

Article

Study on Dominant Frequency Attenuation of Blasting Vibration for Ultra-Small-Spacing Tunnel

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Abstract: The middle rock pillar in ultra-small-spacing tunnels is significantly narrow, and the stability of the primary support and lining are easily influenced by the blasting vibration wave from an adjacent tunnel. Therefore, understanding the vibration frequency characteristics is essential for the blasting vibration control. Based on the blasting works on a double-track roadway tunnel (Jiuwuji tunnel in Guizhou, China), this study investigates the dominant frequency attenuation in the preceding tunnel with the middle rock pillar spacing ranging from 4.0 m to 9.4 m. The results show that the ranges of the dominant frequency distributions on the primary support and lining are widely within 200 Hz, but there are varieties in their propagation laws. The distribution of the dominant frequencies on the primary support is broader than that on the lining; and the dominant frequencies are concentrated on a specific range when the lining is far from the blast face beside a particular value, which is not present on the primary support. As the presence of cavity and changing medium between the lining and the primary support, it made a significant contribution to the filtering the vibration waves. Furthermore, on the primary support, the high-frequency part of the vibration waves attenuates rapidly with distance, and then, the practical prediction equations describing dominant frequency attenuation were proposed. The comparison on frequency characteristics per delay for the millisecond delay blasting shows that multiple delay sequences blast contributes to a multi-structured amplitude spectrum of blast vibration waves; and the varies of the equivalent explosion sources dimensions and numbers of free surfaces in each blast delay resulting in diverse vibration waveforms. Finally, the dominant frequencies determined by different methods were compared, and the results show a nonlinear relationship between the ZCFs and DFs. The above research conclusion expands the understanding of blasting vibration in tunnel engineering, particularly in the frequency distribution.

Keywords: blast vibration; dominant frequency; ultra-small-spacing tunnel; prediction formulas



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1. Introduction

In blasting engineering, a part of the explosion energy is used to break a rock and the remainder is transmitted to the surrounding rocks by the blasting vibration waves [1,2], which may be a significant threat to the safety of the adjacent structure [3,4]. In small-spacing tunnels, after the primary support and secondary lining of the preceding tunnel are completed, its structure and the middle rock pillar may be affected by the blasting vibrations of the succeeding tunnel, which are manifested as seismic cumulative effects [5]. For example, the repeated blast loading during tunnelling works causes damages on jointed basalt rock masses [6]; and the cyclic blast excavations cause the critical damage PPV for the middle rock pillar drops significantly [7]. Meanwhile, the blast vibration waves may cause a decline in the bearing capacity of the rock [8,9] and some increases in the stress of

the anchors [10], concurrently, the excavation damaged zone and deformation modulus of the surrounding rock is also influenced [11]. Recently, owing to the limited space in mountainous areas, small-spacing tunnels are becoming common [12], where the clearance between two tunnels is much shorter than the safe distance to alleviate vibration waves, such as Eurasia Tunnel [13], El-Azhar roadway twin tunnels [14], Liuyuetian bifurcation tunnel [15], Heshang three-lane tunnel [16], and closely spaced triple tunnels in Badaling [17]. Periodic non-uniform natural seismic wave excitation causes shear deformation in underground constructions [18]. And one of the biggest differences between blasting vibration waves and natural seismic waves is the difference in frequency characteristics, where the seismic waves are in low frequency ranges and the blast vibration waves frequency is higher, generally greater than 5 Hz. Therefore, it is necessary to analyze the characteristics of blast vibration waves propagating in the area very close to the tunnels so as to help protect the tunnel structure.

The non-uniform seismic excitation, similar to blast vibration waves, has a great influence on the acceleration amplification in soil and the strain and displacement of the long deep buried pipeline [19]. In a tunnel affected by blast vibration waves, the dynamic stress of the structure is directly related to the peak vibration velocity (PPV) [20]. Xu [21] and Zhang [22] analyzed the effect of blast vibration waves on the safety of tunnel structures without considering the vibration frequency. However, the adverse effect of blast vibration waves is not only related to the vibration amplitude but also to the relationship between the dominant frequency of a blast vibration and the structural natural frequency. Evidently, Lv [23] found that the PPV at a tunnel wall is amplified compared to that of the incident vibration wave, and the amplification coefficient is positively correlated to the frequency of the blast vibration waves. Therefore, it is necessary to study the frequency distribution range of blast vibration waves. In the tunnel construction, Tian [24] found that the frequency range of blast vibrations is within 0–175 Hz, and the minimum distance between the blast source and the ground measurements point in the study was 30 m. However, the distance has an effect on the signal characteristics of the blast vibration wave. Koteleva [25] found that the frequency range is closely correlated with the distance values. Additionally, Zhou [26] established a mathematical relationship between the blast dominant frequency and its principal influencing factors. Triviño [27] found significant differences in the amplitude and spectrum of blast vibration signals collected separately at the surface and underground mines. Nevertheless, these studies on blast vibration frequencies in tunnels do not compare the characteristics of the frequency distribution on the primary support and the lining. In open-pit mines blast, Sun [28] compared the differences in the attenuation laws of three types of dominant frequencies caused by different blast charge structures. Blair [29] analyzed the frequency range of ground vibrations in detail in terms of the instantaneous frequency and by time-frequency analysis. Yang [30] and Liu [31] compared the frequency characteristics for the blast-induced vibration velocity signal at different delay sequences from a millisecond (ms) delay blast. These studies on the propagation law of blast vibration waves in open-pit mines provide useful guidance for the analysis of tunnelling blast vibration waves. Furthermore, Fourier variation is the most common method to analyze the characteristics of seismic waves [32], and these studies also provide a reference to analyzing blast vibration waves. Based on the above investigations, there is still a lack of research on blast vibration frequency distribution the tunnels with a small clearance; and a theoretical study on the prediction and distribution law of the dominant frequencies of blast vibrations still needs a large amount of engineering data for validation, particularly for the two-track tunnel that the distance between two tunnels less than a tunnel span.

In this study, a series of blast vibration tests were conducted on the background of a two-track roadway tunnel in which the clearance between the two tunnels is ranged from 9.4 m to 4.0 m. The blast vibration waves on the structure of the preceding tunnel, with completed primary support and secondary lining, were recorded, and analyzed; and the differences in the dominant frequency distributions on the primary support and

lining were compared. Thus, the differences in the spectrum analysis for complete waveform and the dominant frequency of different delay sequences were studied. Moreover, the relationship between the frequency determined by the different methods was analyzed.

2. Theory of Dominant Frequency

There are two common approaches for defining the dominant frequency of a blast vibration: zero-cross frequency (ZCF) and Fourier dominant frequency (hereafter DF). The ZCF, also known as apparent frequency [28], is determined based on the zero-crossing of the waveform peak; its definition is shown in Figure 1a. The DF corresponds to the peak amplitude in the Fourier power spectrum, as shown in Figure 1b. The mean frequency (MF) and instantaneous frequency (IF) have also been common in recent years. The MF is obtained by calculating the weighted mean of the Fourier amplitude spectrum using Equation (1), as shown in Figure 1b. The above four dominant frequencies are extensively used in research [28,29,31], with the ZCF and the DF being the most common.

$$MF = \frac{\sum f_i A(f_i)}{\sum A(f_i)} \quad (1)$$

where $A(f_i)$ is the amplitude corresponding to frequency f_i in the Fourier amplitude spectrum.

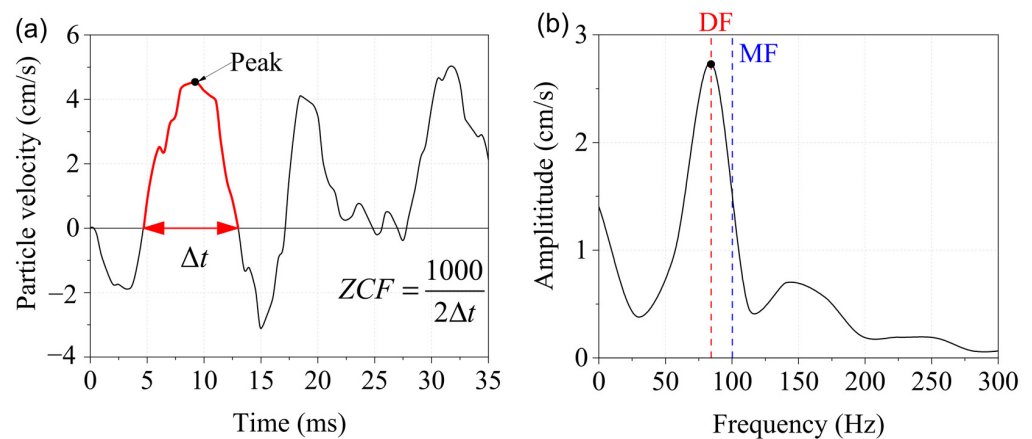


Figure 1. Definitions of three dominant frequencies [28]: (a) typical blast vibration waveform and (b) Fourier amplitude spectrum.

