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The Influence Study of Elevation Difference on the Propagation of Blasting Seismic Wave

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Abstract: *In order to investigate the elevation difference influence on particle peak velocity, frequency characteristics and energy distribution of blasting vibration signals, experiments of blasting vibration were carried out at a Limestone open-pit mine. The blasting vibration signals and propagation law under elevation differences were analyzed with the methods of wavelet packet and numerical simulation respectively. The results of wavelet packet showed that the energy distribution of blasting vibration was mainly concentrated on the blasting frequency from 0Hz to 30Hz. Moreover, with the positive altitude increases, the percentage of the energy under 0～15.6Hz bands increases from 52.6% to 98.1%. However, the percentage of the energy under 15.6 Hz～62.5Hz bands decreases from 47.1% to 1.75%. The results of numerical simulation showed that there were significant amplification effects of blasting vibration velocity under positive elevation difference, and the amplification coefficient increased firstly and then decreased.*

Keywords: *Blasting vibration signal, Elevation difference, Wavelet packet analysis, Energy distribution, Numerical simulation*

1. Introduction

The study showed that elevation difference has a greater impact on seismic wave propagation which causes the amplification effect of blasting vibration and the damage of self-vibration on the slope [1]. Therefore, it is necessary to make a further research on the time-frequency characteristics of blasting vibration signals under different elevation. The destruction of surroundings by blasting vibration is a topic of dynamic response [2], which involving the particle peak velocity value, the frequency characteristics and energy distribution of blasting vibration signals. At present, a bunch of research about elevation effect has been carried out by the experts and scholars at home and abroad which have achieved a wealth of results. These research mainly focus on the theory analysis on the amplification effects of particle peak velocity and the simulation results of blasting vibration [3,4]. Moreover, some researchers have achieved interesting results by the method of the wavelet packets analysis [5,6].

This paper is based on the background of the blasting construction engineering of a Limestone open-pit mine on Guizhou province, plenty of blasting vibration signals on positive altitude (measure sites above the explosion source location) was collected through blasting vibration tests. To optimize the blasting design and protect the permanent slope, the blasting vibration signals were analyzed with the wavelet packets method. Moreover, dynamic finite element method was used to analyze the impact of elevation difference on blasting vibrations peak particle velocity, combining with field tests.

2. Blasting vibration experiments on the Limestone open-pit mine

2.1 Blasting vibration experiments

The blasting vibration was tested by TC-4850 vibration tester with three standard velocity sensors. The sensors were installed on the bedrock with adhesive plaster. Z was set as the vertical direction, Y was set as horizontal direction and pointing to explosive source, and X was set as the horizontal direction and perpendicular to Y. the arrangement of blasting vibration testing instrument is shown in Fig.1.

***Fig.1** The arrangement of blasting vibration testing instrument*

In order to study the variation law of blasting vibration with different elevations, the testing points were set along the positive elevation difference at +15 m, +30 m, +45 m, +60 m, +75 m, +90 m, respectively. Each point was at the same vertical section and on a straight line towards the blasting center. The arrangement of blasting vibration testing points is shown in Fig.2.

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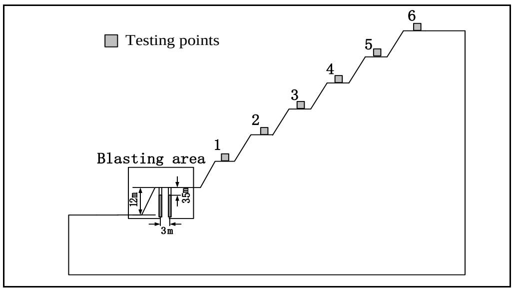


***Fig.2** The arrangement of blasting vibration testing points*

2.2 Testing results and discussion

Blasting vibration experiments were carried out at Zuangou Limestone mine and plenty of testing data were obtained. Part of the data is listed in Table 1.

