Study on blasting vibration characteristics of metro tunnel based on wavelet packet technology

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Abstract: Wavelet packet technology has been widely applied in the study on blasting vibration transmission law of overlapping tunnels. The previous research focused on vibration transmission law of the distant area---a range more than 20m, but for the close area---a range less than 10m, research seldom has been carried out. Therefore, this paper, based on a overlapping tunnel project in Qingdao, reveals the blasting vibration transmission law of the close field as well as how the numbers of free surfaces affect the law. Firstly, at the site, the blasting vibration data both in front and rear of the working faces including the cutting area (a free face) and the spreading area (two free faces) in a newly-built tunnel are obtained; Secondly, the wavelet packet technology is applied to analyze the data of blasting vibration frequency and energy distribution characteristics. Finally, it is concluded that different free facing with different numbers can lead to different main frequency distribution range and different law of main frequency band changing with distance when blasting vibration transmit within the close field; and the vibration signal energy in front and rear of the working face in cutting area and spreading area is differently distributed in the directions of 3 channels. Combining blasting vibration signal frequency with energy factors, this paper puts forward the constructive suggestions on the safety protection of existing tunnels and provides reference for studying the law of blasting vibration transmission of overlapping tunnels.

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1. Introduction

In recent years, China’s transportation has developed rapidly, the construction of railway tunnel, express tunnel and urban metro tunnel is in the peak period[1]. With the increase of lines, the transportation web is becoming more and more complicated[2-3]. As a result, railway, express and subway are inevitably intersected. At present, drilling and blasting method is still the main tunnel-constructing way, and excessive blasting vibration will harm the existing tunnels. In order to reduce this harm, researchers have carried out a great deal of study not only on the controlling blasting technology of overlapping tunnels but also on the law of blasting vibration transmission of
overlapping tunnel\cite{4,6}.

In 2002, Song Guangming\cite{7} proposed to use wavelet packet analysis technology to evaluate blasting vibration damage, which provides a new research method for controlling blasting seismic effect. The subsequent scholars gradually use various ways, such as wavelet packet transformation, improved wavelet packet algorithm and fractal theory to study the frequency and energy distribution characteristics of blasting vibration signal\cite{8,11}. From then on, blasting vibration damage can be evaluated more accurately and more elaborately as the evaluating method has developed from adopting the single factor of particle peak value in the earliest time to combining the comprehensive factors of vibration signal frequency and energy.

As far as the research on the law of partition blasting vibration of tunnel is concerned, Meng Haili\cite{12} studied the attenuation coefficient value of K and a of partitioned blasting vibration of tunnel; Wang Hailiang\cite{13} mainly studied the transmission law of peak vibration velocity of partitioned blasting particle. The energy distribution characteristics of partition blasting vibration signals haven’t been studied by the two scholars, however. Yang Jianhua\cite{14}, using MS3,5,11 delay detonators to form three blasting sections to explode the whole cross section successively, studied how the free face formed by the whole cross section blasting influences the vibration frequency. His experiment was conducted on the slope out of tunnel entrance, and the vibration-measuring points were placed in an area of 28-80m on the side of explosion source. The blasting vibration in such an area is mainly affected by seismic wave. Meanwhile, in this test the vibration energy law in front and rear of working face was not studied. In this paper the studied blasting vibration scope is an area of 0-8m, which is mainly influenced by stress wave.

Based on a blasting project of overlapping tunnel of Qingdao Metro, this paper, supported by measured on-site data and wavelet analysis technology, reveals in detail the energy distribution characteristics of vibration signals in the directions of 3 channels in front and rear of the working face.

2. **Experiment design**

2.1. **Blasting scheme**

Belonging to the single track tunnel, the Carriage-pulling Out Line of Liao Yang East Road Carriage Base of Qingdao Metro Line 2 goes down through the E entrance and exit of the East Bus Station of Qingdao Metro Line 4. The plane angle of the two tunnels is 12°, the vertical distance is only 3m, and the surrounding rock of the overlapping part is V-grade weathered granite. The pull-out line tunnel, whose width and height are 6.2m and 6.63m respectively, is excavated by using the way of “bench+partition” blasting, and the upper bench is divided into 3 areas (cutting area, spreading area 1 and spreading area 2) and is exploded in three times. The constructing procedures are as follows: exploding the cutting area and proceeding 1.5m→exploding spreading area 1 and proceeding 0.75m→mucking→supporting arch frame→concrete spraying→exploding spreading area 2 and proceeding 0.75m→supporting→next circle. The explosive used in the test is No 2 Rock Emulsion Explosive produced by Shandong Yinguang Civil Exploding Equipment Co., Ltd, and the specification of the cartridge is 32mm×300mm, 300g/roll. The detonator is the No 1 series of Milisecond Delay Plastic Detonating Tube produced by Shandong TaiShan Civil Exploding Equipment Co., Ltd. The construction procedures of partitioned blasting excavation of the upper bench is shown in Figure 2, and the blasting parameters are shown in Table 1.
2.2. Monitoring points arrangement