On the basis of the Chinese Safety Regulations for Blasting (GB6722-2014), a safety PPV criterion for traffic tunnels considering the blast vibration frequency has been proposed, and it defines the vibration frequency as that corresponding to the maximum amplitude of the particle velocity, i.e., the ZCF. However, in the regulations of other countries, such as DIN4150 of Germany and AS 2187.2 of Australia [33], the dominant frequency for a structured safety blast vibration is obtained by the Fourier transform. Sun [28] believed that the ZCF can better express the attenuation law of the dominant frequency than DF and MF, whereas according to Blair [29], the well-known zero-crossing method cannot be used to obtain the frequency associated with the peak vibration level. In addition, Nor'en-Cosgriff [4] found that the dominant frequencies determined by different methods vary significantly. Therefore, considering that there is no uniform method to describe the frequency in the current research on blast vibration waves, both ZCFs and DFs are used to describe the blast vibration frequency.

3. Field Test

3.1. Overview

The newly constructed Jiuwuji tunnel is a double-track tunnel located in the Xingyi Ring Expressway, Guizhou, China. The tunnel has a total length of 393 m and a maximum buried depth of 169 m; the exit of the tunnel is located on a steep hillside. As the blast

face was excavated from the entrance to the exit, the clearance between the two tunnels gradually decreased to 0.6 m, which belongs to the category of ultra-small-spacing tunnels. In the two tunnels, the left tunnel is a preceding one and the right tunnel is the succeeding tunnel. In this study, a series of blast vibration tests were conducted at clearance ranges from 9.4 m to 4.0 m. The blast vibration waves from the succeeding tunnel inevitably affected the structure of the preceding tunnel. The site conditions are shown in Figure 2. In the blasting test area, the average burial depth of the soil above the structures of the left and right tunnels is 100 m and 20 m, respectively; and the main surrounding rock of the tunnel is moderately weathered dolomite, with broken rock mass and developed joints and fissures.

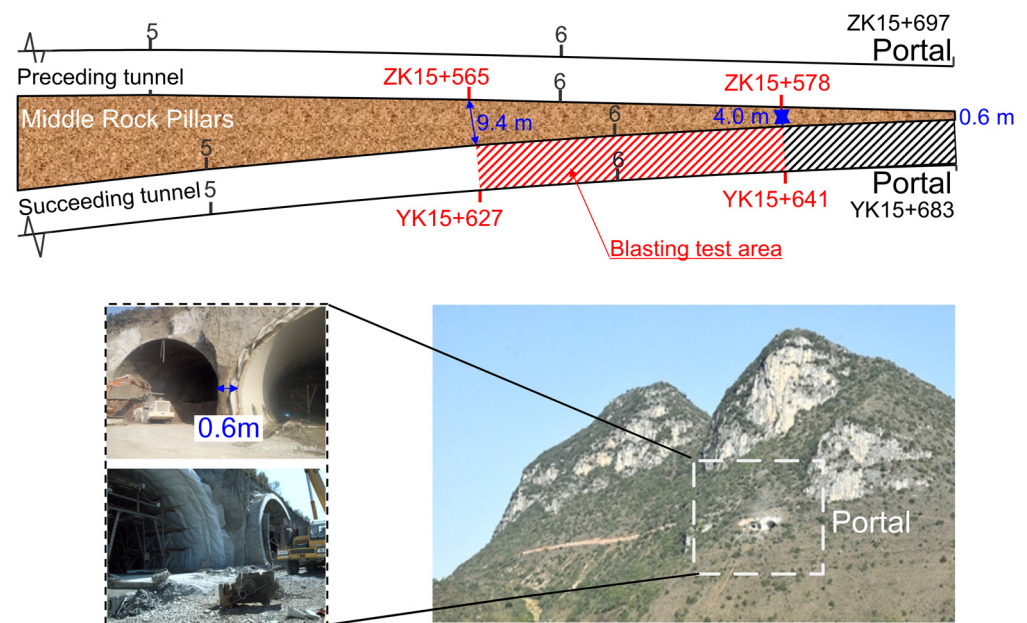


Figure 2. Site engineering conditions.

The design of the tunnel is shown in Figure 3. To ensure the safety and stability of the construction, the middle rock pillar was reinforced. Small grouting conduits were used. An extended hollow grouting bolt was set above the middle rock pillar, and four hollow grouting bolts were installed under the middle rock pillar, to reinforce the arch foot. The deformation space reserved for the primary support and the secondary lining was 15 cm.

3.2. Blasting Parameters

The typical blast parameters of the succeeding tunnel at the upper bench were recorded, and are shown in Figure 4 and summarized in Table 1. The blast section size was 15.7 m × 6.8 m (span × height). The blasting parameters were the basically same in each blast circle: the number of blastholes was approximately 140–150, and the footage per cycle was approximately 3.5 m. There was a continuous charge in each blasthole (with 42 mm in diameter), and a single weight of the rock emulsion explosive was 300 g, with a diameter of 32 mm and a length of 300 mm. Each full-face blasting was divided into several delays, and the non-electric MS detonators were employed. The cutting blastholes were detonated in MS1, creating new free surfaces for the subsequent blastholes. The helper blastholes were successively detonated in MS3–MS11. The contour and floor blastholes were detonated in MS13.

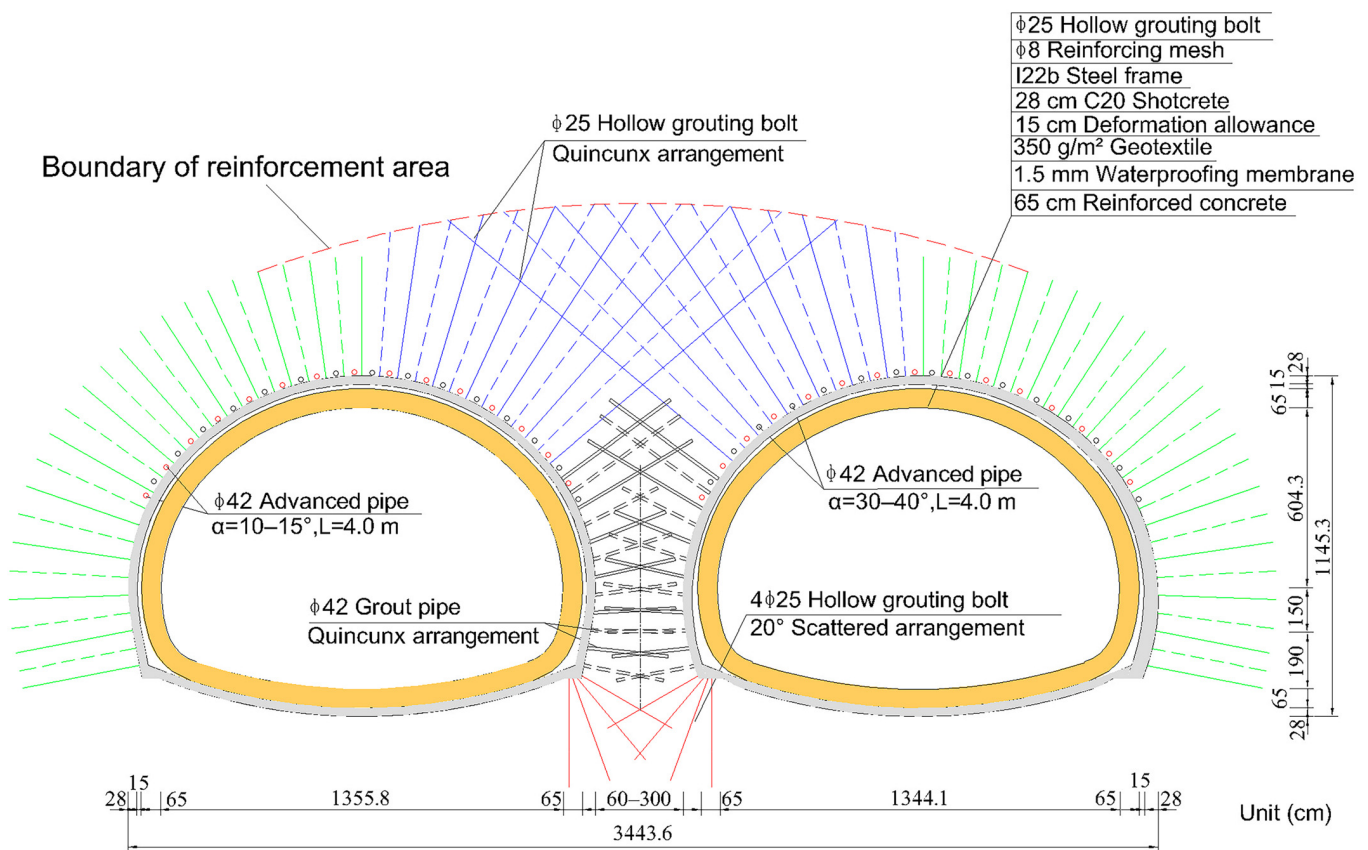


Figure 3. Structural design of ultra-small-spacing tunnels.

