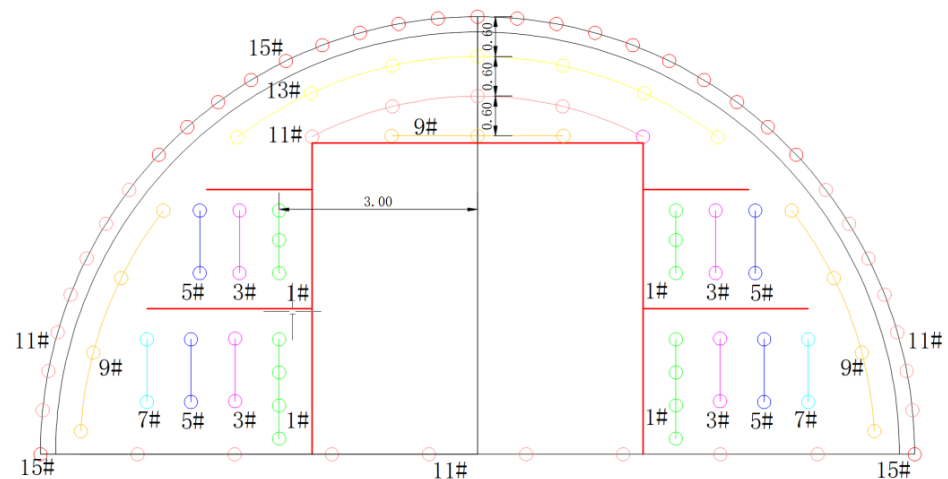


Figure 2. Blasting excavation of the upper steps of the tunnel.

Table 1. Blasting excavation parameters.

Blasthole Type	Blasthole Diameter	Blasthole Spacing	Amount	Blasthole Depth	Detonator Segment	Per Hole Charge	Total Charge
Cut hole	42 mm	500 mm	14	3.8 m	MS1	1.2 kg	16.8 kg
Auxiliary cut hole	42 mm	950 mm	8	3.8 m	MS3	2.4 kg	19.2 kg
Breast hole #1	42 mm	950 mm	12	3.8 m	MS5/MS7	1.8 kg	21.6 kg
Breast hole #2	42 mm	-	8	4.3 m	MS9/MS11	2.1 kg	16.8 kg
Second-ring hole	42 mm	1200 mm	15	3.8 m	MS11/MS13	1.8 kg	27 kg
Baseplate hole	42 mm	1450 mm	8	3.8 m	MS15	1.8 kg	14.4 kg
Bottom-corner hole	42 mm	-	2	3.8 m	MS15	0.9 kg	1.8 kg
Peripheral hole	42 mm	600 mm	33	3.8 m	MS15	1.2 kg	16.8 kg

2.2. Blasting Vibration Monitoring

2.2.1. Vibration Monitoring Instruments

In this study, NUBOX-8016 (Sichuan Tuopu Measurement and Control Technology Co., Ltd., Chengdu, China) and Blast-UM (Chengdu Taice Technology Co., Ltd., Chengdu, China) blasting vibration monitoring systems are used, including 3D velocity sensors, data transmission cables, and waveform data LCD display devices. Dozens of monitoring data groups were conducted on the tunnel excavation. According to the analysis results of monitoring data and the safety allowance standard for blasting vibration (GB6722-2014) [35], blasting technical parameters are adjusted and optimized to reduce the impact of single blasting on target tunnel, adjacent tunnel, and residential area.

2.2.2. Monitoring Points Arrangement

The tunnel monitoring layout diagram is shown in Figure 3. The target tunnel monitoring points are arranged on the ground to the right of the tunnel centerline. The outermost measuring point is 60 m away from the blasting face. A total of 3 target tunnel measuring points are laid, with a spacing of 10 m. The adjacent tunnel monitoring points are arranged with gypsum bonding cloth at a distance of 1.2 m from the ground on the tunnel sidewall. A total of 4 adjacent tunnel measuring points are laid, with a spacing of 5 m. The mountain slope measurement points are arranged on a weathered stone platform 20 m away from the ground. A total of 2 mountain slope measuring points are laid, with a spacing of 1 m. A total of 2 residential area measuring points are laid, with a spacing of 20 m.

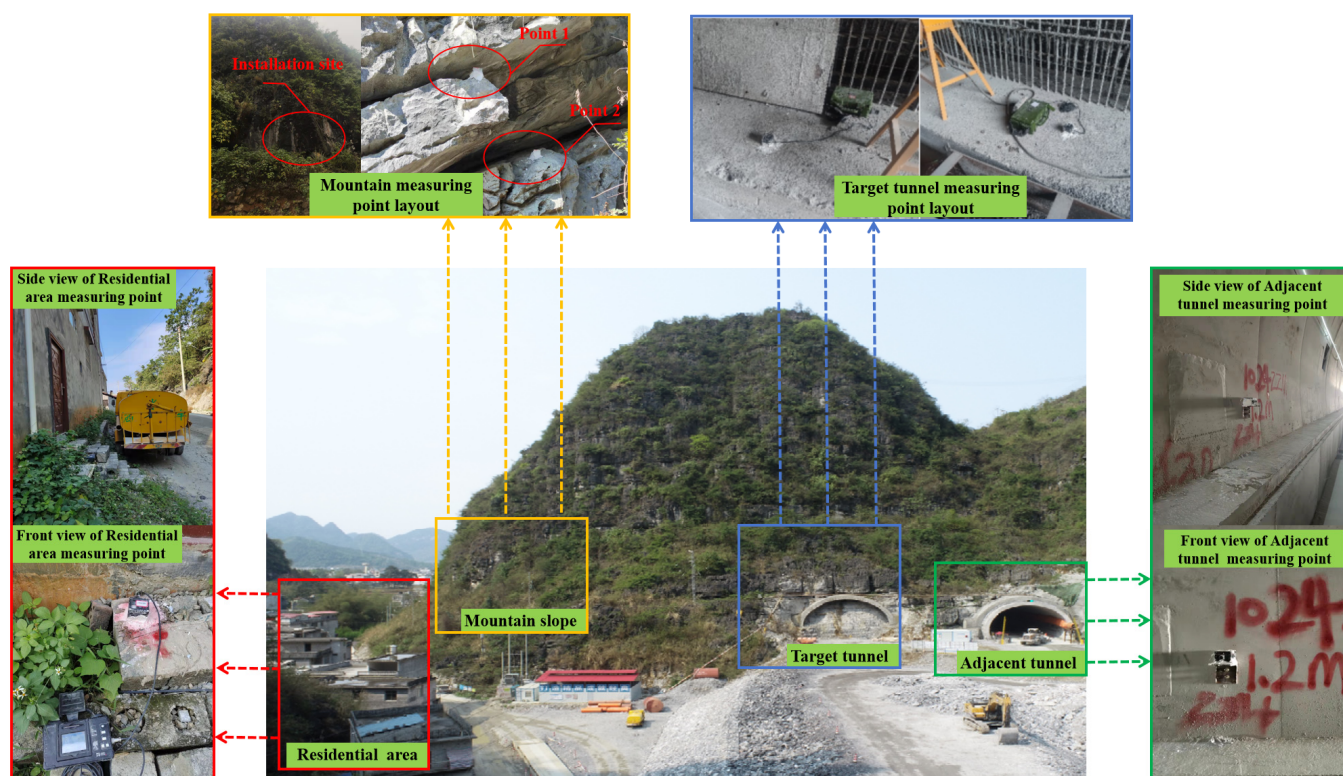


Figure 3. Tunnel monitoring points layout diagram.

2.2.3. Specific Monitoring Schemes

Figure 4 is a plan view of the tunnel monitoring scheme. In order to investigate the impact and propagation law of tunnel blasting on the vibration response of surrounding structures and slopes, corresponding models are established to predict the PPV based on blasting vibration data to optimize the blasting scheme. Since the research on the vibration attenuation law is based on accurate measurement data on site, this study establishes models to verify the vibration attenuation law through Sadowski empirical formula.

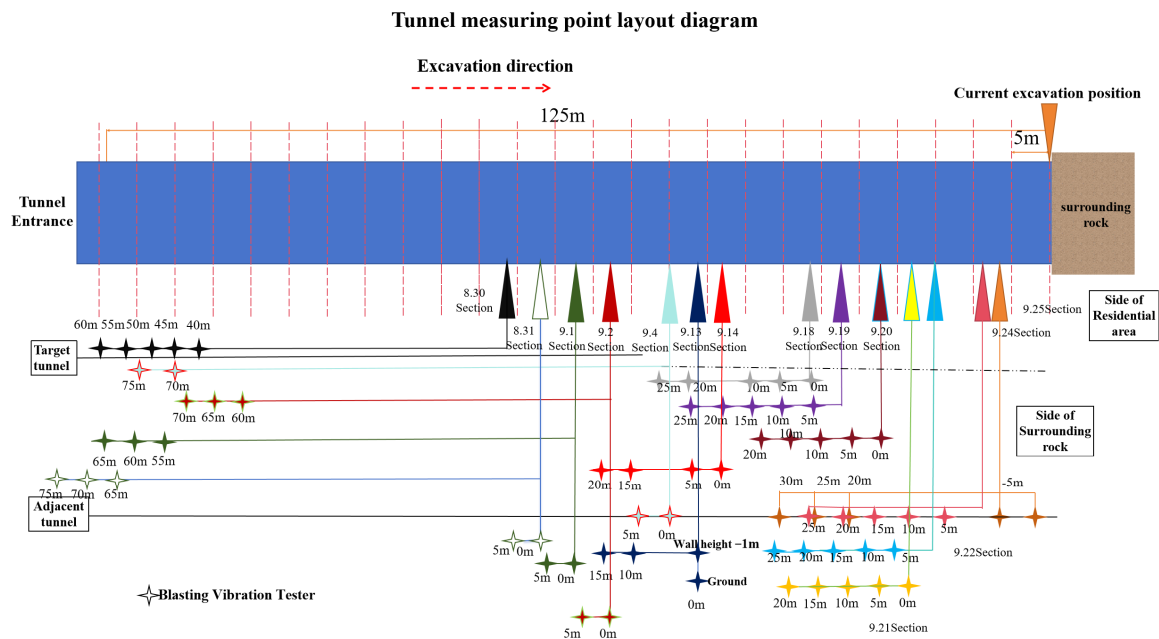


Figure 4. Tunnel monitoring scheme from August 30th to September 31th.

2.3. Tunnel Profile Measurement

Based on the measurement results of the Hovermap 3D laser scanner and ZT-30 total station, overbreak and underbreak analysis of the tunnel was carried out after blasting. The measurement process is shown in Figure 5. The measurement location of overbreak and underbreak is selected at the section of the tunnel entrance 50–65 m. The surrounding rock at this section is classified as grade IV with horizontal layered joints, and the results of overbreak and underbreak are typical. The above equipment are used to collect images of tunnel overbreak and underbreak, and the tunnel overbreak–underbreak profiles are visualized based on the Python image processing method.

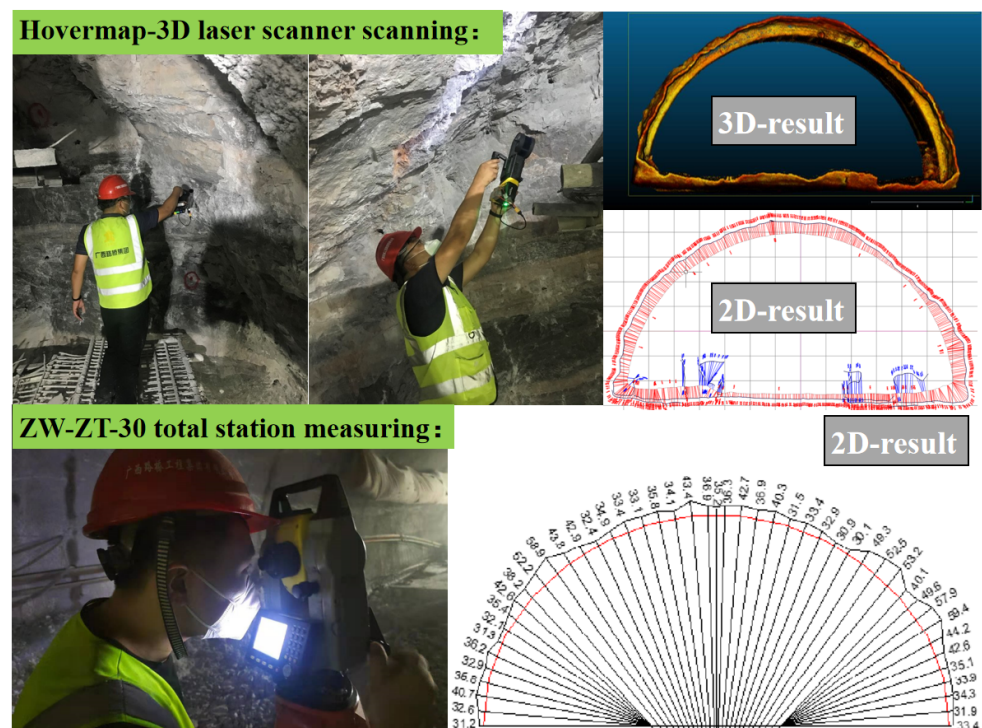


Figure 5. On-site overbreak and underbreak measurement process.