***Table 1:** The monitoring data of blasting vibration*

Data No.	Elevation /m	Horizontal distance /m	Charge per delay /kg	PPV of X/cm·s^{-1}	Frequency /HZ	PPV of Y/cm·s^{-1}	Frequency /HZ	PPV of Z/cm·s^{-1}	Frequency /HZ
1	+15	85	108	2.93	18.86	2.59	24.46	3.49	22.57
2	+30	93	108	3.28	13.87	3.17	21.38	5.21	20.34
3	+45	124	108	0.87	13.45	0.79	20.41	0.47	20.61
4	+60	129	108	1.34	13.29	1.36	19.05	0.85	19.58
5	+75	187	108	0.68	9.84	0.63	12.87	0.57	13.29
6	+90	194	108	0.89	7.52	0.71	9.76	0.72	11.35

According to the data in Table 1:

- It can be concluded that the elevation amplification effect is becoming more obvious with the increase of the elevation difference when compare the results of data 1 and data 2, data 3 and data 4, data 5 and data 6 respectively under the same distance from borehole.
- To study the effect of amplification of blasting vibration by calculating the amplification coefficient. The results show that the average amplification coefficient is 1.27 when the elevation is +15 m, the average amplification coefficient is 1.69 when the elevation is +45 m, and the average amplification coefficient is 1.27 when the elevation is +75 m at the same horizontal distance. It can conclude that there are obviously amplification effects on blasting vibration, the amplification coefficient tend to increase firstly and then decrease.

2.3 Blasting vibration velocity regression analysis

Several groups of positive elevation vibration data were chosen to be calculated by binary linear regression equation. The coefficients, K, a and β, of Steve Sadove formula were obtained under different elevation. And the seismic wave propagation law was obtained accordingly.

$$V = K\left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha}\left(\frac{\sqrt[3]{Q}}{H}\right)^{\beta} \tag{1}$$

Where V is peak particle velocity of blasting vibration, cm/s; Q is the charge per delay, kg; R is the horizontal distance between blasting point and testing point, m; H is the elevation difference between blasting point and testing point, m.

In the case of positive elevation difference, the formulas of different direction are as follows:

$$V_x = 146.51\times\left(\frac{\sqrt[3]{Q}}{D}\right)^{1.587}\times\left(\frac{\sqrt[3]{Q}}{H}\right)^{-0.002} \tag{2}$$

$$V_y = 234.25\times\left(\frac{\sqrt[3]{Q}}{D}\right)^{1.781}\times\left(\frac{\sqrt[3]{Q}}{H}\right)^{-0.028} \tag{3}$$

$$V_z = 396.84\times\left(\frac{\sqrt[3]{Q}}{D}\right)^{2.136}\times\left(\frac{\sqrt[3]{Q}}{H}\right)^{-0.034} \tag{4}$$

According to positive elevation difference equations, β is less than 0, which shows that blasting vibration velocity will be amplified because of positive elevation difference.

3 Influence of elevation difference on the energy distribution of blasting vibration signals based on wavelet packet analysis

3.1 Wavelet packet analysis of blasting vibration signals

Wavelet packet analysis provides a more precise analysis method for vibration signal. This method can divide the signal frequency band into multi-level evenly and makes a further decomposition with the high frequency part of the signal. The energy of the special signal can be concentrated into a smaller and more uniform frequency band by wavelet packet, and the time-frequency characteristic analyzed by wavelet packet is more accurate than wavelet transform. And the method has a stronger superiority in dealing with the blasting seismic wave, a non-stationary signal. This is a better method than wavelet decomposition because the wavelet packets decomposition was developed from rigorous mathematical theory and supported by numerical calculation verification. Many monographs have since been written and expounded [7,8].

In the family of wavelet, Daubechies wavelet has good compactness, smoothness and approximate symmetry [9,10], which has been successfully applied to the non-stationary signal problems include blasting vibration. At present, db6 and db8 are widely used in blasting vibration signal processing. And db8 was chosen as the basis function of wavelet packet analysis to study the signals of blasting vibration.

When signals are decomposed by wavelet packet, the decomposition layers depend on the signal characteristics and working frequency band of the seismic instrument. Because the frequency of blasting vibration signals is commonly less than 200 Hz. When the sampling rate of signal is set for 4000Hz according to sampling theorem, blasting vibration signal's Nyquist frequency is 2000 Hz. In this way, blasting vibration signal can be decomposed to 8th layer, and its lowest frequency band is from 0Hz to 7.8125Hz [11].