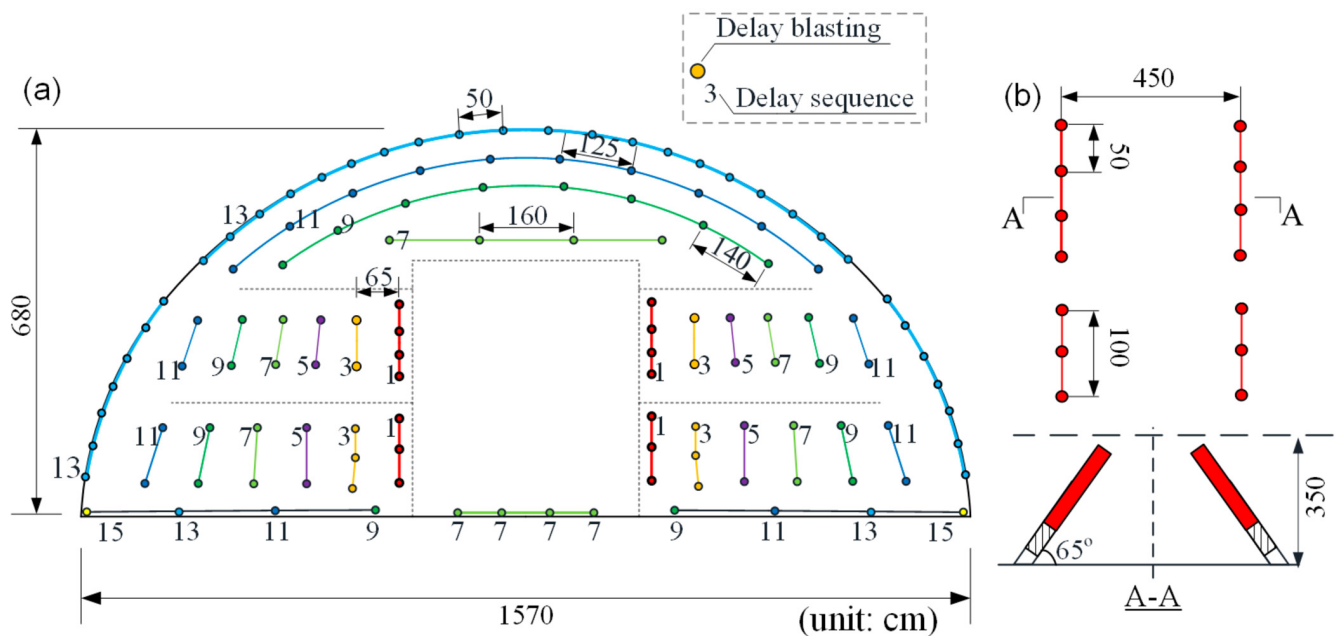


Figure 4. Design of typical blasting parameters: (a) blasthole arrangement and delay setting (b) cut blasthole settings.

Table 1. Drilling and blasting parameters.

Blasting Type and Detonator Series	Cut Blastholes			Helper Blastholes			Contour Blastholes
	MS1	MS3	MS5	MS7	MS9	MS11	MS13
Blasthole diameter (mm)	42	42	42	42	42	42	42
Blasthole length (m)	3.9	3.5	3.5	3.5	3.5	3.5	3.5
Explosive diameter (mm)	35	35	35	35	35	35	35
Explosive weight per blasthole (kg)	3.6	3.3	2.7	2.4	2.1	1.8	0.6

Note: MS1: first delay sequence.

3.3. Arrangement of Measuring Points

The blasting face of the succeeding tunnel was gradually advanced, and its parallel position passed through the secondary lining and primary support of the preceding tunnel sequentially. Measuring sensors were arranged on the inner surfaces of the preceding tunnel; they were fixed on the primary support and secondary lining using gypsum stirred on site. The arrangement of the measuring points on the site is shown in Figure 5. The sampling frequency of the blasting vibrometer was 2 kHz.

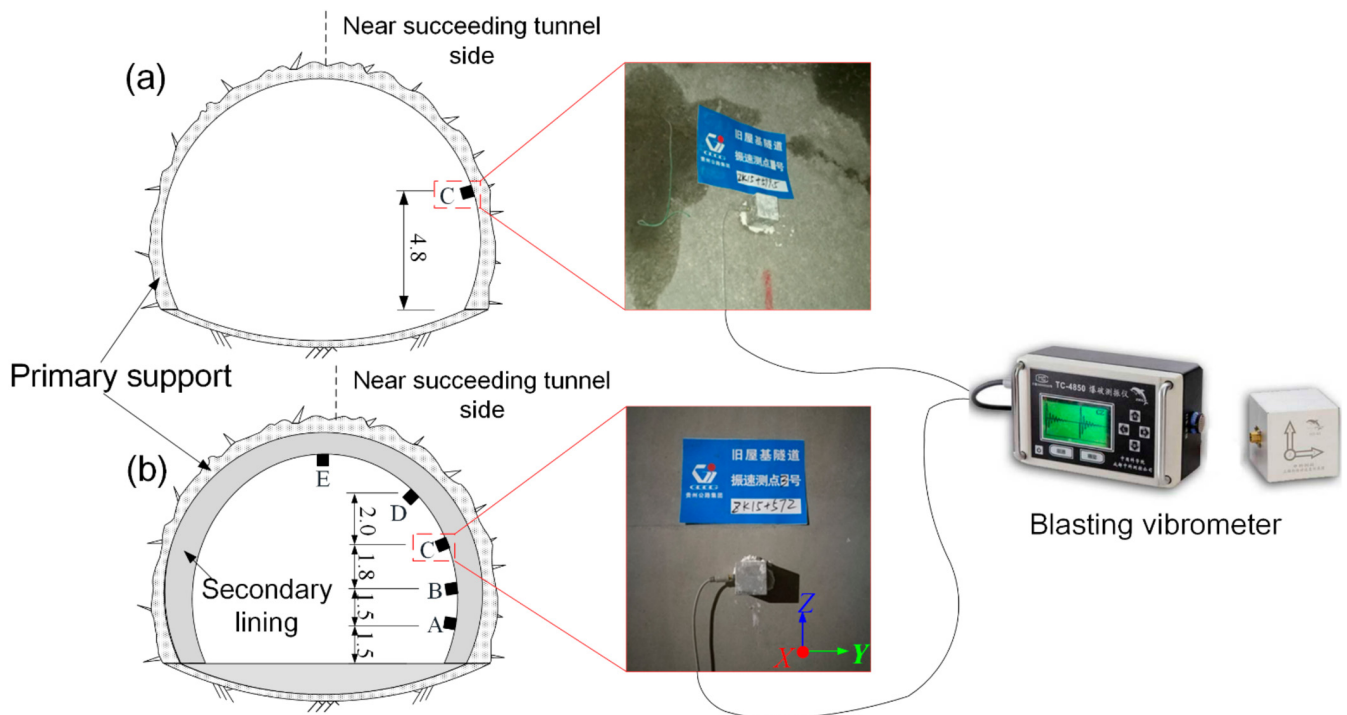


Figure 5. Layout of measuring points on site. (a) along longitudinal direction of tunnel. (b) along circumferential direction of lining.

Table 2 summarizes the 14 conducted tests. The measuring points of tests 1–3 were arranged along the circumference of a section, from Point A to Point E. The measuring points of tests 4–14 are Point C in each case, which was located at the arch waist, to record the blast vibrations distributed along the longitude of the preceding tunnel. The relative distance (RD) indicates the positional relationship between the monitoring section of the preceding tunnel and the blasting face of the succeeding tunnel. $RD > 0$ implies that the monitoring section is parallel to the unexcavated area of the succeeding tunnel, and $RD < 0$ implies that the monitoring section is located in an already excavated area.

Table 2. Summary of tests.