2.4. Optimization of Tunnel Blasting

Based on a large amount of on-site monitoring and geological survey data, the construction of the tunnel right-line is carried out using the traditional drilling and blasting method. The cut hole adopts the form of one-stage wedge cut, and the poor cutting effect leads to a large block problem. The peripheral holes are continuously charged at the bottom of the holes, and the poor effect of smooth blasting leads to the increase in support cost in tunnel construction. Meanwhile, there are some structures near the construction tunnel such as mountain slopes and residential buildings, which lead to serious conflicts from residents during the blasting operation. Therefore, it is necessary to control blasting vibration and optimize smooth blasting parameters.

2.4.1. Optimization of Cutting Hole Area

The design of the cutting hole area is the most critical part of tunnel excavation, which largely determines the blasting effects such as the big block rate and vibration effect. The design of the cutting hole area depends on factors such as cyclic footage, cross-sectional size, cutting form, and minimum burden size, as well as the drilling equipment and drill platform on site. Therefore, it is very important to determine the cutting parameters reasonably.

The grade of the surrounding rock determines the size of the cyclic footage, and the grade of the surrounding rock on target tunnel right-line is grade IV. In the application process of wedge cutting, different cyclic footage has different forms of wedge cutting. According to relevant design specifications and engineering cases, two-stage wedge cutting is adopted on site, with a cyclic footage of 3 m each time. The original single-stage cutting method with a large amount of charge results in a high large block rate, unsatisfactory rock throwing effect, and insufficient utilization of explosive energy. Therefore, two-stage wedge cutting is adopted in this optimization. It can not only increase the free surface of the palm cutting blasting, reducing the pinch making of the surrounding rock, but also expand the angle between the cutting hole and the palm face so as to reduce the size of the bottom minimum burden and ensure that the rock is fully broken and thrown. Optimized two-stage wedge cutting is shown in Figure 6.

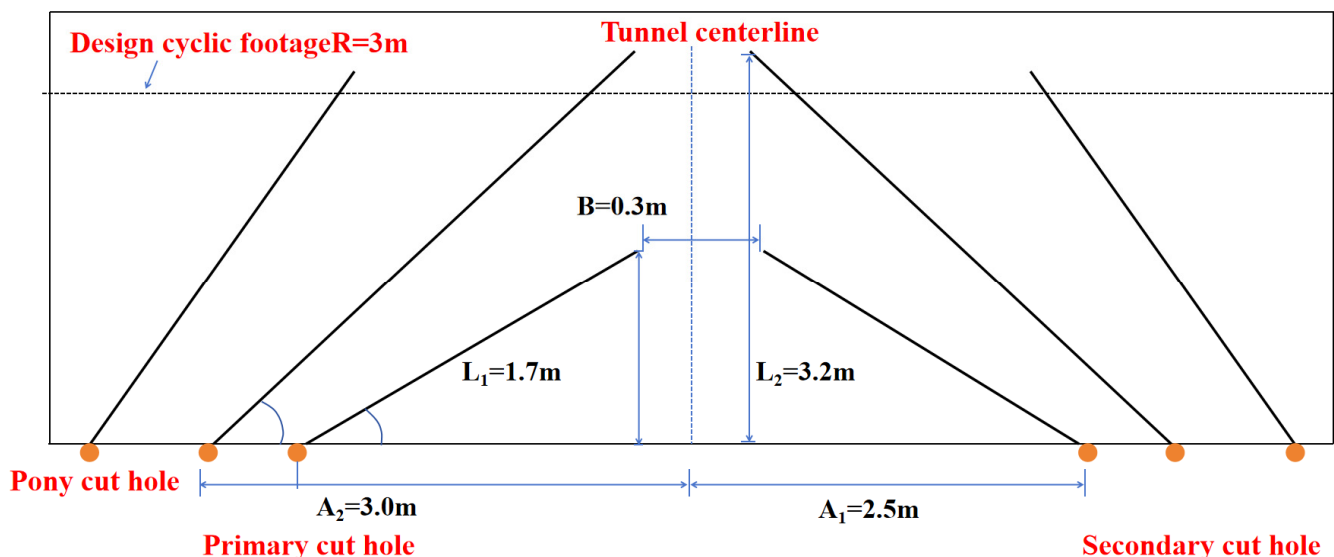


Figure 6. Layout of two-stage wedge cutting.

2.4.2. Optimization of Delay Time Interval for Detonator

As the most used electronic equipment in the field of blasting equipment applications, digital electronic detonators have been widely used in mine blasting, tunnel and underground engineering blasting, underwater special blasting, and controlled blasting under complex conditions. With its ability to precisely control the time intervals of each segment,

it effectively reduces blasting vibration by utilizing the superposition effect of vibration waves [36,37].

Digital electronic detonator blasting experiments were conducted on the target tunnel right-line with different delay time intervals. The electronic detonator was set to 25 ms and 60 ms, respectively. Taking a two-time continuous cycle of 3 m excavation as an example, the corresponding waveform signals and spectral characteristics are compared through vibration signal monitoring, as shown in Figure 7. The peak vibration velocity is mainly produced in the cutting holes, which is the maximum single shot explosive dosage section, and the wedge cutting method can be improved by implementing the detonator with accurate delay. If each wedge cutting hole is detonated as a whole one by one, it is better to use a detonator about 50 ms between each wedge cutting [38]. Therefore, the optimized delay interval of 60 ms for detonators can meet on-site requirements.

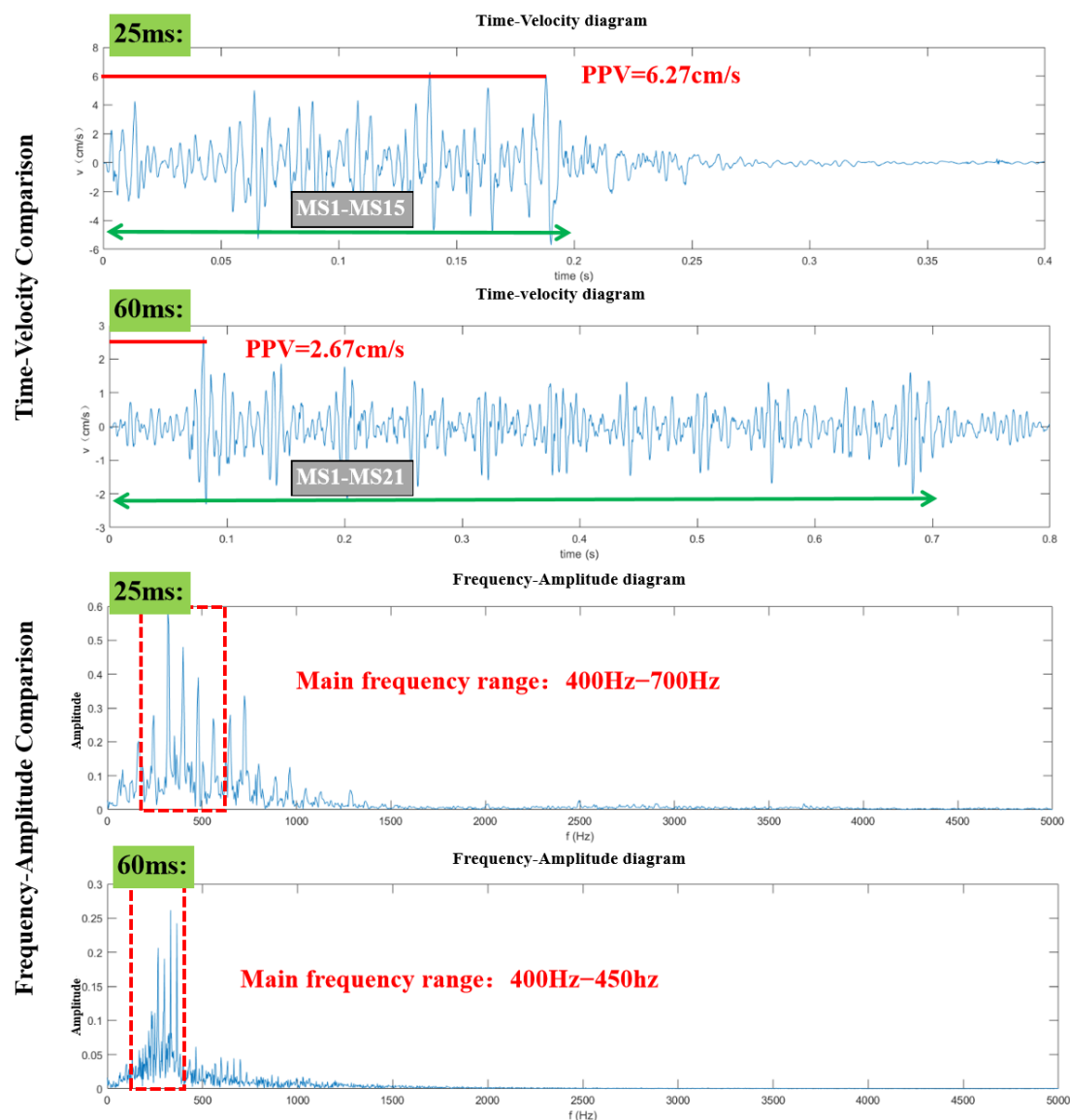


Figure 7. Comparison of signals and spectrum characteristics of digital detonators.

2.4.3. Optimization of Peripheral Hole Charge Structure

Researches have shown the blasting forming effect of the tunnel contour is largely determined by the charging parameters of the peripheral holes [13,39]. The charge structure used in the original scheme of smooth blasting is a coupled charge structure. But, through monitoring and investigation, it is found that the phenomenon of overbreak and underbreak

in blasting is significant, especially at the left and right arch waist. The reason is that the charge amount in the surrounding holes is too concentrated, which produces a crushing effect on the surrounding rock around the pore-wall after detonation. This behavior is not conducive to the penetration of peripheral holes. Therefore, it is decided to adjust the charging structure of the peripheral holes on site to decoupled charging to improve the blasting effect. It also reduces blasting vibration to a certain extent. The charging parameters of the peripheral holes on site were improved. The original scheme used 4 rolls of 300 g-2# rock emulsion explosive for centralized charging, while the optimized scheme used 4 rolls of charge and 0.43 m hollow PVC pipe for interval charging. The depth of the peripheral holes was 3 m, and the blockage of the gun mud was 0.2 m. The axial uncoupled charging structure of the peripheral holes is shown in Figure 8.

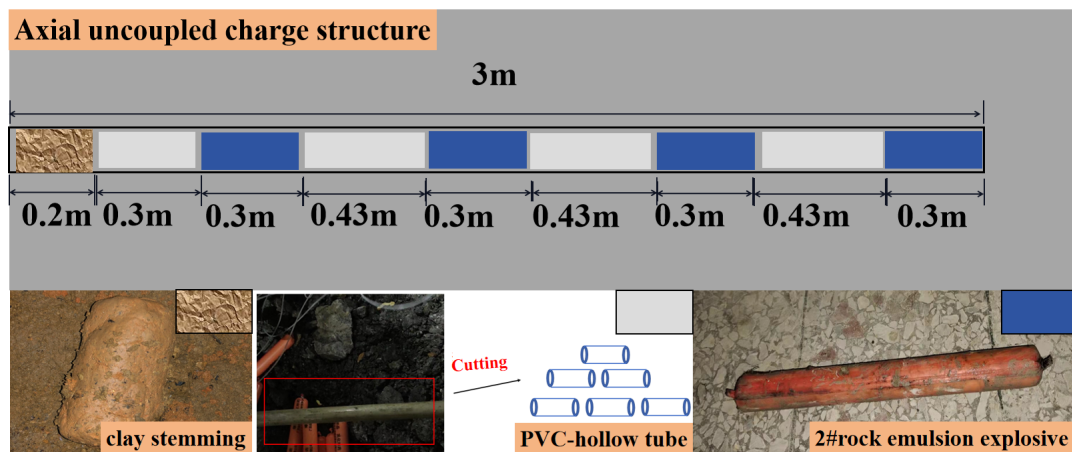


Figure 8. Axial uncoupled charging structure of peripheral holes.