If blasting vibration signal is decomposed to the eighth layer, and supposing $E_{8,j}$, represents the energy of $S_{8,j}$, then

$$E_{8,j} = \int \left| S_{8,j}(t) \right|^2 dt = \sum_{k=1}^{m} \left| x_{j,k} \right|^2 \quad (5)$$

Where, $x_{j,k}$ is the amplitude of reconstructed vibration signal,

$S_{8,j}$.(j=0, 1, 2…2^8-1, k=1, 2…m, m is the discrete sampling amount of signal.)

If the total energy of signals is E_0, then

$$E_0 = \sum_{j=0}^{2^8-1} E_{8,j} \quad (6)$$

The proportion of different frequency band energy to the total energy of the analyzed signal is defined as follows.

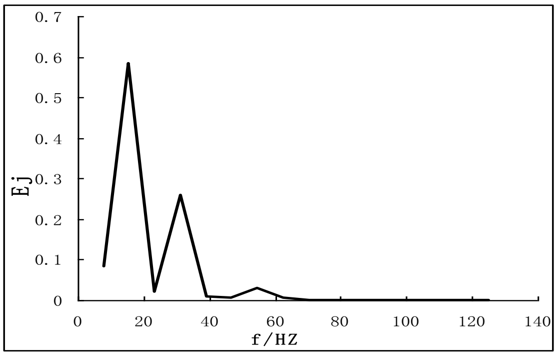
$$E_j = \frac{E_{8,j}}{E_0} \times 100\% \quad (7)$$

Where, j=0, 1, 2, …, 2^8-1.

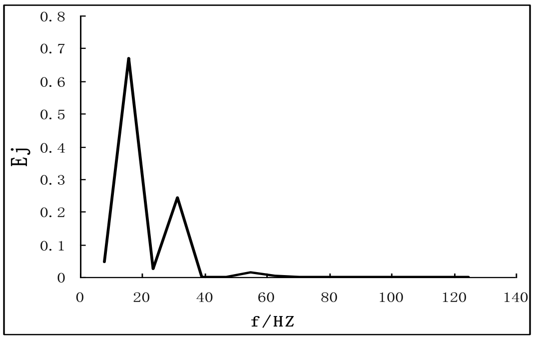
In this way, energy of different frequency bands can be obtained by wavelet packet analysis though function (5), function (6) and function (7). And the energy distribution law of blasting vibration signals during propagation can be found at the same time.

3.2 Influence of elevation difference on energy distribution of blasting vibration signals

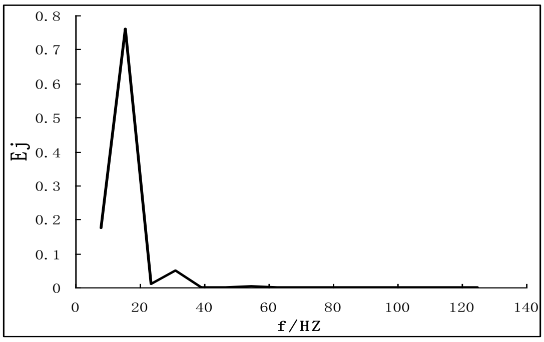
The blasting vibration signals chosen from Table 1(Data 1, 2, 3, 4) are decomposed into eighth layer with db8 wavelet basis function [12,13]. Frequency band energy distribution of blasting vibration signals can be obtained after the signals analyzed by calculating program according to Eq. (5), Eq. (6) and Eq. (7), and the results are shown in Fig.3.



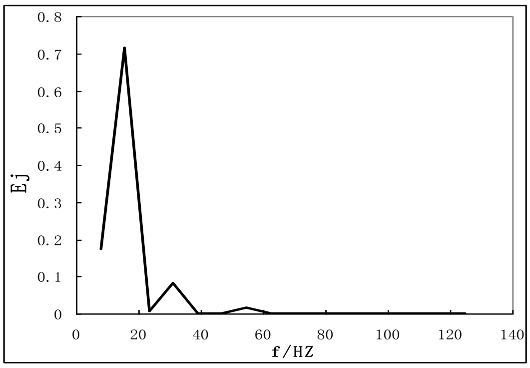
(a)Testing point 1 （+15m）



(b)Testing point 2 （+30m）



(c)Testing point 3 （+45m）



(d)Testing point 4 （+60m）

Fig. 3. *Frequency band energy distributions under positive elevation difference*

Under the condition of positive elevation difference, the percentage of frequency band energy distribution of different frequency band (from 0Hz to 125Hz) is listed in Table 2.