Test No.	Thickness of Middle Rock Pillar (m)	Measurements Point	Measurement Point Location	Relative Distance, RD (m)
1	9.4	Point A	Secondary lining	−21.5–+8.5
2	9.1		Secondary lining	−25.6–+17.9
3	8.8		Secondary lining	−28.6–+14.9
4	7.1		Primary support, Secondary lining	−39.6–+14.8
5	6.9		Primary support, Secondary lining	−50.0–+23.4
6	6.6		Primary support, Secondary lining	−30.7–+35.3
7	5.7		Primary support	−37.5–+26.5
8	4.8		Primary support	−5.7–+21.3
9	4.5		Primary support	−13.8–+20.3
10	4.2		Primary support	−13.8–+20.3
11	4.0		Primary support	−12.9–+26.1
12	8.3	Points A–E	Secondary lining	+3.8
13	8.1		Secondary lining	+1.8
14	7.8		Secondary lining	−1.2

4. Results

Table 3 summarizes the data of 71 measurements points obtained from 14 tests. The scaled distance (*SD*) is the ratio of the cube root of the distance (m) from the center of the explosive charge to the target and the weight of the charge (kg), also known as Hopkinson–Cranz scaling. The default data in the table is because the sensor was not triggered.

Table 3. Measurements data and frequency spectrum analysis.

No.	Test No.	Location	Measurements Point	SD (kg/m ³)	RD (m)	X-Directions		Y-Directions		Z-Directions	
						DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)
1	1	Secondary lining	Point A	4.3	8.5	35.0	23.5	28.6	55.6	97.0	36.4
2	1	Secondary lining	Point A	3.7	1.5	12.1	166.7	42.0	60.6	50.2	37.7
3	1	Secondary lining	Point A	3.6	1.5	26.8	21.5	44.1	64.5	98.8	23.8
4	1	Secondary lining	Point A	3.9	−5.5	27.7	64.5	51.2	51.3	61.7	41.7
5	1	Secondary lining	Point A	6.8	−21.5	39.1	60.6	35.6	87.0	69.0	64.5
6	2	Primary support	Point A	6.0	17.9	19.1	222.2	54.3	51.3	81.7	80.0
7	2	Secondary lining	Point A	3.6	0.9	23.4	76.9	30.5	47.6	59.9	90.9
8	2	Secondary lining	Point A	4.4	−9.6	36.3	54.1	50.5	47.6	70.0	142.9
9	2	Secondary lining	Point A	5.4	−15.1	41.9	55.6	41.9	80.0	99.1	76.9
10	2	Secondary lining	Point A	7.8	−25.6	16.8	55.6	55.2	80.0	73.0	51.3
11	2	Secondary lining	Point A	8.4	−28.6	61.0	57.1	111.0	87.0	76.0	64.5
12	3	Secondary lining	Point A	5.9	−18.1	3.0	52.6	42.0	55.6	64.0	71.4
13	3	Secondary lining	Point A	4.8	−12.6	2.0	80.0	41.0	66.7	4.0	28.2
14	3	Secondary lining	Point A	3.5	−2.1	48.0	52.6	64.0	45.5	75.0	87.0
15	3	Secondary lining	Point A	5.2	14.9	—	—	56.0	46.5	7.0	42.6
16	4	Primary support	Point A	4.9	14.8	61.0	87.0	62.0	74.1	88.0	90.9
17	4	Primary support	Point A	2.9	3.1	182.0	95.2	52.0	48.8	7.0	133.3
18	4	Secondary lining	Point A	3.9	−10.1	52.0	62.5	74.0	71.4	63.0	64.5

Table 3. Cont.

No.	Test No.	Location	Measurements Point	SD (kg/m ³)	RD (m)	X-Directions		Y-Directions		Z-Directions	
						DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)
19	4	Secondary lining	Point A	6.6	−22.1	56.0	66.7	57.0	55.6	64.0	52.6
20	4	Secondary lining	Point A	11.1	−39.6	46.0	52.6	51.0	50.0	78.0	74.1
21	5	Primary support	Point A	6.9	23.4	60.0	62.5	57.0	87.0	93.0	142.9
22	5	Primary support	Point A	2.9	4.0	52.0	51.3	3.0	57.1	5.0	33.3
23	5	Secondary lining	Point A	4.1	−11.5	52.0	76.9	57.0	71.4	84.0	74.1
24	5	Secondary lining	Point A	7.6	−26.0	—	—	—	—	—	—
25	5	Secondary lining	Point A	13.8	−50.0	62.0	69.0	138.0	83.3	92.0	95.2
26	6	Primary support	Point A	9.9	35.3	44.0	44.4	14.0	44.4	117.0	133.3
27	6	Primary support	Point A	6.1	20.3	63.0	80.0	53.0	90.9	93.0	71.4
28	6	Primary support	Point A	2.7	2.3	54.0	100.0	62.0	74.1	9.0	44.4
29	6	Secondary lining	Point A	4.9	−15.2	54.0	66.7	59.0	105.3	91.0	83.3
30	6	Secondary lining	Point A	8.7	−30.7	87.0	74.1	73.0	71.4	42.0	80.0
31	7	Primary support	Point A	7.5	26.5	48.0	35.7	24.0	71.4	85.0	105.3
32	7	Primary support	Point A	4.3	13.5	14.0	80.0	14.0	90.9	14.0	71.4
33	7	Primary support	Point A	2.3	1.5	76.0	83.3	9.0	34.5	4.0	47.6
34	7	Secondary lining	Point A	3.7	−10.5	103.0	117.6	59.0	90.9	131.0	26.0
35	7	Secondary lining	Point A	10.4	−37.5	48.0	83.3	48.0	71.4	48.0	87.0
36	8	Primary support	Point A	6.1	21.3	61.0	71.4	4.0	55.6	85.0	125.0
37	8	Primary support	Point A	2.6	6.3	116.0	142.9	47.0	87.0	2.0	69.0
38	8	Primary support	Point A	2.2	3.3	44.0	46.5	94.0	111.1	6.0	47.6
39	8	Primary support	Point A	2.0	0.3	27.0	64.5	40.0	38.5	37.0	46.5
40	8	Primary support	Point A	2.5	−5.7	302.0	40.8	5.0	105.3	14.0	30.3
41	9	Primary support	Point A	5.8	20.3	37.0	47.6	41.0	37.7	23.0	76.9
42	9	Primary support	Point A	3.3	10.3	125.0	62.5	57.0	41.7	3.0	12.8
43	9	Primary support	Point A	1.9	0.3	44.0	74.1	37.0	29.4	16.0	166.7
44	9	Primary support	Point A	3.2	−9.8	98.0	71.4	168.0	181.8	5.0	142.9
45	9	Primary support	Point A	4.2	−13.8	59.0	58.8	194.0	133.3	186.0	133.3
46	10	Primary support	Point A	5.7	20.2	45.0	57.1	13.0	38.5	85.0	133.3
47	10	Primary support	Point A	3.3	10.2	128.0	80.0	125.0	57.1	93.0	142.9
48	10	Primary support	Point A	1.8	0.2	4.0	60.6	5.0	54.1	8.0	66.7
49	10	Primary support	Point A	3.2	−9.8	203.0	142.9	172.0	117.6	172.0	166.7
50	10	Primary support	Point A	4.1	−13.8	165.0	142.9	89.0	142.9	6.0	14.6
51	11	Primary support	Point A	7.3	26.1	4.0	33.3	99.0	16.8	3.0	37.7

Table 3. Cont.

No.	Test No.	Location	Measurements Point	SD (kg/m ³)	RD (m)	X-Directions		Y-Directions		Z-Directions	
						DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)	DF (Hz)	ZCF (Hz)
52	11	Primary support	Point A	5.7	20.1	33.0	36.4	49.0	25.6	93.0	27.0
53	11	Primary support	Point A	3.2	10.1	114.0	16.5	58.0	29.9	6.0	19.0
54	11	Primary support	Point A	2.2	5.1	15.0	71.4	30.0	39.2	29.0	80.0
55	11	Primary support	Point A	1.7	0.1	82.0	55.6	41.2	54.1	40.4	105.3
56	11	Primary support	Point A	3.9	−12.9	188.0	80.0	203.0	222.2	203.0	153.8
57	12	Secondary lining	Point A	3.4	3.8	7.0	18.7	3.0	36.4	5.0	28.2
58	12	Secondary lining	Point B	3.3	3.8	38.0	48.8	5.0	35.7	5.0	69.0
59	12	Secondary lining	Point C	3.3	3.8	11.0	19.4	2.0	48.8	4.0	36.4
60	12	Secondary lining	Point D	3.4	3.8	60.0	66.7	4.0	69.0	27.0	60.6
61	12	Secondary lining	Point E	3.6	3.8	117.0	58.8	3.0	30.3	92.0	105.3
62	13	Secondary lining	Point A	3.2	1.8	8.0	35.1	3.0	46.5	4.0	46.5
63	13	Secondary lining	Point B	3.2	1.8	58.0	55.6	3.0	15.3	3.0	20.0
64	13	Secondary lining	Point C	3.2	1.8	10.0	20.4	62.0	48.8	85.0	52.6
65	13	Secondary lining	Point D	3.2	1.8	44.0	40.0	71.0	60.6	20.0	64.5
66	13	Secondary lining	Point E	3.4	1.8	124.0	69.0	2.0	30.8	78.0	142.9
67	14	Secondary lining	Point A	3.1	−1.2	10.0	26.0	2.0	46.5	43.0	64.5
68	14	Secondary lining	Point B	3.0	−1.2	41.0	57.1	62.0	62.5	91.0	32.3
69	14	Secondary lining	Point C	3.0	−1.2	36.0	90.9	64.0	166.7	4.0	28.2
70	14	Secondary lining	Point D	3.1	−1.2	68.0	54.1	64.0	64.5	21.0	40.0
71	14	Secondary lining	Point E	3.3	−1.2	36.0	44.4	26.0	34.5	67.0	55.6