According to the field investigation and drilling experience of drilling personnel, adding multiple empty holes near the peripheral holes can improve the blasting effect of the contour surface better and reduce the phenomenon of overbreak and underbreak. This is the application of the “empty hole effect” in peripheral holes. The empty hole effect refers to the phenomenon of stress concentration caused by the action of blasting stress waves on the empty hole near the blast hole, resulting in a more obvious damage effect on the surrounding rock. At present, the “empty hole effect” is widely used in the field of cutting technology. The purpose of laying empty holes in cutting blasting is to increase the free surface and create good blasting conditions for subsequent holes. Meanwhile, the arrangement of empty holes around the periphery holes utilizes its guiding function [40]. Therefore, a row of empty holes can be arranged near the arch waist to solve the overbreak and underbreak after several blasting cycles on site. Based on the above measures, the parameters of the blasthole are optimized according to the design principle. The two-stage wedge cutting form has been adopted. The peripheral holes charging structure has been improved, and the delay time of digital detonators have been adjusted. The detailed parameters are summarized in Table 2, and the optimized blasting scheme is shown in Figure 9.

Table 2. Optimization scheme—the smooth blasting holes parameters.

Blasthole Type	Blasthole Parameters			Explosive Parameters		Charge (kg)	
	Amount	Depth (m)	Angle (°)	Segment	Time Delay (ms)	Per Hole Charge	Total Charge
Primary cut hole	10	3.1	34	MS1	0–60	1.2	12.0
Secondary cut hole	14	4.5	47	MS3	60–120	2.1	29.4
Auxiliary cut hole	14	3.8	60	MS5	120–180	2.4	33.6
Breast hole #1	12	3.2	70	MS7	180–240	2.1	25.2
Breast hole #2	12	3.1	80	MS9	240–300	1.5	18.0
Breast hole #3	6	3.0	85	MS11	300–360	1.5	9.0
Vault breast hole #1	3	3.0	90	MS11	300–360	1.5	4.5
Vault breast hole #2	5	3.0	90	MS13	360–420	1.5	7.5

Table 2. Cont.

Blasthole Type	Blasthole Parameters			Explosive Parameters		Charge (kg)	
	Amount	Depth (m)	Angle (°)	Segment	Time Delay (ms)	Per Hole Charge	Total Charge
Arched waist second-ring hole	8	3.0	90	MS13	360–420	2.1	16.8
Vault second-ring hole	7	3.0	90	MS15	420–480	1.8	12.6
Arched waist peripheral hole	24	3.0	90	MS17	480–540	1.2	28.8
Vault peripheral hole	21	3.0	90	MS19	540–600	0.6	12.6
Bottom-corner hole	2	3.2	90	MS21	600–660	1.5	3.0

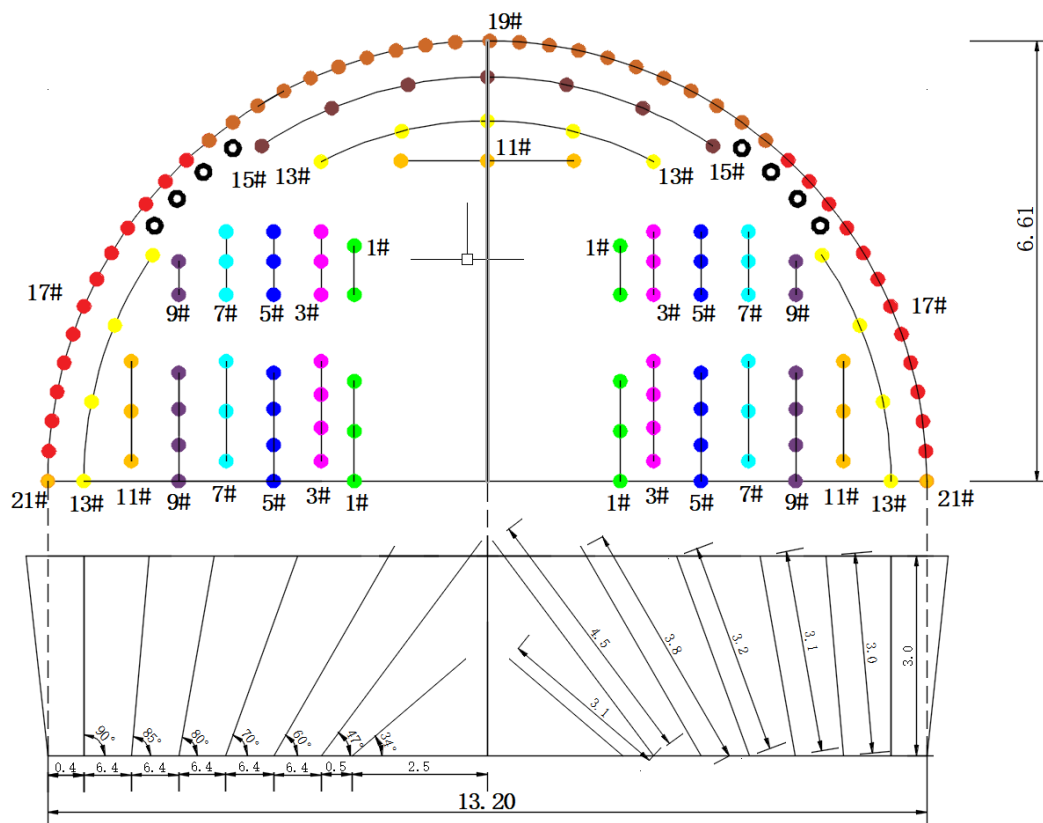


Figure 9. Optimization scheme—smooth blasting.

2.5. Fractal Evaluation Method of Tunnel Overbreak–Underbreak Based on Python Image Processing

2.5.1. Fractal Theory and Boxing-Counting Dimension

In nature, most things without smoothness and with complexity are randomly generated, such as rugged and winding coastlines and unpredictable Brownian motion trajectories. These types of curves can be described by irregular fractals through strict mathematical iterations to calculate the fractal dimension [41,42]. Fractals can be regarded as a set of points embedded in Euclidean space, and the key to determining dimension is how to measure the size of a set of points. In fractal geometry, the boxing-counting dimension, also known as the Minkowski dimension, is a method of calculating the fractal dimension in distance spaces (X, d) such as the Euclidean space R . To calculate the boxing-counting dimension value of a certain fractal, imagine the fractal is placed on a evenly divided grid and count the minimum number of grids needed to cover the fractal. Through the refinement of the grid step by step, the change in the required coverage number is checked to calculate the boxing-counting dimension. Assuming that when the side length of a grid is ε , the space is divided into N grids in total. Furthermore, the boxing-counting dimension value is expressed as formula (1):

$$\dim_{box}(L) = \lim_{\varepsilon \rightarrow 0} \frac{\log N(\varepsilon)}{\log\left(\frac{1}{\varepsilon}\right)}. \quad (1)$$

The research object of this article is the profile of tunnel overbreak and underbreak, which is described by the boxing-counting dimension.

2.5.2. Visualization Algorithm of Overbreak–Underbreak Based on Python Image Processing

Based on the visualization algorithm developed by Python, a study of tunnel overbreak and underbreak is carried out. The acquisition of two-dimensional profile sections during on-site construction is performed not only by the measurement of geological personnel but also occurs using various advanced section scanning machines. The use of Python image processing technology can achieve feature recognition and analysis of two-dimensional profiles [43]. This technology mainly extracts the pixel values and coordinates of two-dimensional overbreak and underbreak contour images. It uses denoising methods such as threshold segmentation and median filtering to efficiently screen pixel data to obtain useful features of tunnel overbreak and underbreak. Firstly, visualize and digitize the profile images of overbreak and underbreak based on target features, and identify the profile curves of overbreak and underbreak. Secondly, analyze the characteristic laws of overbreak and underbreak curves through the recognition results of the tunnel profile. The method provides relevant guidance for subsequent control of tunnel overbreak–underbreak and optimization of tunnel smooth blasting parameters. It involves three modules with a total of seven steps.

1. Overbreak–underbreak Profile Curve Data Collection Module

Step 1: Collect 2D images of tunnel overbreak–underbreak profiles from the relevant literature [44,45], which are obtained from two aspects: 3D laser scanning equipment and technical personnel with the help of a total station. This step is the mark processing of the overbreak–underbreak profile images. The retouching software is mainly used to depict lines in red or green colors for different tunnel 2D profile images, and the images are exported in PNG format.

2. Overbreak–Underbreak Profile Curve Data Visualization Module

Step 2: This step involves the representation and recognition of the HSV model algorithm for the overbreak–underbreak curve, and the preliminary processed images are processed using the HSV color space model algorithm. This algorithm converts the input PNG color image into HSV color space, and the useful information of these images is screened in HSV color model for image segmentation [46]. In this study, the selected and identified objects are overbreak–underbreak profiles curves represented by red or green lines.

Step 3: Through preliminary processing of overbreak–underbreak profiles images, it was found that some images have noise issues, which affect the storage of subsequent overbreak–underbreak curve data. In this study, Hough transform [47,48], threshold segmentation and median filter algorithms are combined to denoise images. This step is performed to denoise the overbreak–underbreak curve. Firstly, the standard Hough line transformation algorithm is used to identify the “noise” of the linear features in the image and the gray value of the region where the feature straight-line is located and converted. Secondly, the common binary thresholding algorithm is used to process the identified pixels. Median filtering can not only remove the noise but also protect the edge details of the image from blur processing. Therefore, the median filter is used to remove the discrete noise around the overbreak–underbreak curve as much as possible to preserve the original curve features.

Step 4: This step is performed to store the data of the overbreak–underbreak curves. Grayscale processing of the overbreak–underbreak curve images is carried out. Each pixel

in a grayscale image has only one sample color, and its grayscale has a multi-level color depth between black and white. Pixels with large grayscale values are brighter, and those with small grayscale values are darker. The maximum pixel value is 255 for white, and the minimum value is 0 for black. Using the Numpy library of Python, the coordinates of gray pixel 0 of the overbreak–underbreak profile images are recorded and stored in CSV format for the convenience of subsequent data processing.

3. Overbreak–underbreak Profile Curve Data Feature Analysis Module

Step 5: Through the above steps, the data related to overbreak–underbreak curves are obtained. Digitizing these coordinate data is conducive to the analysis and processing of overbreak–underbreak curves in the next step. The interpolation module of Python and the interpolation algorithm developed via this study were used to fit the overbreak–underbreak curve. During the fitting process, it was found that the problem of line width in the drawing process has a great impact on the fitting of the curve. Therefore, this study independently developed the “Triangle Configuration Optimization Algorithm” (TCO) to participate in the process of fitting the overbreak–underbreak curve. The specific algorithm is shown in Figure 10.