Table 2: *Percentage of frequency band energy distribution of blasting vibration*

Frequency band /HZ	Percentage of energy distribution/%			
	Testing point1 （+15m） /%	Testing point 2 （+30m） /%	Testing point 3 （+45m） /%	Testing point 4 （+60m） /%
0~7.8	3.209	6.4871	18.278	19.258
7.9~15.6	41.414	52.083	61.293	73.603
15.7~23.4	3.9657	2.5038	0.8498	0.4821
23.5~31.3	38.983	30.157	16.7504	5.763
31.4~46.9	0.6457	0.261	0.1368	0.0258
47.0~62.5	11.617	8.3623	2.536	0.846
62.6~85.9	0.0028	0.0018	0.0013	0.0008
86.0~125	0.1015	0.0863	0.0562	0.0126

Conclusions drawn from Fig.3 and Table 2 are as follows.

- The energy of blasting vibration signals under positive elevation difference is distributed widely, but the major part of the energy is concentrated in 0~60Hz range, the energy of this part accounted for about 99% of the total energy. The energy of high frequency (above 60Hz) is almost zero.
- With the positive elevation difference increases from +15m to +60m, the percentage of the energy of 0～15.6Hz bands increases from 44.6% to 92.8%. However, the percentage of the energy of 15.6 Hz～62.5Hz bands decreases from 55.2% to 7.12%. Obviously, the increase of elevation difference will increase the proportion of the energy of lower-frequency signal, and the frequency is very close to the natural frequency of the buildings surrounding the mine, so the harm of the blasting vibration on buildings cannot be ignored.

4 Numerical simulations

In order to study the impact of the elevation difference on the blasting vibrations, ANSYS/LS-DYNA is used to make the numerical simulations, combining with field tests. The blasting parameters are that borehole diameter is 115mm, bench height is 12m, borehole depth is 13m, the safety platform width is 8m, spacing is 4.5, and stemming length is 3m.

4.1 Calculation Model

Two sides and the bottom of the model are defined as non-reflective boundary, and others are defined as free boundary. In order to simplify the calculation, the finite mesh elements far away from the blasting area in the model were divided into sparse grid units, the finite mesh elements near the blasting area were divided into fine grid units, and transition mesh is used to connect with above two grid units.

The study chooses the upper of measuring sites as examples, to analysis the propagation of blasting vibration under the positive elevation difference. The layout of blasting charge and testing points is shown in Fig.4.

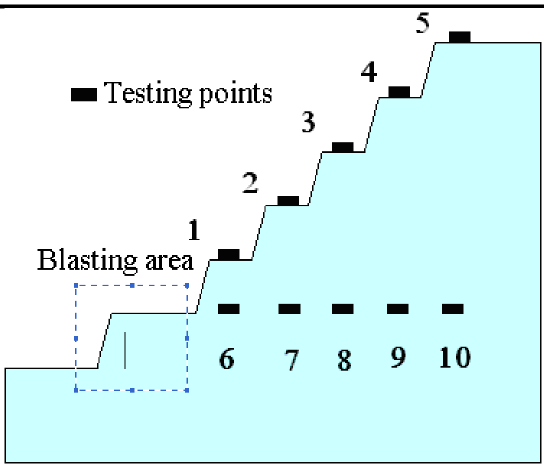


Fig.4 *The arrangement of testing points*

4.2 Material models and state equation

(1) Rock mass and stemming material

MAT_PLASTIC_KINEMATIC was used to simulate rock and stemming [14]. The parameters are listed in Table 3.

Table 3: *The parameters of rock and packing segments*

P / kg·m^{-3}	E / GPa	μ	δ_s / MPa	E_t / GPa
2580	2.8	0.32	46	0.38

(2) Detonation wave and gas

High explosive model and the state equation of JWL were used to simulate detonation wave and gas. And the state equation of JWL defines the relationship between detonation pressure (P) and unit volume inner energy of the explosive (E_0) and a relative volume (V) [15].

$$p = A\left(1-\frac{w}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{w}{R_2 V}\right)e^{-R_2 V} + \frac{wE_0}{V} \quad (8)$$

Where V is the relative volume; E_0 is the unit volume inner energy of the explosive; A, B, w, R_1, R_2 are the characteristic parameters which are constants when choosing a certain explosives. The parameters of explosive materials and JWL are shown in Table 4.