5. Data Analysis

5.1. Difference in Dominant Frequency Distributions on Primary Support and Secondary Lining

The blasting vibration waves on the primary support and the secondary lining were monitored. The relationships between the SD and the frequencies (DF and ZCF) were illustrated in Figure 6. In the data of the primary support, the dominant frequencies in the Y- (longitudinal) and X- directions (vertical) show some regularity, whereas the regularity of those in the Z- direction (transverse) is poor. The dominant frequencies are mainly distributed within 200 Hz, and the distribution range of the ZCFs generally exceeds 10 Hz, whereas a part of the DFs is widely distributed below 10 Hz. In the range of the SD less than 5.0 kg/m³, the dominant frequency of the vibration wave is greater than 100 Hz; and in the range of more than 10.0 kg/m³, the high frequencies part attenuates to the range of less than 50 Hz. The prediction of the dominant frequency was extensively developed by the SD [31,34]. The variations in the upper and lower bound values of the dominant frequency on the primary support with the SD can be expressed as power functions (as shown in Figure 6 and listed in Table 4). The change in the upper bound can be understood as the attenuation of the high-frequency part of the dominant frequency, in which the dominant frequencies in the X- and Y- directions decay rapidly, whereas that in the Z- direction (transverse) decays gradually. The characteristic that the dominant

frequency gradually attenuates with the increase in the distance is mainly caused by the damping of the surrounding rock and the high-frequency absorption by the nonlinear properties [4]. An alternative explanation for these phenomena may be that the vibration waves close to the blast are more affected by characteristics of blast design, while at larger distances the propagating medium dominates the vibration response [4].

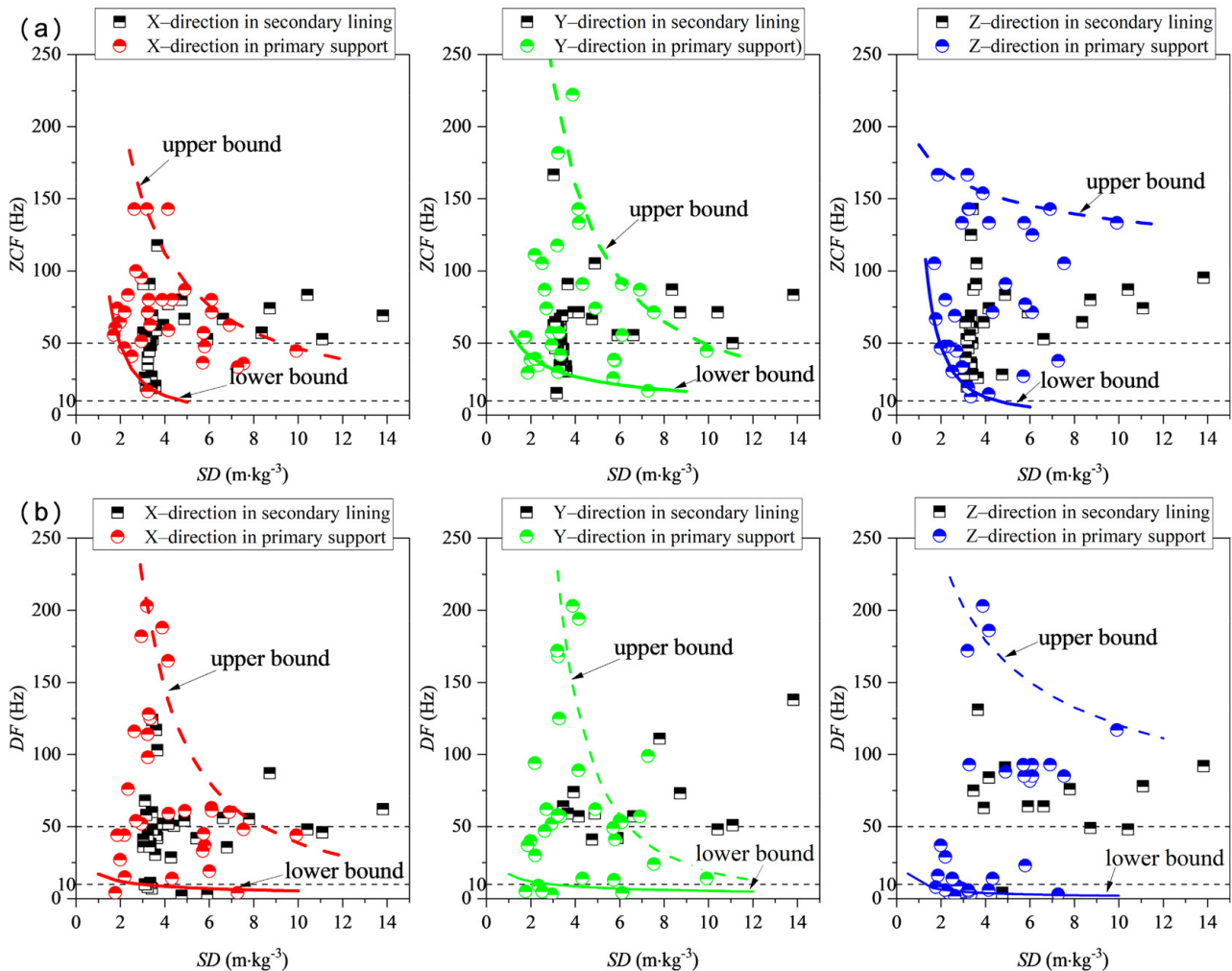


Figure 6. Relationships between frequencies and SD. (a) ZCF and (b) DF.

Table 4. Fitting analysis of vibration data at primary support in blasting experiments.

Frequency Types		X-Direction	Y-Direction	Z-Direction
ZCF	upper bound:	$ZCF = 427.6 \times SD^{-0.97}$, $R^2 = 0.91$	$ZCF = 814.6 \times SD^{-1.23}$, $R^2 = 0.96$	$ZCF = 187.43 \times SD^{-0.14}$, $R^2 = 0.91$
	lower bound:	$ZCF = 173.6 \times SD^{-1.85}$, $R^2 = 0.87$	$ZCF = 61.2 \times SD^{-0.60}$, $R^2 = 0.76$	$ZCF = 179.1 \times SD^{-1.93}$, $R^2 = 0.92$
DF	upper bound:	$DF = 1082.2 \times SD^{-1.41}$, $R^2 = 0.94$	$DF = 2862.9 \times SD^{-2.18}$, $R^2 = 0.77$	$DF = 429.7 \times SD^{-0.68}$, $R^2 = 0.67$
	lower bound:	$DF = 17.1 \times SD^{-0.51}$, $R^2 = 0.13$	$DF = 7.0 \times SD^{-0.33}$, $R^2 = 0.16$	$DF = 10.5 \times SD^{-0.73}$, $R^2 = 0.27$

Note: Underlined correlative coefficient R^2 is less than 0.60, i.e., formula only describes mathematical data, which cannot guide practical engineering.

The difference of the dominant frequency distributed on the primary support and lining is reflected in two aspects. One is concerning the frequency range of the vibration wave distribution on the lining is not as wide as that on the primary support; another is the

dominant frequencies on the lining are concentrated in an interval when the RD is less than a certain value.

As the blast face in the succeeding tunnel advances gradually, the blast-affected area in the preceding tunnel changes from the secondary lining to the primary support. As shown in Figure 7, when the lining is located at different RD, the dominant frequency distributed on it is variant. For example, the dominant frequencies do not have a specific range when the blasting face is close to the lining (RD = 0). When the RD is less than a certain value (RD = −16 m), the dominant frequencies on the lining are concentrated in an interval, either ZCFs or DFs. In contrast, in the range of RD > 16 m, the dominant frequencies on the primary support are still relatively discrete. To a clear illustration, Figure 7a,b are divided into zones I, II, and III, respectively. The measurement points on the lining are distributed in zones I and II, while the measurement points on the primary support are distributed in zone II and III. The dominant frequencies of the primary support are obeyed with the characteristics of high-frequency attenuation, while the data on the lining are not submitted to it.