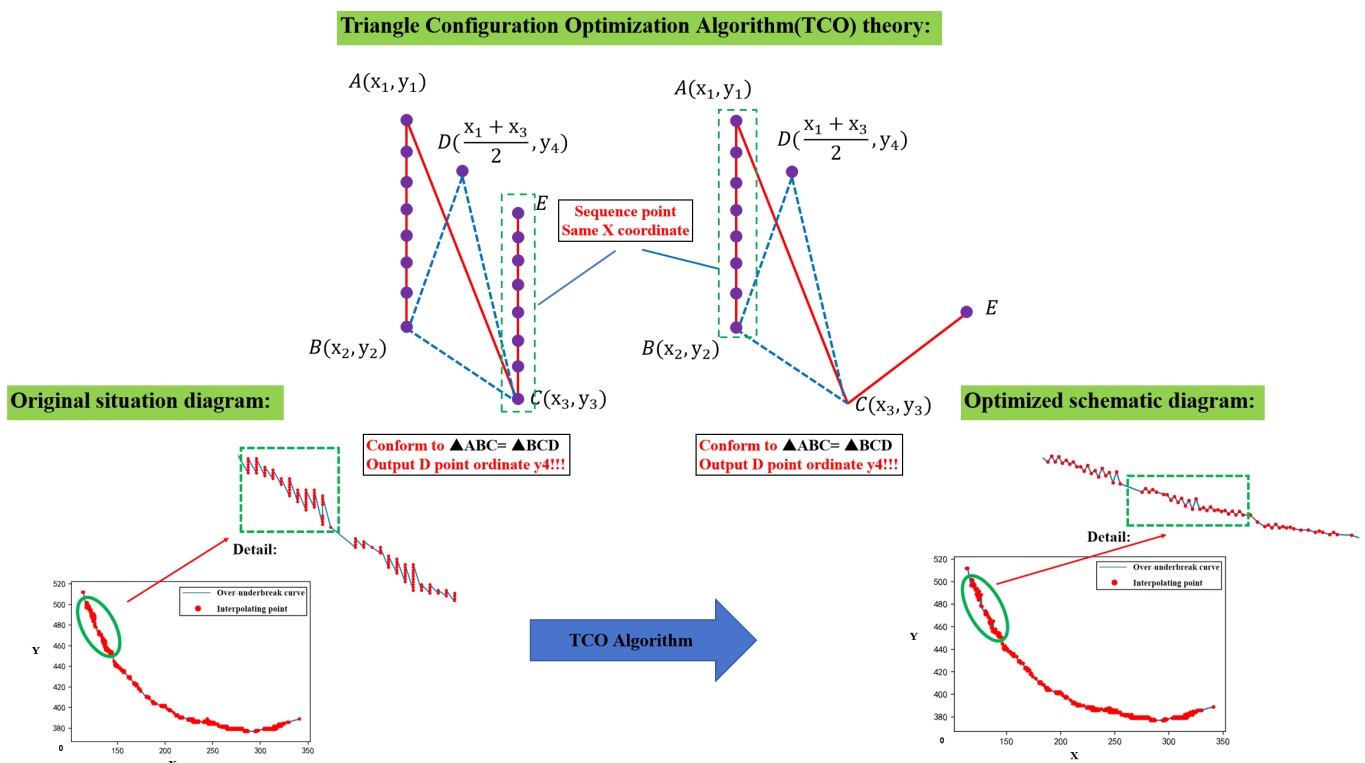


Figure 10. Process flowchart of “Triangle Configuration Optimization Algorithm” (TCO).

Due to the width of the lines, the same X value of the curve shown in Figure 10 corresponds to multiple Y values, which affects the fitting of the overbreak–underbreak curves. In order to preserve the characteristics of the curve as much as possible, this study adopts the idealized treatment that the area of triangle ABC and triangle BDC are equal, which is called the “Triangle Configuration Optimization Algorithm”.

Step 6: Accurately functionalize the overbreak–underbreak curve using the “Triangle Configuration Optimization Algorithm”, and divide it into left half curve and right half curve. Two methods are adopted, namely Python’s built-in interpolation method and Python’s self-developed interpolation method. The built-in interpolation method of Python uses the two-point formula of a straight line, while the self-developed interpolation method of Python uses the point–slope formula of a straight line. These two methods can mutually

verify the accuracy of the interpolation results. The whole overbreak–underbreak profile curve is utilized in the form of a piecewise function by solving the line piecewise.

Step 7: This step involves dividing the area of the overbreak–underbreak curve. In the process of tunnel construction, technicians divide the different positions of the tunnel profile into the vault, arch waist, and arch foot. This study is divided into a region every 36° clockwise, namely the left arch foot 0° – 36° , left arch waist 36° – 72° , vault 72° – 108° , right arch waist 108° – 144° , and right arch foot 144° – 180° . This study divides the overbreak–underbreak curve into 5 equal parts in terms of angles, and selects the center point of the boundary between the upper and lower steps of the profile section. Different straight lines passing through this point divide the overbreak–underbreak curve of the upper step into five specific areas—left arch foot, left arch waist, vault, right arch waist, and right arch foot—with equal divisions of 36° .

The analysis and calculation process of the visualization algorithm of overbreak–underbreak based on Python image processing is shown in Figure 11.

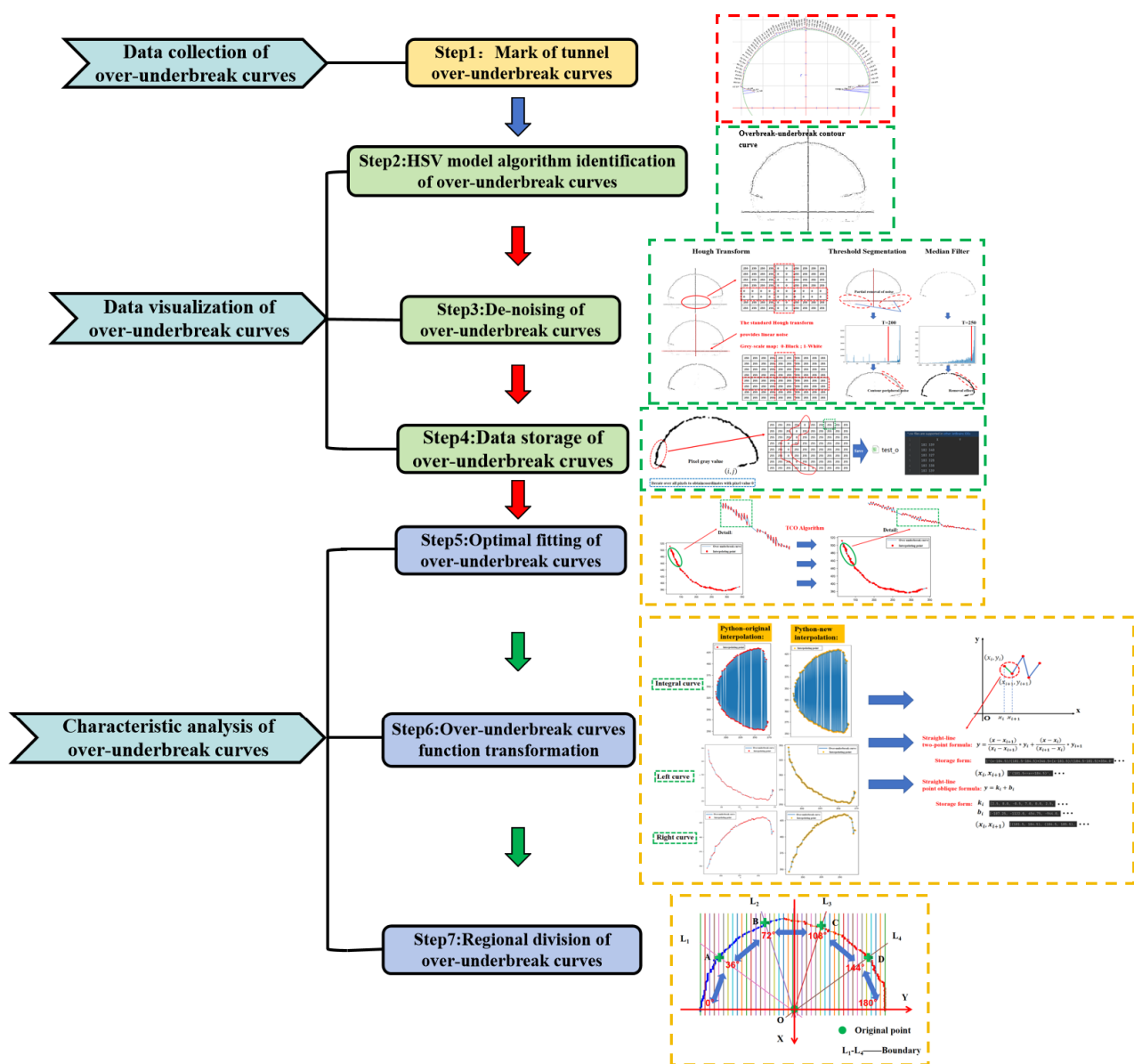


Figure 11. The analysis and calculation process of visualization algorithm of overbreak–underbreak based on Python image processing.

3. Results and Discussion

3.1. Analysis of Blasting Vibration Data on Site

3.1.1. Analysis of Blasting Vibration Velocity Characteristics

In order to accurately obtain the blasting vibration characteristics of different structures around the target tunnel, the data obtained from more than 30 tunnel sections blasting monitoring are selected. Among them, the different monitoring areas are four different locations: target tunnel, adjacent tunnel, residential buildings, and mountain slopes. The maximum single charge corresponding to blasting at different section positions is between 32.4 and 51 kg. The peak blasting vibration velocity of different monitoring points at different positions from the blasting source is shown in Figures 12–15.

1. Target tunnel

In the analysis of target tunnel blasting vibration velocity, the Z-axis vertical blasting vibration velocity presents the maximum value, followed by the Y-axis horizontal tangential blasting vibration velocity, and the X-axis horizontal radial velocity is the lowest. We prove that the Z-axis vertical vibration wave contributes the most to the vibration response of target tunnel.

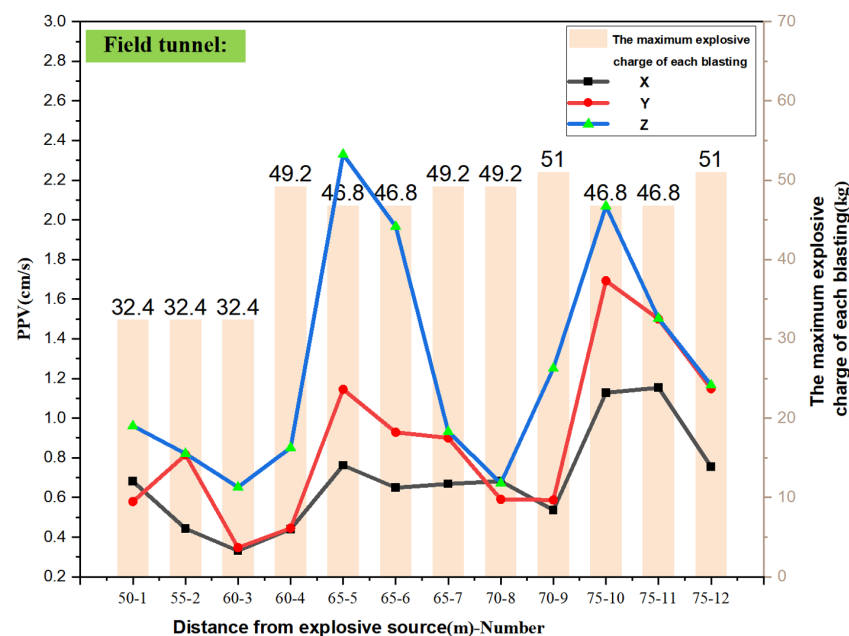


Figure 12. Blasting vibration velocity distribution at target tunnel monitoring points.

2. Residential buildings

Analysis of blasting vibration velocity at residential area measurement points revealed that the blasting vibration velocity in the Z-axis vertical direction showed the maximum value, while the Y-axis horizontal tangential blasting vibration velocity and X-axis horizontal radial velocity showed a similar pattern. We prove that the Z-axis vertical vibration wave has the greatest contribution to the vibration response of residential buildings. According to the literature analysis, the Z-axis vertical direction belongs to the vibration direction of the seismic shear wave. Since the amplitude of the shear wave is larger than the longitudinal wave and the damage energy level is higher, it is the main culprit for the Z-axis vertical direction blasting vibration velocity of residential buildings [49].

3. Adjacent tunnel

Analysis of blasting vibration velocity at adjacent tunnel measurement points revealed that the blasting vibration velocity in the X-axis horizontal radial direction showed the

maximum value, while the Y-axis horizontal tangential blasting vibration velocity and the Z-axis vertical direction velocity showed a similar pattern. We prove that the X-axis horizontal radial vibration wave contributes the most to the vibration response of adjacent tunnels.

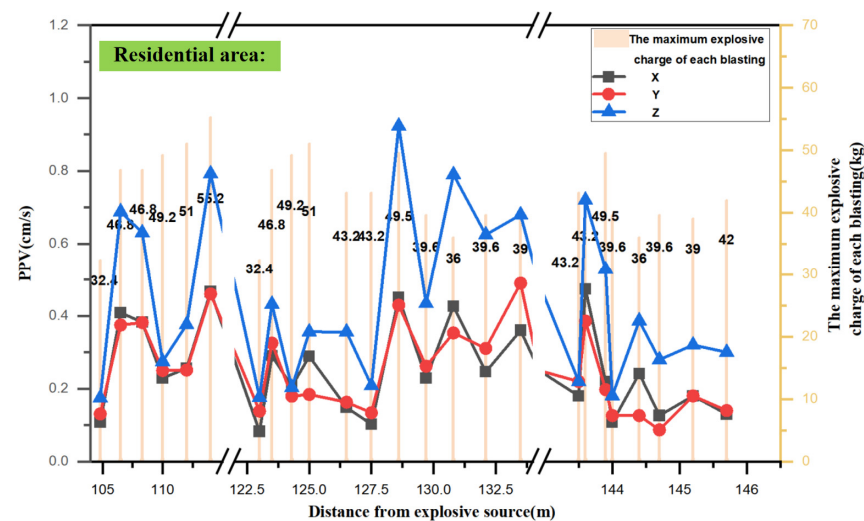


Figure 13. Blasting vibration velocity distribution at residential area monitoring points.