***Table 4**: Explosive materials and JWL equation of state parameters*

P / kg·m^{-3}	V / m·s^{-1}	A / GPa	B / GPa	R_1	R_2	w	E / GPa	V
1150	3600	214.4	0.182	4.2	0.9	0.15	4.192	1.0

4.3 Simulation results and analysis

The blasting vibration simulation data, the particle peak velocities (PPV) of blasting vibration at horizontal and vertical direction under positive elevation is shown in Table 5.

***Table 5**: Blasting vibration Data under positive elevation and horizontal points*

Testing point number	Height /m	Distance /m	PPV of horizontal direction /cm·s^{-1}	Amplification factor	PPV of vertical direction /cm·s^{-1}	Amplification factor
1	12	30	7.68	1.15	6.34	1.21
6	0	30	6.67	—	5.24	—
2	24	42	6.23	1.23	6.17	1.43
7	0	42	5.07	—	4.31	—
3	36	54	7.32	1.48	6.47	1.57
8	0	54	4.95	—	4.12	—
4	48	66	5.95	1.32	4.68	1.41
9	0	66	4.51	—	3.32	—
5	60	78	4.83	1.18	3.54	1.23
10	0	78	4.09	—	2.88	—

According to the simulation results of PPV under different elevations and horizontal points, calculated the amplification factors of blasting vibration between different elevations. The law of the amplification factors shows in Fig 5.

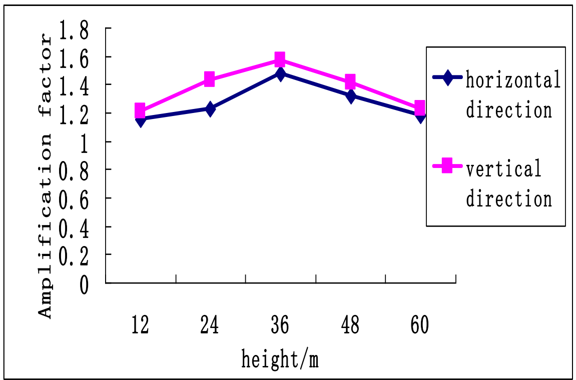


***Fig.5** The amplification factors of blasting vibration between different elevations*

According to the data in Table 5 and Fig 5:

(1) When the distance between explosion source and testing point is 30 meter, the PPV of the horizontal testing point 6 is 6.67 cm/s, the PPV of the vertical testing point 1 is 7.68 cm/s. When the distance between explosion source and testing point is 42 meter, the PPV of the horizontal testing point 7 is 5.07 cm/s, the PPV of the vertical testing point 2 is 6.23 cm/s. this results show that under the same condition of the distance, the PPV increase obviously with the increase of the elevation.

(2) The results show that the blasting vibration exist the elevation amplification effects under the positive elevation, due to the amplification factor is greater than 1.0. With the increase of elevation, the amplification factor increases firstly and then decreases.

5. Conclusions

According to the characteristics of Zuangou Limestone surface mine and its blasting engineering, blasting vibration experiments were carried out, the influence of elevation difference on blasting vibration was analyzed with the methods of wavelet packet and numerical simulation respectively. The conclusions are as follows.

(1) Results from wavelet packet analysis show that energy of the blasting vibration is concentrated between 0Hz ~ 30Hz, which accounted for over 96% of the total energy. With the increases of positive elevation difference, the blasting vibration energy of blasting vibration frequency from 0Hz to 15.6Hz increases by 86.5%, while the proportion of blasting vibration energy of blasting vibration frequency from 15.7 Hz to 62.5Hz decreases by 96.3%.

Obviously, as the increase of elevation difference will increase the proportion of the energy of low-frequency signal, and the frequency is very close to the natural frequency of the buildings surrounding the mine, so the harm of the blasting vibration cannot be ignored.

(2) The numerical simulation results show that under the condition of positive altitude blasting vibration amplifies significantly, and the amplification coefficient increases firstly and then decreases.

(3) Compared the numerical simulation results with the testing results, a conclusion can be drawn that blasting vibration velocities from numerical simulation and experiments are in the same order of magnitude, and the results of numerical simulation are close to the measured results. Because rock mass was deemed as isotropic homogeneous body in the process

of numerical simulation, the blasting vibration velocities from numerical simulation are slightly larger than those from experiments.

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