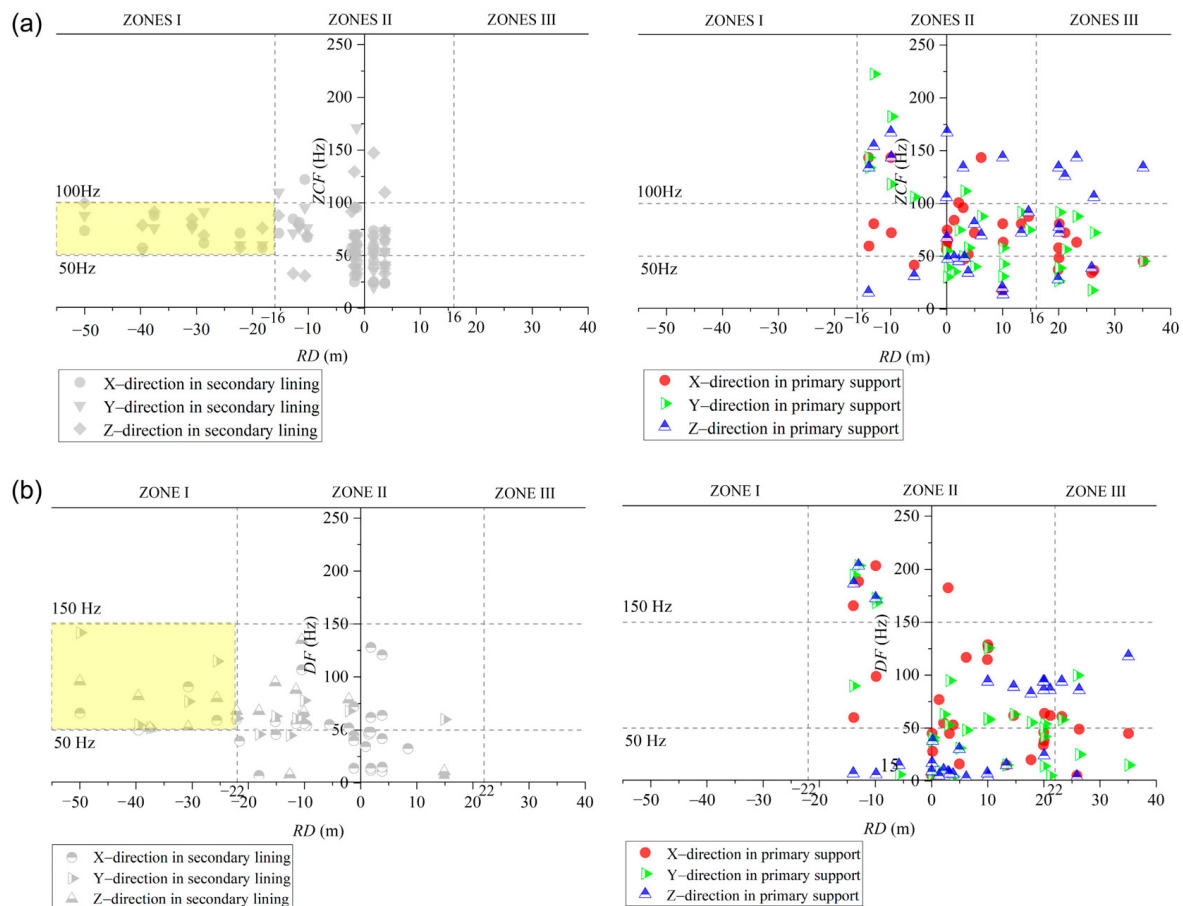


Figure 7. Relationship between dominant frequencies and RD. (a) ZCF and (b) DF.

Another phenomenon is that the propagation of dominant frequencies on the lining does not decay regularly but gradually concentrates in an interval besides a certain distance. For example, in Figure 7a, the dominant frequencies on the lining in zone II are widely distributed within 200 Hz, while only distributed in a range of 50–100 Hz in zone I. The specific range in Figure 7b is from 50 Hz to 100 Hz. Each type of rock mass and each terrain has a propagated dominant frequency, which is conducive to the propagation of a wave having this frequency [35]. The test data of this study show that the advantageous propagation of the dominant frequency of the lining is in the range of 50–150 Hz, which favours wave propagation for that frequency.

The difference of the dominant frequency distributed on the primary support and lining is because of the changes that have occurred during the propagation of the vibration wave. First, the distribution of the dominant frequencies on the primary support is wider than that on the lining, which is evidently in zone II. For example, in Figure 7a, in the range higher than 150 Hz of zone II, more data are distributed on the primary support than on the lining; moreover, in Figure 7b, the range higher than 150 Hz of zone II is distributed including the data of the primary support without any data of the lining. A portion of the frequency of the vibration wave has been wholly attenuated and is related to the gap between the primary support and the secondary lining. The primary support is closely bonded with the surrounding rock mass and directly receives the full vibration waves from the inside of the surrounding rock. Due to space between the lining and the primary support for installing a waterproof board and a geotextile (as shown in Figure 3) and inevitable cavities caused by concrete casting in situ, there is a notifiable interface for seismic wave propagation. Second, blasting seismic wave is usually composed of body waves (P wave and S wave) and Rayleigh surface waves (R wave) [36]. The surface wave propagates on the free surface, and the body waves propagate inside the surrounding rock; body waves at a non-vertical incidence angle on a free surface will produce reflected and mode-converted body waves as well as surface waves [37]. Therefore, when the vibration waves are transmitted from the primary support to the lining, part of the blasting vibration waves (mainly body waves) did not pass through from an abrupt change in the medium.

5.2. Spectrum Analysis of Entire MS Delay Blast Vibration

In the blasting works of tunnels, the MS delay blasting technique was typically adopted to restrict the charge weight in a single detonated sequence for meeting the control criterion of safety [30]. Two typical vibration velocity waveforms of an MS delay blasting are illustrated in Figure 8, and the Arabic numerals marked at the top of each figure are the delay sequence. The PPV in the curve in Figure 8a occurs in MS12, whereas in the Figure 8b curve, it is observed in MS1, which is mainly related to the average explosive weight in each delay sequence. It can also be seen from the figure that the complete vibration velocity waveform of the MS delay blasting is composed of multiple vibration waveforms that are detonated in different delays. On converting the vibration velocity waveform from the time domain to the frequency domain, the power spectrum contains several frequency components that are contributions of multiple vibration waveforms (as shown in Figure 9).

The Fourier power spectrum of the waveform in Figure 8 is shown in Figure 9. There are several peak amplitudes in the power spectrum, indicating that the complete vibration velocity waveform is a superposition of different frequency vibrations. When the MS delay blasting was used in excavation, if a power spectrum reflecting all sequences respectively could be obtained, it may better present the true scenario of the entire vibration compared with a global frequency of all delays [30].

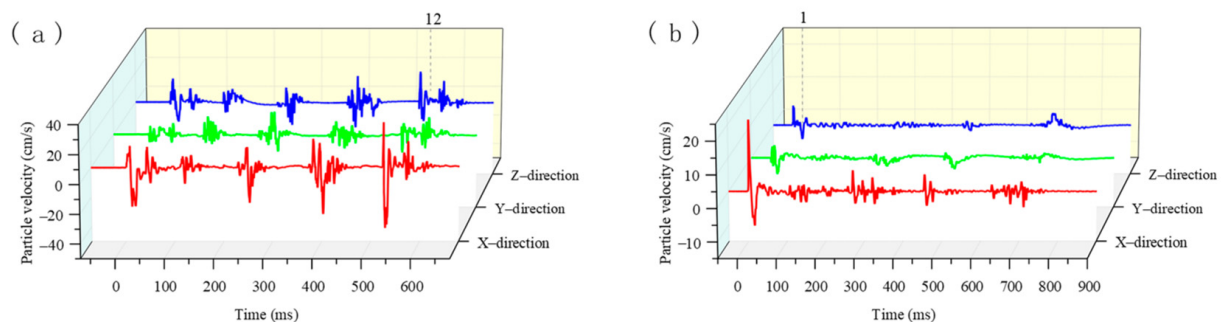


Figure 8. Vibration velocity waveforms of blasting vibration waves. (a) PPV occurs in MS12 and (b) PPV occurs in MS1.