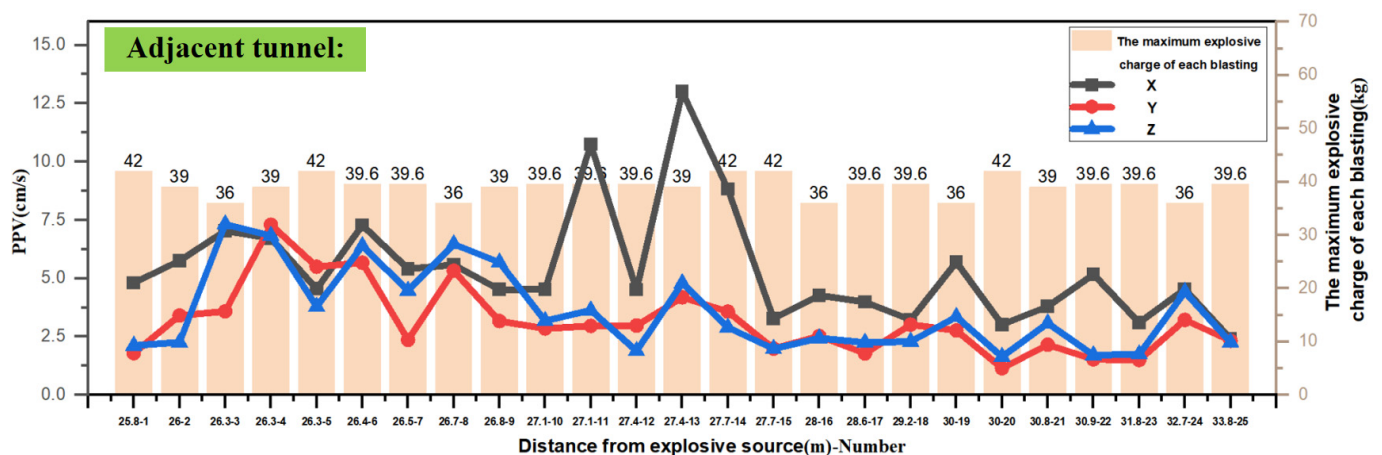


Figure 14. Blasting vibration velocity distribution at adjacent tunnel monitoring points.

4. Mountain slopes

In the analysis of mountain slopes blasting vibration velocity, the Z-axis vertical blasting vibration velocity presents the maximum value, followed by the Y-axis horizontal tangential blasting vibration velocity, and the X-axis horizontal radial velocity is the lowest. We prove that the Z-axis vertical vibration wave has the greatest contribution to the vibration response of mountain slopes. Due to mountain slopes and the placement of residential area measurement points on the same side of the monitoring section, the Z-axis vertical blasting vibration velocity in the same direction as the seismic shear wave has a greater impact.

Some of the literature shows that PPV changes with detonation distance and charge amount, but this trend is not obvious from the analysis of collected blasting vibration data. This is due to uncontrollable factors such as the complexity of geological conditions [11,50]. Although the acquisition of monitoring data is performed in the excavation section with similar geological conditions, it is still affected by other uncontrollable variables. Meanwhile, the data from this target tunnel, residential buildings, and mountain slopes show the same conclusion that the Z-axis vertical blasting vibration velocity is the largest, but the data of adjacent tunnel show the X-axis horizontal radial vertical blasting vibration

velocity is the largest. The directional phenomenon is caused by the difference in measurement point layout directions between the former and the latter. Hence, further monitoring research requires strict control of variables to draw more precise conclusions.

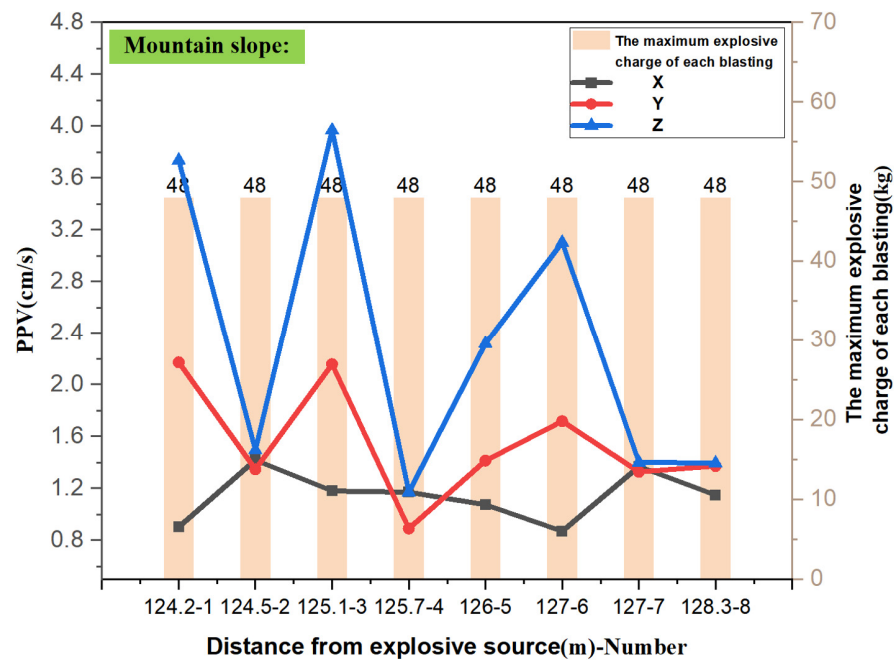


Figure 15. Blasting vibration velocity distribution at mountain slope monitoring points.

3.1.2. The Attenuation Law of Blasting Vibration Velocity in Different Areas

According to the analysis of the characteristics of blasting vibration velocity, there are differences in the blasting vibration velocity in the X, Y, and Z directions of monitoring points in different regions. The values of blasting vibration velocity at the target tunnel, residential buildings, and mountain slopes in the Z-axis direction are much higher than in the X-axis and Y-axis directions, while the value of the X-axis horizontal radial velocity at the adjacent tunnel measurement points is the highest. In order to analyze the attenuation law of blasting vibration velocity in different tunnel areas, the traditional empirical formula of Sadowski is used in this study. This formula is based on the fitting of the peak blasting vibration velocity (PPV) with two factors, namely the blast center distance (R) and the maximum single charge quantity (Q). The peak velocity of blasting vibration is selected as the velocity component in the dominant direction at the monitoring point. The Z-axis vertical velocity is selected as the measurement point at the target tunnel, residential buildings, and mountain slopes, while the X-axis horizontal radial velocity is selected as the measurement point at the adjacent tunnel. The fitting formula is shown below:

$$PPV = K \left(\frac{R}{Q^{\frac{1}{3}}} \right)^{-\alpha} \quad (2)$$

In the formula, R is the distance from the blasting source center, Q is the maximum single charge quantity, K is the proportional coefficient, and α is the site correlation coefficient. To perform linear fitting, logarithmize both sides of formula (2) to obtain formula (3):

$$\ln PPV = \ln K - \alpha \ln \frac{R}{Q^{\frac{1}{3}}} \quad (3)$$

Simplify formula (3) to (4), so that $y = \ln PPV$, $A = \alpha$, $B = \ln K$, $SD = R/Q^{1/3}$, and $x = \ln SD$:

$$y = B - Ax. \quad (4)$$

Linear fitting of the above steps is carried out on the data of monitoring points. Figure 16 shows the fitting results of the peak vibration velocity of blasting vibration at the monitoring points of the target tunnel, residential buildings, the adjacent tunnel, and mountain slopes, respectively. It can be observed that the attenuation law of blasting vibration at different monitoring points on different areas has differences in characteristics. Table 3 presents the corresponding fitting equations, in which the α values of the fitting equations for the target tunnel, residential buildings, and mountain slopes are 1.52, 1.45, and 1.23, respectively. The three values are similar, which proves that there is little difference in the geological lithology parameters of these blasting experiments. Meanwhile, the α value of the adjacent tunnel is 2.02, which is much different from the former. The reason is that the location of the measuring point is contrary to other measuring points. The monitoring points at the target tunnel, residential buildings, and mountain slopes are on the right side of the center line of the blasting source, and the adjacent tunnel is on the left side. Based on the geological radar detection in Figure 17, it can be seen that the fracture development and the presence of muddy rock layers near the tunnel monitoring points may lead to a larger α value. The proportional parameter K values are 58.25, 60.26, 411.86, and 90.51, respectively, with significant differences, indicating that the distribution of measurement points in different areas has an impact on the attenuation of blasting vibration velocity.

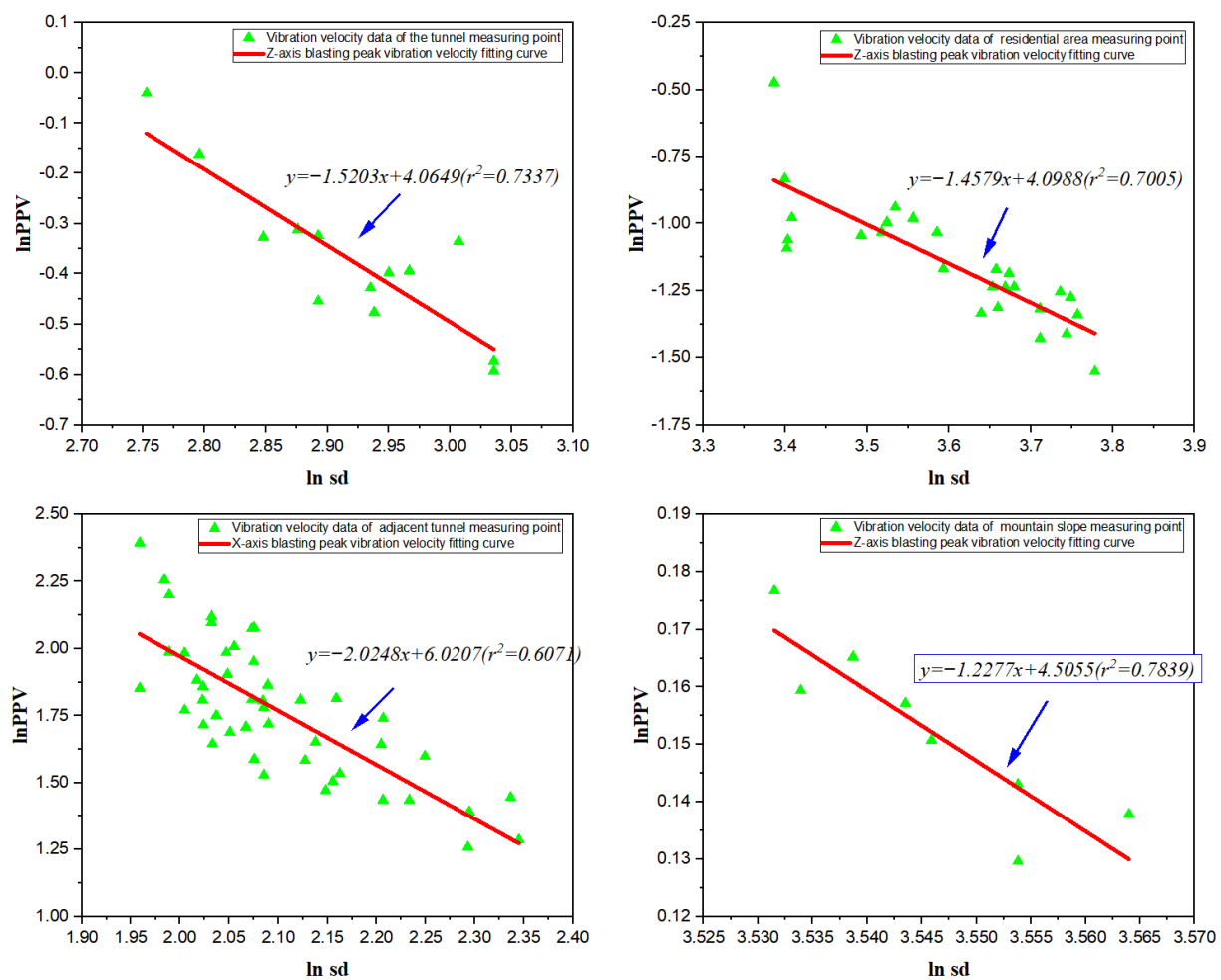
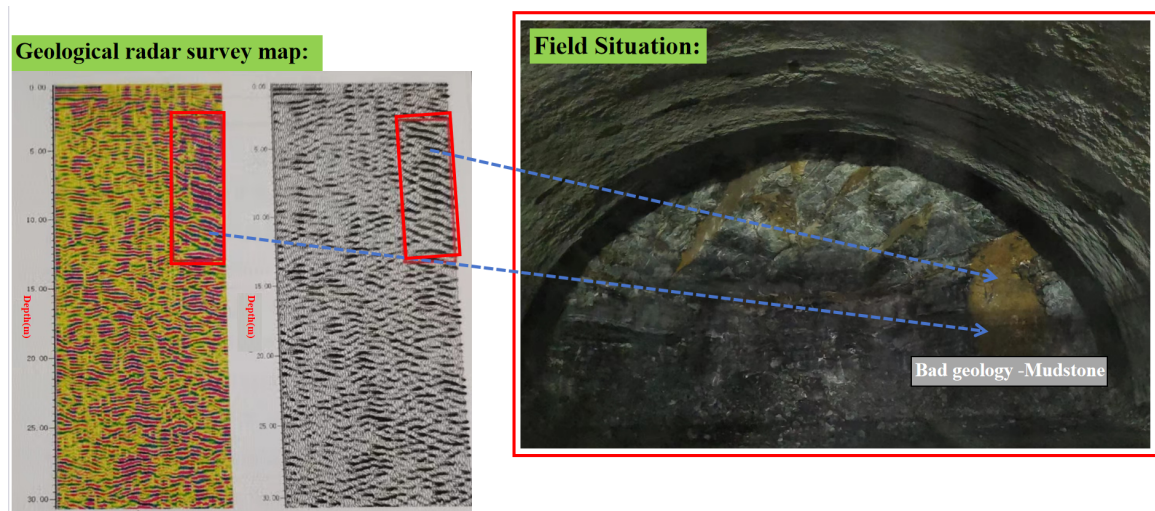