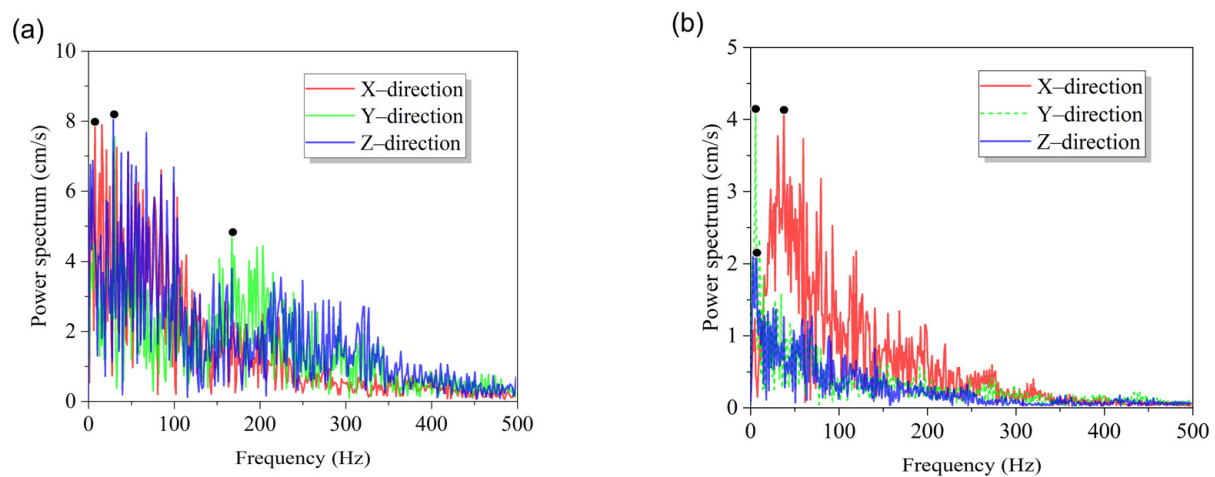


Figure 9. Power spectrum of vibration waveform in (a) Figure 8a, (b) Figure 8b.

5.3. Spectrum Analysis of Each Delay Sequence Vibration

Analyzing the X-direction curve in Figure 8b, the entire vibration velocity waveform is divided into six curves based on the detonator delay time, as shown in Figure 10. The Arabic numerals above each waveform represent the delay sequence, and the dotted line corresponds to the setting time of the detonator initiation. The initiation time of each sequence does not fully correspond to the setting time, owing to the accuracy of the MS detonator and the variation of the seismic wave during propagation. The delay sequences of this vibration waveform are 1, 5, 7, 9, 11, and 13. Noticeably, the waveform and spectrum analysis in Figure 10 show that the vibration waveforms for all sequences have different characteristics (PPV, frequency, and duration). The characteristics of each delay sequence are listed in Table 5.

Table 5. Characteristics of all sequence waveforms in X-direction shown in Figure 8b.

Blast Parameters	MS1 Delay	MS5 Delay	MS7 Delay	MS9 Delay	MS11 Delay	MS13 Delay
ZCF (Hz)	57.0	66.4	67.8	82.0	76.8	130.5
DF (Hz)	29.9	60.3	45.9	81.6	78.1	91.8
MF (Hz)	93.7	111.8	107.9	111.9	99.1	119.0
Number of holes	16	8	22	16	22	42
Explosive weight amount (kg)	52.8	21.6	47.4	28.8	33.6	29.4
Effective vibration duration (ms)	24.2	83.9	55.3	91.7	77.0	146.5
EBVS (cm)	22.5	35.2	41.7	48.2	55.98	65.5

As shown in Figure 10, the ZCF is depicted near the peak of each waveform and the DF is depicted at the peak amplitude in the power spectrum. Overall, the ZCF and the DF are increased as the delay sequence grows; however, it is not a completely linear trend. To better describe it, the MFs are calculated in Table 5, and three dominant frequencies (ZCF, DF, and MF) of each delay sequence are depicted in Figure 11. It is seen that the global frequency of the entire vibration is close to the DF of the cutting blastholes in MS1.

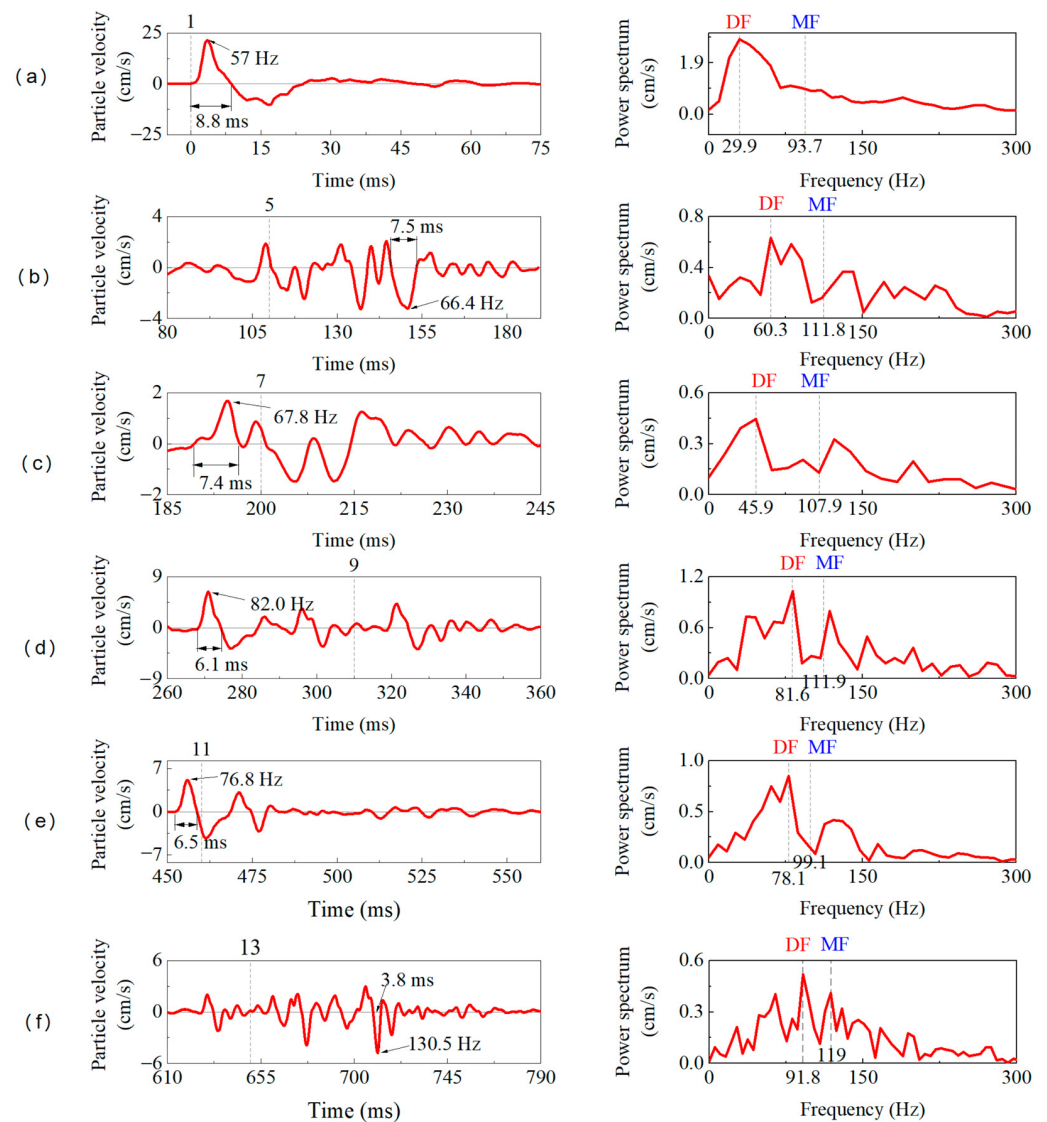


Figure 10. All sequence waveforms in X-direction shown in Figure 6b and their power spectra. (a) MS1, (b) MS5, (c) MS7, (d) MS9, (e) MS11, (f) MS13.

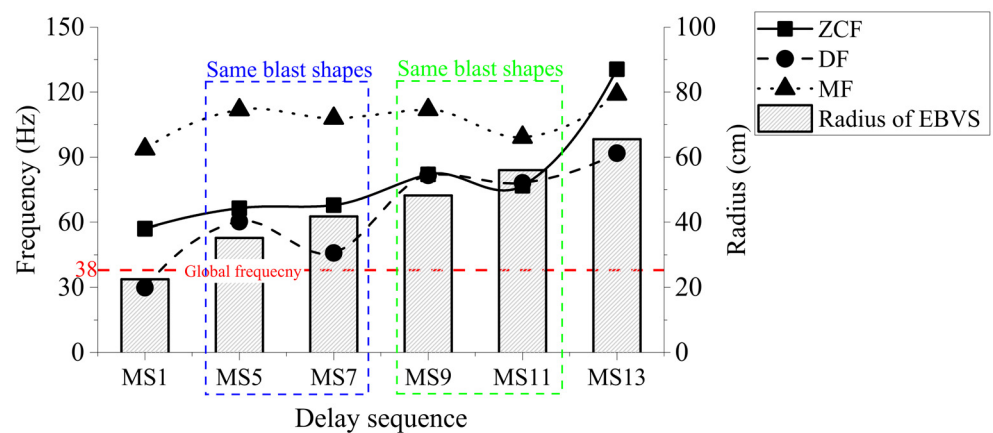


Figure 11. Relationship between frequency and delay blast sequences.