Figure 16. Fitting results of blasting vibration velocity attenuation at monitoring points in different areas.

Table 3. The attenuation law of blasting peak vibration velocity at different areas.

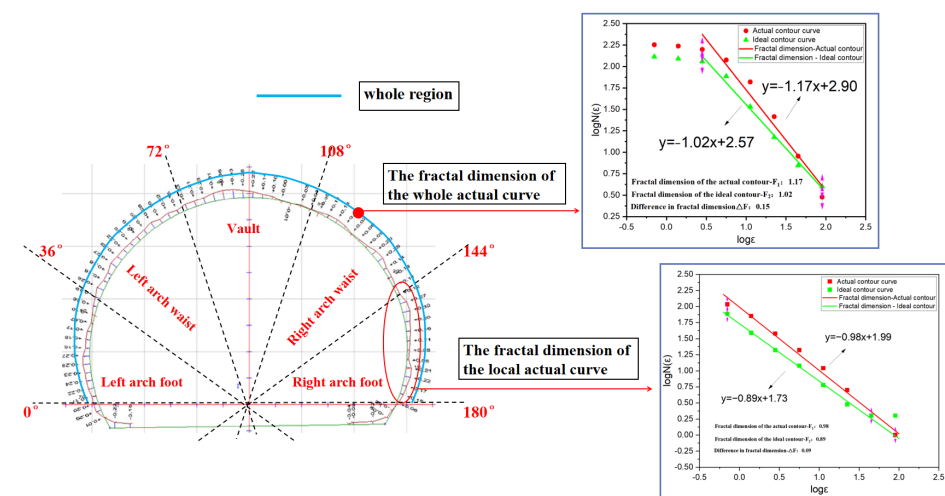
Position	Proportionality Coefficient-K	Site Coefficient- α	Fitting Formula
Target tunnel	58.25	1.52	$PPV = 58.25 \cdot SD^{-1.52}$
Residential areas	60.26	1.45	$PPV = 60.26 \cdot SD^{-1.45}$
Adjacent tunnel	411.86	2.02	$PPV = 411.86 \cdot SD^{-2.02}$
Mountain slopes	90.51	1.23	$PPV = 90.51 \cdot SD^{-1.23}$

Note: SD (scaled distance) represents $r/q^{1/3}$.

**Figure 17.** Geological radar detection information map.

3.2. Analysis of Tunnel Overbreak–Underbreak Data

Based on the overbreak–underbreak curve data obtained in Section 2.5 above, the fractal algorithm is used to calculate the fractal parameters of the tunnel profile. The calculation diagram is shown in Figure 18. Brenner Base Tunnel (BBT) [45] and a short mountain tunnel in southwest China are taken as cases for analysis. The figure shows the fractal results of a certain cross-sectional profile curve from the overall analysis to the analysis of five different regions. The absolute value of the slope of the fitted curve in each graph represents the boxing-counting dimension by processing the data of the tunnel overbreak–underbreak.

**Figure 18.** Fractal dimension calculation diagram of tunnel profile curves. (See reference [45] Figure 9b). Reproduced with permission from Automation in Construction granted copyright by Central South University; published by ELSEVIER, 2019.

3.2.1. Brenner Base Tunnel (BBT) Case

The fractal analysis results of this case are shown in Figure 19. The fractal dimension value of the actual profile curve is larger than that of the ideal profile curve, because the actual profile surface generated by blasting is sharp and uneven, exhibiting an increase in fractal dimension value in a geometric sense. From the fractal dimension values of the overall profile curve, the fractal dimension of the ideal profile curve is close to 1 while the actual profile curve is greater than 1, because the ideal profile of the tunnel is close to a semicircle, and the fractal dimension of the semicircle curve is exactly 1. From the fractal dimension values of the ideal profile curves in various local areas, the value close to 0.88 is a fixed value, which proves that the contour surface is not in the form of an ideal semicircle but in the form of an arc with a fractal value of 0.88. Therefore, the specific tunnel profile has a specific value.

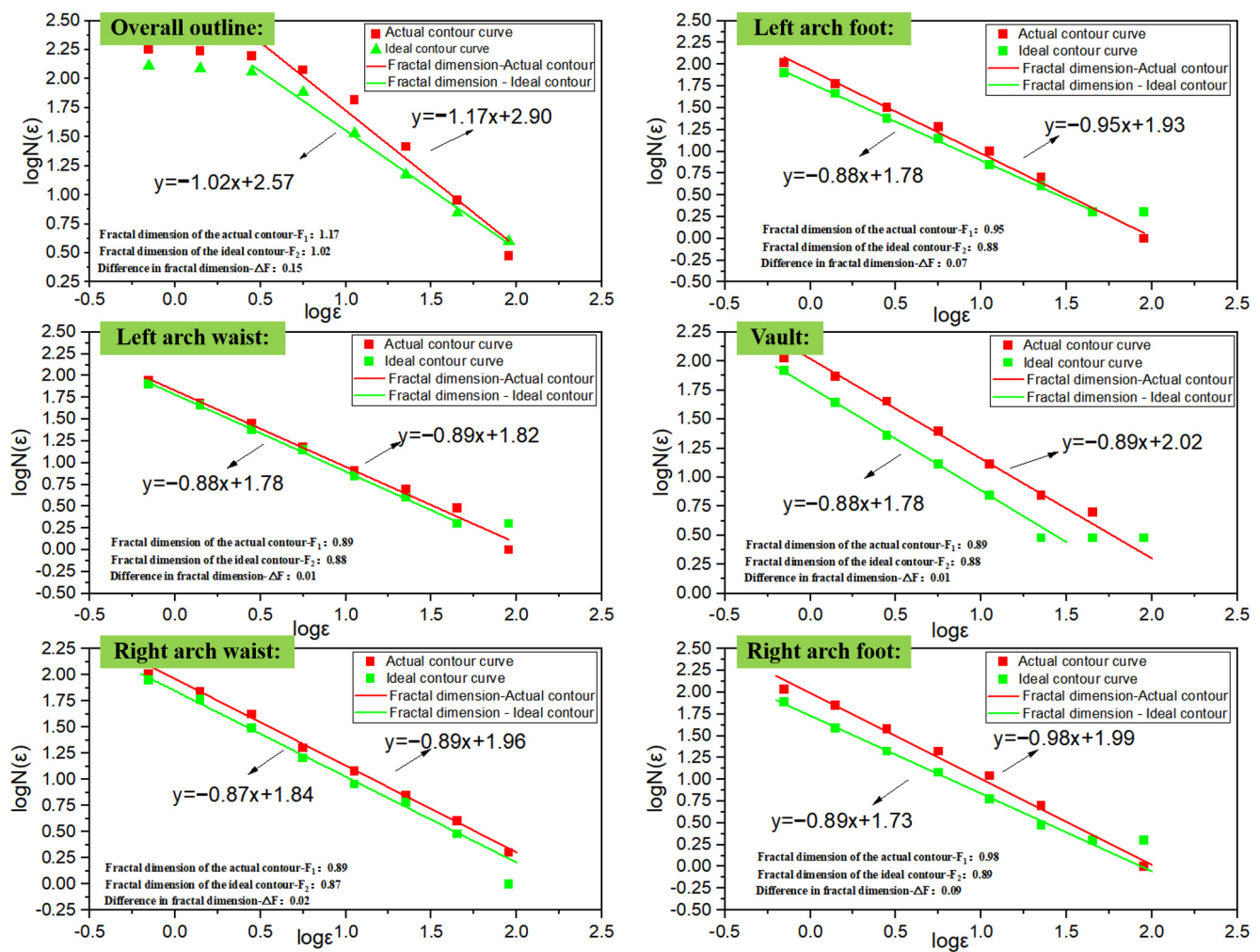


Figure 19. Calculation and analysis of fractal dimension of profile curves in different regions.

By comparing the fractal difference between the actual profile curve and the ideal profile curve in different local areas, it is found that the fractal dimension difference between the two arch foot regions is the largest, followed by the vault region, and the smallest is the two arch waists regions. From the on-site photograph, the degree of profile roughness after blasting in the area of the two arch foot is far worse than that in the area of the two arch waists and the vault, while the degree of roughness in the area of the two arch waists is smaller, as shown in Figure 20. Therefore, the difference in fractal dimension plays an important role in evaluating the roughness of the tunnel blasting profile.

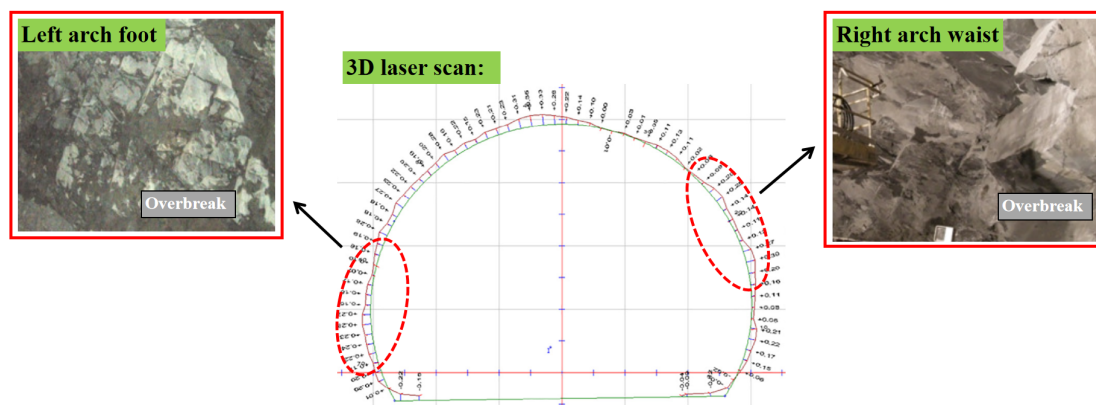


Figure 20. On-site investigation results of a profile the BBT tunnel case. (See reference [45] Figures 9b and 11). Reproduced with permission from Automation in Construction granted copyright by Central South University; published by ELSEVIER, 2019.

The degree of roughness of the tunnel profile curve can be expressed using the fractal dimension. However, in order to obtain the corresponding overcut and undercut values of different angles more accurately, the calculation results of the calculation program set by Python software 3.7 are compared and verified using the on-site measured values. The actual overbreak–underbreak values on site are measured at intervals of 2.5° . The calculated results are shown in Figure 21. The ratio of the measured value to the calculated value is between 85 and 115%, with an error of only $\pm 15\%$, indicating that the calculated result is relatively accurate.

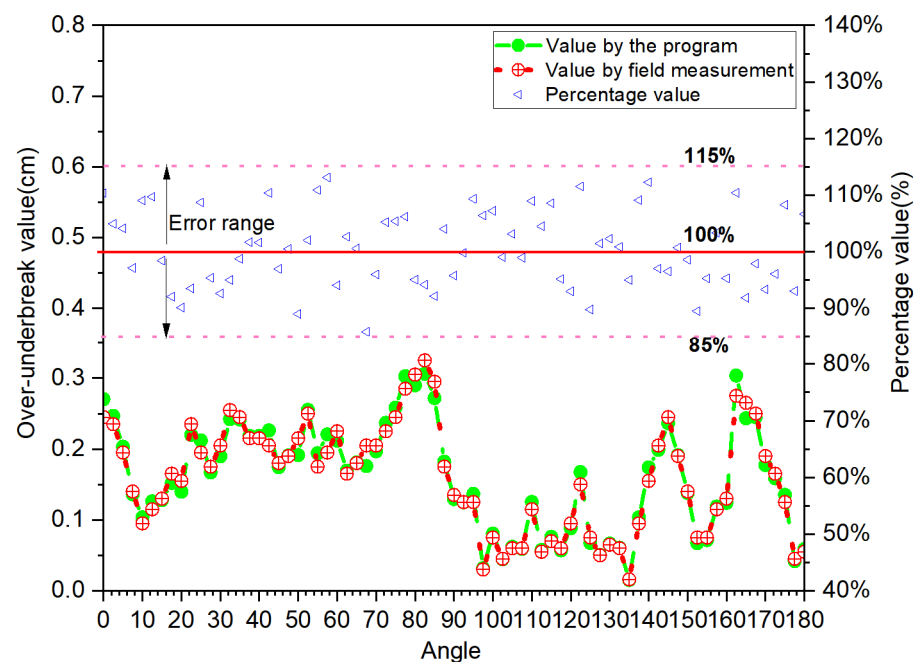


Figure 21. Verification results of overbreak–underbreak value calculation.

3.2.2. A Short Mountain Tunnel in Southwest China Case Study

The results on site measured using the ZT-30 total station and Hovermap 3D laser scanner were analyzed in combination with the image processing method proposed in Section 2.5. Figure 22 shows the calculation results of overbreak–underbreak at a distance of 50m from the entrance of the target tunnel. The fractal value of the overall overbreak–underbreak profile of the section is 1.11, while the fractal value of the ideal design profile is 0.99, which is close to 1 and approximates the fractal value of a circle. Figure 22 shows

the analysis results of different regions of the left arch foot, left arch waist, vault, right arch waist, and right arch foot, respectively. In different regions, the ideal fractal value of the design profile approaches a constant value of around 0.80. The difference between the actual fractal dimension value and the ideal design contour fractal dimension value at the arch foot and arch waist is larger than that at the arch waist. Therefore, it can be inferred that the profile is not smooth and the crack propagation effect is not good after blasting in these places. Figure 23 shows the comparison between the overbreak–underbreak values calculated using the image processing method and the overbreak–underbreak values measured using on-site instruments. As shown in the figure, the accuracy rate of the image processing method adopted in this study is above 85%, and the error fluctuates within the range of 15%.

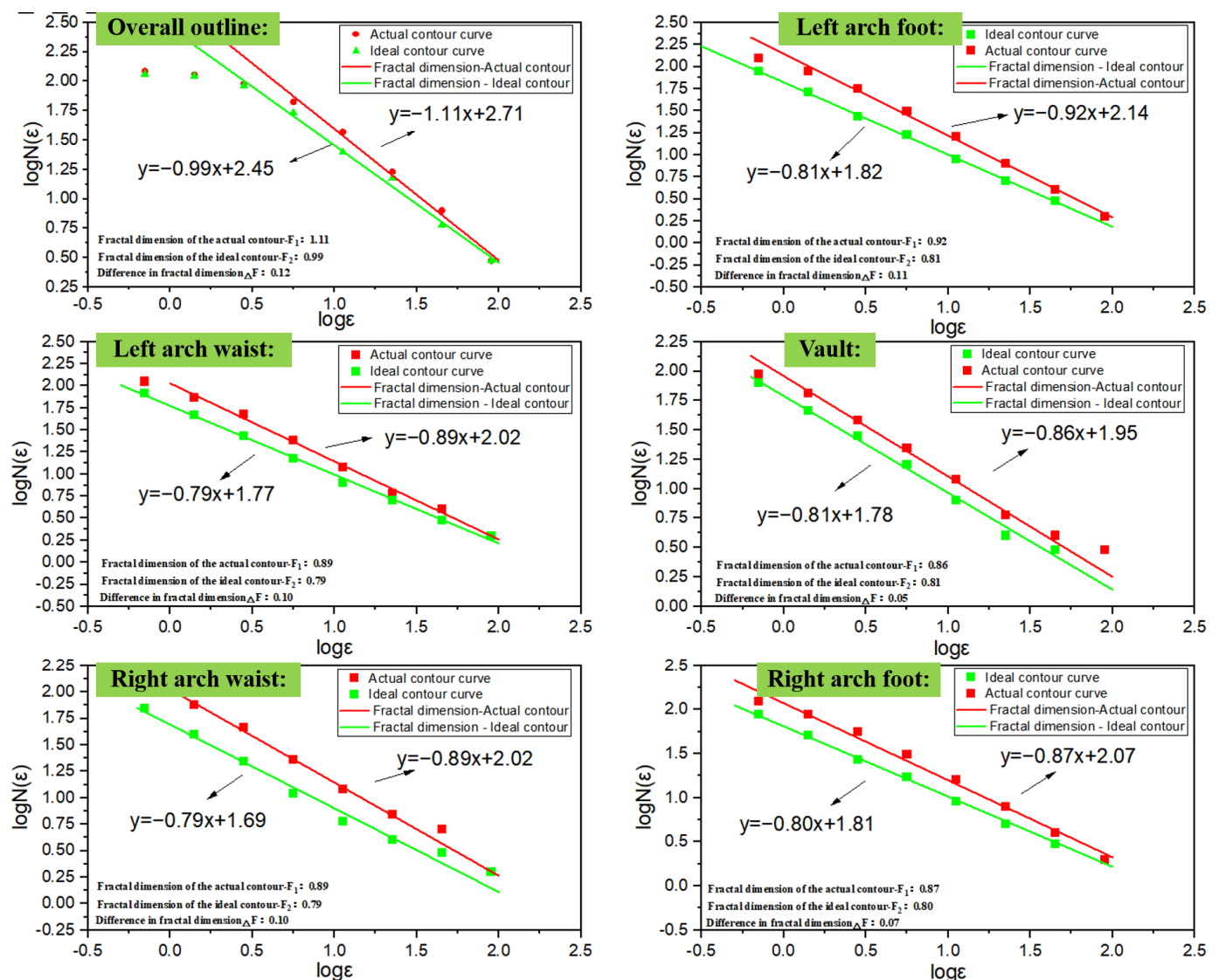


Figure 22. Calculation results of target tunnel profile fractal dimension value.

Table 4 is a summary of the calculation results of fractal dimensions of different tunnel profiles. According to the results in the table, the fractal dimension of the overbreak–underbreak profile of the target tunnel is analyzed in the range of 1.09–1.11, and similar results are also obtained in the relevant literature [51,52]. The fractal dimension values of overbreak–underbreak profiles vary in different regions. By comparing the difference between the fractal dimension values of the overbreak–underbreak profile and the design

profile, it is found that the fractal dimension difference of the arch waist is the largest, followed by the fractal dimension difference at the arch foot and the vault. Figure 24 shows the on-site investigation results of the target tunnel. The blasting effect at the arch waist and arch foot is poor, which is prone to overbreak–underbreak. Therefore, it is necessary to optimize the peripheral holes in these areas.

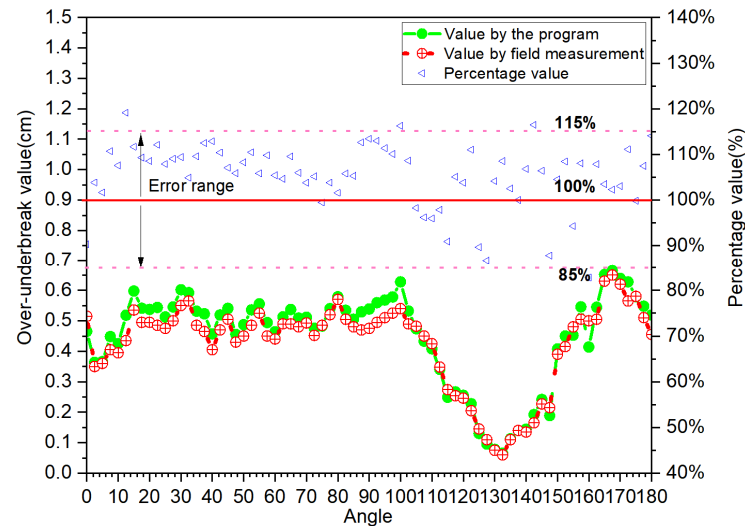


Figure 23. Analysis and calculation results of relevant parameters for target tunnel overbreak–underbreak.

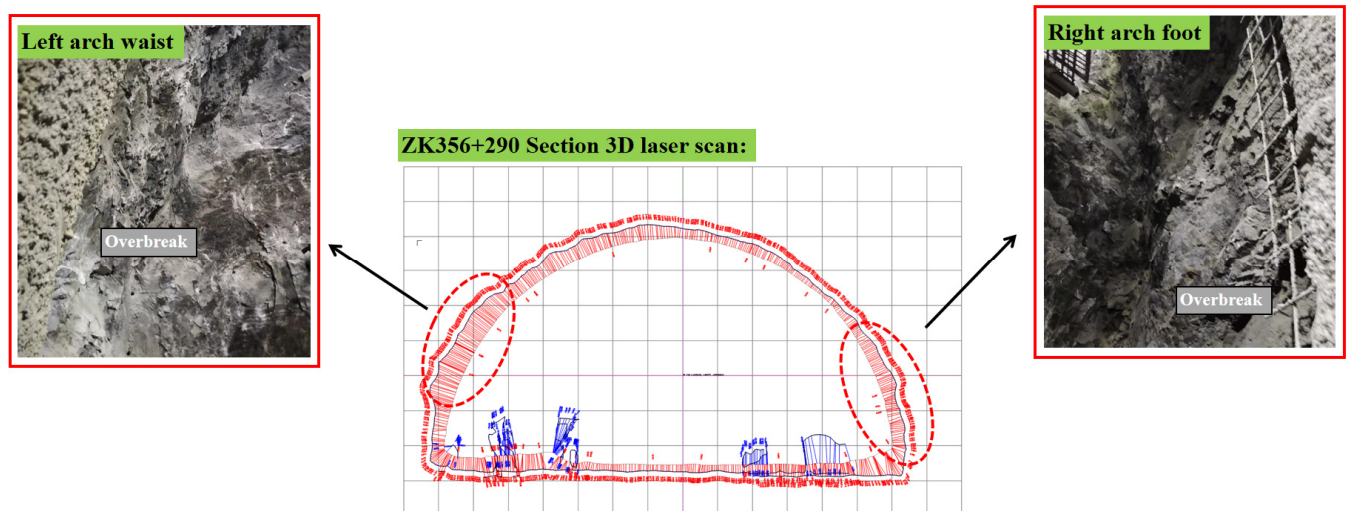


Figure 24. On-site investigation results of the target tunnel profile.

Table 4. Calculation results of fractal dimension of different tunnel profiles.