The dominant frequency of vibration is greatly influenced by the structure of the charge [28]. Understandably, in this study, the change in the dominant frequency of each sequence is independent of the charge structure because the charge structure is

the same in all sequences. There are two other theories for the propagation law of the dominant frequency. One is the blasting cavity theory [31]: for the same free surface or the same blast shapes, a large equivalent blasting vibration source (EBVS) implies a low vibration frequency. The other is the free surface theory [30]: multiple free surfaces cause superposition of blasting vibration waves and increase of frequency; for example, as the cutting blastholes are detonated under a confined boundary condition in the MS delay blasting, the dominant frequency of it is smaller than those of the subsequent blastholes. The abovementioned not-completely-linear trend of the dominant frequency with the increase in the delay sequence (as shown in Figure 11) can be explained by the free surface theory. In contrast, the curve fluctuates for some sequences with the same blast shapes conforms to the blasting cavity theory. Based on the blasting parameters (as shown in Figure 4), the EBVS at MS5 and MS7 have the same shapes but different sizes, and there is a negative correlation between the dominant frequency and the radius of the EBVS. This rule, which conforms to the blasting cavity theory, is also observed for MS9 and MS11.

5.4. Nonlinear Relationship between ZCF and DF

The relationship between the ZCF and the DF is not completely linear (as shown in Figure 12), and the frequency determined by the different methods deviates considerably. Particularly, the DFs are widely distributed below 10 Hz, in which range the ZCFs are almost absent. In the range of DFs higher than 10 Hz, it has a certain linear relationship with ZCFs. Obviously, the use of a single frequency value gives a poor description of the vibration frequency. As shown in Figure 11, although the frequencies obtained by different methods show a consistent law, there are different values of DF and ZCF when describing a specific vibration wave. This is because the DF describes the entire waveform, while the ZCF only describes the frequency of the cycle with the maximum amplitude. The ongoing revision of the Norwegian standard is considering an alternative approach by implementing a frequency-weighted filter that directly describes the damage potential at different frequencies [4].

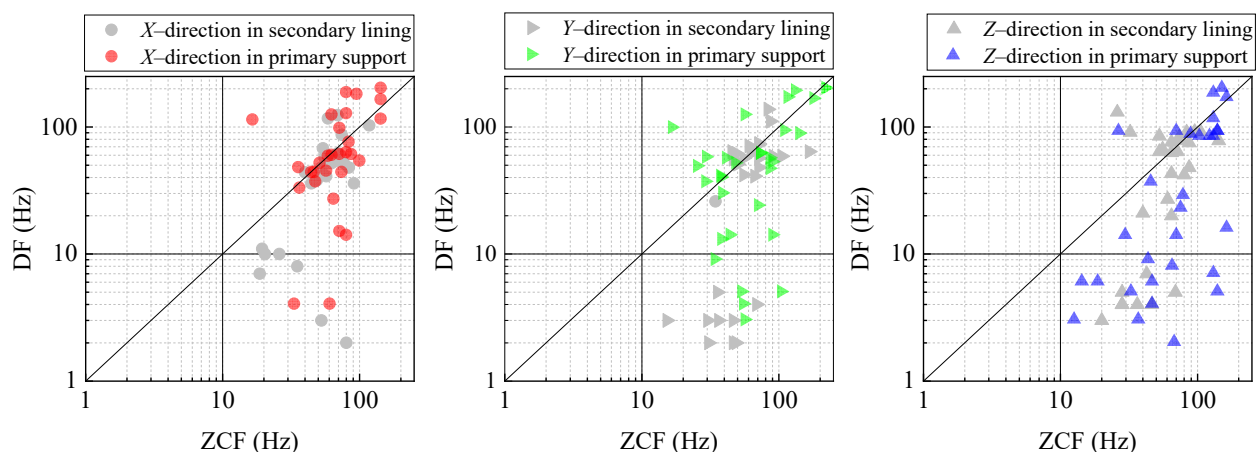


Figure 12. Relationship between ZCF and DF.

6. Discussion

The most critical measure to control blast vibration is establishing a threshold for PPV, which can be selected according to the characteristics of frequency distribution in different areas. As shown in Figure 6, the dominant frequency of the blast vibration wave undergoes a fluctuating decrease at a certain distance, only the high-frequency part decays rapidly with the distance, and the dominant frequency shifts from a higher band to a lower one (upper bond shown in Figure 6). The main reason is that, for multi-sequences delay blast, the spectrum of the vibration waves is multi-structured (as shown in Figure 9); and variant delay sequences produce different frequencies of vibration waves (as shown in Figure 10); and different frequency components in the propagation with different attenuation rate

decay (as shown in Figure 6). On the other hand, the abrupt change of the propagation medium leads to a significant difference in the distribution of the dominant frequencies of vibration on the lining and the primary support (as shown in Figure 7).

On the basis of Chinese Safety Regulations for Blasting (GB6722-2014), a safety PPV criterion for traffic tunnel considering dominant frequency has been proposed (as shown in Table 6). Its definition of dominant frequency is corresponding to the maximum amplitude of the particle velocity, which means ZCF.

Table 6. Safety PPV for blasting vibration (GB6722-2014, China).

Structure Type	$f \leq 10$ Hz	10–50 Hz	$f > 50$ Hz
General civil buildings	1.5–2.0	2.0–2.5	2.5–3.0
Hydraulic tunnel	7–8	8–10	10–15
Traffic tunnel	10–12	12–15	15–20
Mine roadway	15–18	18–25	20–30

Therefore, the way to select the right critical PPV for the tunnel structure is to choose a frequency band based on frequency-based vibration criteria. For the range of SD greater than 5.0 kg/m^3 , a safe PPV less than 50 Hz band is recommended; while the SD is below 5.0 kg/m^3 , it is determined by experience; and a more stringent PPV is more secure for the structure. For a point at the lining is exceeds 20 m away from the blast, because the distribution of the frequency is generally greater than 50 Hz, the safe PPV can be selected appropriately larger compared to the primary support.

However, it should be noted that the ZCF and DF exhibit a non-linear relationship, and the blast vibration wave frequencies obtained by different methods may lead to a different selection for safe vibration frequency bands.

7. Conclusions

Based on the framework of this research, the following conclusions can be drawn. The dominant frequencies of blast vibration have a wide range of distribution in areas relatively close to the blast, which are mainly distributed within 200 Hz. There is a clear difference in the distribution of the dominant frequency on the primary support and the lining: (1) The distribution of the dominant frequencies on the primary support is broader than that on the lining, and (2) the dominant frequencies on the lining are concentrated in the range when the lining is far from the blast face beside a specific value. The main reasons are the cavities and gaps between the primary support and the lining have the characteristics of vibration damping and filtering, hindering the propagation of the blasting vibration waves with some frequencies. Additionally, the vibration waves are more affected by characteristics of blast design in areas relatively close to the blast, while at larger distances the propagating medium dominates the vibration response.

The high-frequency part of the vibration waves attenuates rapidly on the primary support under the damping effect of the rock, whereas the Z-direction (transverse) dominant frequency decays gradually. The power function of the upper and lower bounds of the dominant frequency on the primary support with the SD was proposed.

Multiple delay sequences blast contributes to a multi-structured amplitude spectrum of blast vibration waves. There are distinct differences between the global frequency of the entire vibration time series and the dominant frequencies at different delay sequences. The global frequency determined in all delays of the vibrations is close to the dominant frequency detonated in the cutting blastholes. The dominant frequencies in different sequences correspond to two parameters of the different delay sequences. Multiple free surfaces cause the overall trend of dominant frequency increase, and a large EBVS implies a low vibration frequency.

The ZCFs and DFs exhibit a nonlinear relationship. This is because the DF describes the entire waveform, while the ZCF only describes the frequency of the cycle with the maximum

amplitude. Nevertheless, the distribution of dominant frequencies in the different scaling distances obtained in this paper can be used to guide the selection of a suitable safe PPV.

Because of the fluctuating drop of the vibration dominant frequency with the distance, further discussion is needed on how the different frequency components are decayed. Since the selection of safe PPV depends on the dominant frequency of blast vibration, finding a frequency that is more appropriate than the above for engineering is still worthy of further research.

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