Profile Position	Fractal Dimension Values of Different Regions																	
	Overall Profile			Left Arch Foot			Left Arch Waist			Vault			Right Arch Waist			Right Arch Foot		
	A	I	ΔD	A	I	ΔD	A	I	ΔD	A	I	ΔD	A	I	ΔD	A	I	ΔD
50 m	1.11	0.99	0.12	0.92	0.81	0.11	0.89	0.79	0.10	0.86	0.81	0.05	0.89	0.79	0.10	0.87	0.80	0.07
53 m	1.13	1.01	0.12	0.91	0.82	0.09	0.91	0.78	0.13	0.83	0.80	0.03	0.91	0.80	0.11	0.85	0.79	0.06
56 m	1.09	0.99	0.11	0.88	0.80	0.08	0.90	0.79	0.11	0.84	0.81	0.03	0.93	0.81	0.12	0.84	0.80	0.04
59 m	1.12	0.98	0.14	0.89	0.80	0.09	0.92	0.80	0.12	0.85	0.80	0.05	0.90	0.79	0.11	0.86	0.79	0.07
62 m	1.11	1.01	0.10	0.88	0.81	0.07	0.93	0.81	0.12	0.86	0.81	0.05	0.92	0.80	0.12	0.88	0.81	0.07
65 m	1.10	0.99	0.11	0.90	0.81	0.09	0.91	0.79	0.12	0.85	0.81	0.04	0.91	0.80	0.11	0.87	0.81	0.06

Note: A—Actual, I—Ideal, ΔD—Difference.

3.3. Analysis of Optimization Effect of Tunnel Blasting Scheme

Through on-site investigation of the blasthole layout, the utilization rate of blastholes, the effect of overbreak–underbreak, and the optimization plan, smooth blasting was proposed in combination with the site condition, as shown in Figure 9 of Section 2.4. The spacing of tunnel peripheral holes in the original scheme is adjusted from 0.6 m to 0.45 m, the thickness of smooth blasting layer is adjusted from 0.6 m to 0.55 m, the distance between the primary cutting hole and the tunnel center line is adjusted from 2 m to 2.5 m, the distance between the secondary cutting hole and the tunnel center line is adjusted from 2.5 m to 3.0 m, and the total number of blastholes is adjusted to 147.

Overall, in terms of drilling operations and charging, the total number of blastholes, the total length of blastholes, and the total powder charge increased by 20%, 10%, and 14% respectively. But, the optimized scheme shows a good effect in the aspect of vibration reduction via blasting. The adjacent tunnel monitoring points peak blasting vibration velocity at a distance of 5 m and 15 m from the blasting source decreased by 26% and 7%, respectively. Meanwhile, in terms of tunnel profile control, the fractal dimension of the overbreak–underbreak profile, the maximum roughness, and the dosage of shotcrete reduced by 26%, 8%, and 65% respectively (as Table 5). Therefore, the optimized scheme can effectively meet the safety and efficiency requirements of on-site blasting construction.

Table 5. Comparison between the original scheme and the optimized scheme.

Blasting Parameter	The Original Scheme	The Optimized Scheme	Effect (Growth rate)
Number of blastholes	121	147	21%
Total length of blastholes/m	411.8	451.2	10%
Total powder charge/kg	134.4	153	14%
5 m PPV cm/s	10.37	7.68	−26%
15 m PPV cm/s	3.11	2.87	−8%
Depth of cutting hole/m	4.8	Primary cutting hole: 4.5 Secondary cutting hole: 3.1	-
Distance between the cutting hole and the tunnel center line/m	3.0	2.5	-
Distance between peripheral holes/m	0.6	0.45	-
Thickness of smooth blasting layer/m	0.6	0.55	-
Utilization ratio of blasthole/%	76%	90%	14%
the maximum roughness/cm	60 cm	25 cm	−26%
Profile fractal dimension value	1.21	1.09–1.11	−8%
Shotcrete dosage m ³ /m	15.61	5.33	−65%

3.3.1. Analysis of Vibration Reduction Effect at Adjacent Tunnel Measurement Points

In order to verify the vibration reduction effect of the optimized scheme, the vibration of the adjacent tunnel is monitored according to the similar blasting vibration monitoring points arranged in Section 2.2. The blasting vibration of the optimized blasting scheme is compared with that of the original scheme. The results are shown in Figure 25 below.

According to Figure 25, it can be seen that under the working condition of maintaining a 3 m advance for each cycle, using a two-stage compound wedge cutting form and drilling peripheral empty holes can effectively reduce the blasting vibration velocity in three directions of adjacent tunnel monitoring points. For the X-axis horizontal radial direction, the blasting peak vibration velocity is reduced by 19.8% from 12.31 cm/s in the original scheme to 9.87 cm/s in the optimized scheme. For the Y-axis horizontal tangential direction, the blasting peak vibration velocity is reduced by 14.9% from 11.47 cm/s in the original scheme to 9.76 cm/s in the optimized scheme. For the Z-axis vertical direction, the blasting peak vibration velocity is reduced by 7.5% from 10.44 cm/s in the original scheme to 9.65 cm/s in the optimized scheme.

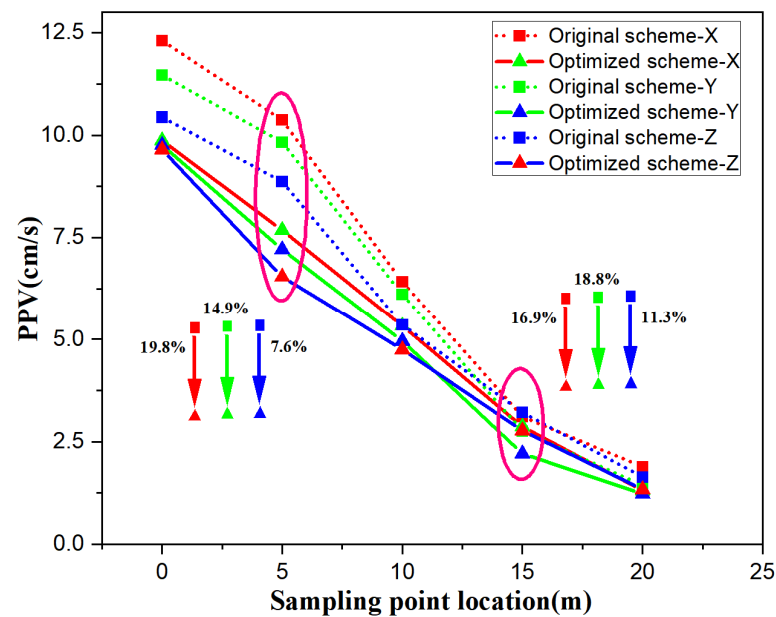


Figure 25. Comparison of the original scheme and the optimized scheme peak blasting vibration velocity.

3.3.2. Analysis of Smooth Blasting Effect of Tunnel

According to the drilling survey in Figure 26, it was found that the utilization rate of blastholes is more than 90% and clear half-hole traces can be left on the tunnel profile-wall after blasting.

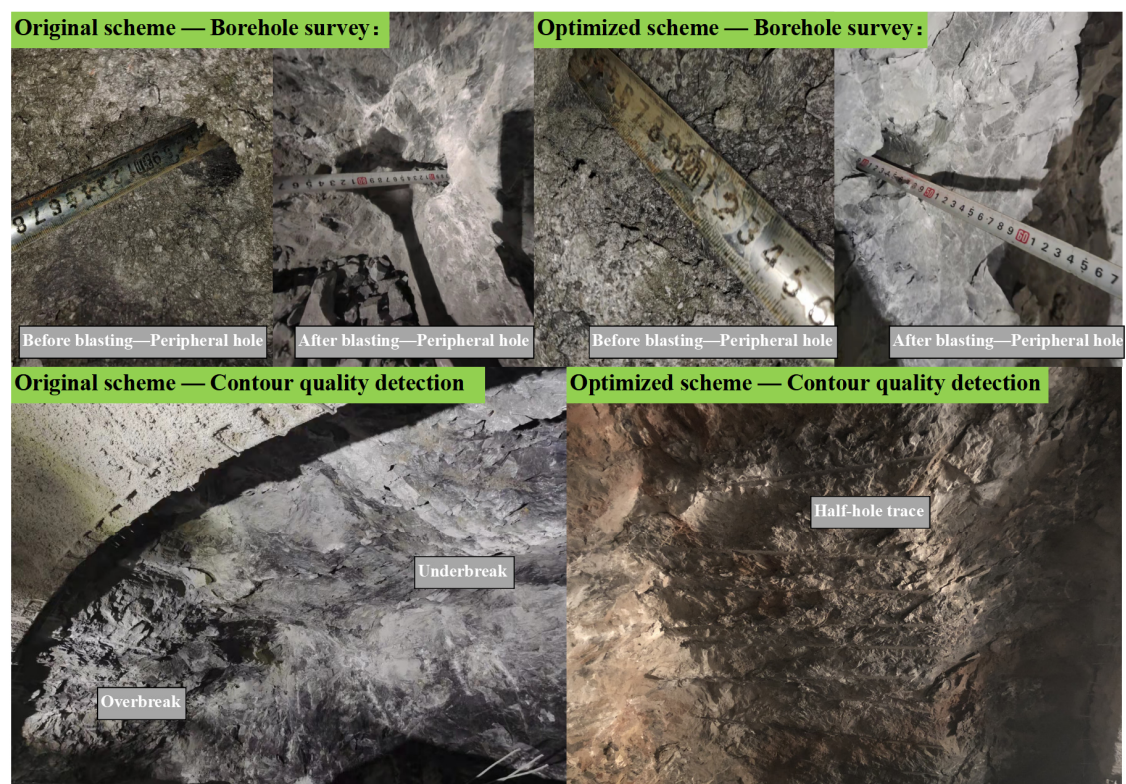


Figure 26. The blasting drilling survey and the half-hole traces on site.

As above, the blasting parameters depend on the rock mass along the tunnel route. With on-site blasting experiments, they can only be determined to not correspond to these explored geological parameters; these parameters can be optimized. The application

of smooth blasting occurs in order to ensure the stability of the surrounding rock mass orientationally and reduce overbreak and underbreak [53,54].

4. Conclusions

In order to explore the vibration response rule of tunnel excavation using the drilling and blasting method and control the quality of the tunnel profile, this study used a blasting excavation project on the right-line of a mountain tunnel in southwest China as the background. This study employed methods such as on-site monitoring, blasting experiments, and image processing. Through the vibration monitoring of blasting excavation on the upper step of the tunnel, the characteristics of blasting vibration and the attenuation law of peak vibration velocity of different areas such as the target tunnel (right-line), the adjacent tunnel (left-line), residential areas, and mountain slopes were analyzed. Based on the quality monitoring of tunnel profile overbreak–underbreak, the corresponding image processing method was developed using Python and the fractal characteristics of tunnel profile overbreak–underbreak were analyzed in combination with fractal theory. Based on the problem of tunnel blasting construction and excavation, the blasting scheme for the upper step on the right-line was optimized, achieving tunnel vibration reduction and profile quality control. The main research conclusions are as follows:

1. According to on-site blasting vibration monitoring technology, the vibration response law of the tunnel different areas during the construction of the upper step blasting were studied. The blasting vibration velocity of the target tunnel, residential areas, and mountain slopes were analyzed. The vibration wave in the Z-axis vertical direction contributed the most to the vibration response of the target tunnel, residential areas, and mountain slopes. Meanwhile, the blasting vibration velocity was analyzed at the adjacent tunnel. The vibration wave in Z-axis horizontal radial direction contributed the most to the vibration response of the adjacent tunnel.
2. By collecting and analyzing the blasting peak velocity data of different areas, the attenuation law of blasting vibration velocity in different areas of the target tunnel was revealed based on the Sadowski empirical formula. Sadowski's empirical prediction formula for different areas were constructed, which provided a theoretical basis for vibration control of the tunnel's right-line blasting construction.
3. A visualization method for tunnel the overbreak–underbreak profile was developed based on Python image processing technology combined with fractal theory. The fractal dimension value can analyze and evaluate the degree of overbreak–underbreak of the tunnel profile after blasting, to a certain extent. Taking the BBT tunnel and target tunnel as case studies of overbreak–underbreak analysis, it provides a new method for overbreak–underbreak evaluation. The comparison between the calculated overbreak–underbreak values using this method and the on-site measured values shows an error range of 15%, which can be used to effectively and accurately evaluate the blasting effect of the tunnel profile. Moreover, the findings of this study are limited to the data used in the study. Every underground excavation is unique and should be evaluated regarding its very unique properties. However, the fractal evaluation approach in this study can be used in any tunnel excavation. So, once the fractal value of tunnel excavation profile for any tunnel is identified, it can be easily applied by the crew.
4. Through on-site blasting experiments, the optimal design of a blasting scheme was carried out from the aspects of cutting hole form, detonator interval time, and the peripheral hole charge structure. The optimized design scheme can not only meet the requirements of tunnel blasting vibration control but also effectively control the problem of tunnel overbreak–underbreak.

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