Seven TC-4850 blasting vibration meters are respectively placed in front and rear of the upper bench working face to monitor the blasting vibration velocity of each partitioned area. The monitoring scheme is planned as follows: Scheme A: take the projection of the place over the blasting workplane on the E entrance and exit of the existing tunnel as the standard point to establish the measuring point A-1, then successively to establish ahead six measuring points A-2～A-7. Limited by the on-site construction condition, the horizontal intervals between these points are 1m, 2m, 3m, 4m, 6m and 8m. Scheme B: the arrangement is the same as Scheme A, in the rear of the workplane there are also seven measuring points B-1～B-7, and the intervals are 1m, 3m, 6m, 9m,13m and 17m respectively. The waveform diagram of blasting vibration signal measured in the field are shown in Figure 3.
2.3. The principle of wavelet packet analysis

The wavelet packet analysis is the extension of wavelet multi-resolution analysis, which respectively overcomes the shortcomings of the poor frequency resolution in high frequency band and poor time resolution in low frequency band. It’s a more precise signal analysis method to divide the frequency band into multiple levels and further decompose the high frequency part which is not subdivided in the multi-resolution analysis, so as to improve the time-frequency resolution of signal[15]. After the blasting vibration signal \( s(t) \), is decomposed by wavelet packet technology, \( 2^i \) subspace signal on frequency bands can be obtained, then \( s(t) \) can be formulated as[16]:

\[
s(t) = \sum_{j=0}^{2^i-1} f_{i,j}(t_j) = f_{i,0}(t_0) + f_{i,1}(t_1) + \ldots + f_{i,2^i-1}(t_{2^i-1}),
\]

(1)

in the formula: \( f_{i,j}(t) \) is the reconstructed signal at the decomposing node \( (i, j) \) on the level \( i \), which is decomposed by blasting vibration signal wavelet. If the lowest frequency of \( s(t) \) is 0, and the highest frequency is \( \omega_m \), the frequency width of each frequency band on the decomposing level \( i \) will be \( \omega_m / 2^i \). According to the Principle Parseval in signal spectrum analysis[17], from (1) the blasting vibration energy spectrum analysed by wavelet can be formulated as:

\[
E_{i,j} = \int_{-\infty}^{\infty} |f_{i,j}(t)|^2 dt = \sum_{k=1}^{m} |X_{j,k}|^2
\]

(2)

in the formula: \( j = 0, 1, 2, \ldots, 2^i-1 \); \( k = 1, 2, \ldots, m \) is the discrete point amplitude of the reconstructed signal, \( k \) is the sampling point number of blasting vibration signal. And so the general energy of signal \( E \) can be formulated as:

\[
E = \sum_{j=0}^{2^i-1} E_{i,j}(t_j)
\]

(3)

The percentage \( p_{i,j} \) of sub-frequency band energy occupying general signal energy is

\[
P_{i,j} = \frac{E_{i,j}(t_j)}{E} \times 100\%
\]

(4)

The sampling frequency of the seven TC-4850 blasting vibration meters is 8KHZ, the sampling frequency of Nyquist is 4KHZ. The measured vibration signal is decomposed in eight levels, and the corresponding lowest frequency band is \( 0 \sim 15.625 \) Hz. In this paper the decomposition is finished by the widely applied wavelet base db8. The energy distribution of each frequency band of the signal can be obtained from the formula (1) ~ (4).

3. The frequency and energy distribution characteristics of blasting vibration signal

3.1. The frequency characteristics of vibration signal over the blasting face

Blasting vibration signal frequency is very important information in the transmission law of blasting vibration. The amplitude spectrum curves of blasting vibration signal in four tests are obtained by
wavelet package analysis technique, as shown in Figure 4.

From Figure 4, it can be seen that the corresponding main vibration frequencies of blasting vibration in cutting area are 16.2 Hz, 19.5 Hz, 21.3 Hz, 23.4 Hz, respectively. The corresponding main vibration frequencies of blasting vibration in spreading area 1 are 82.1 Hz, 79.3 Hz, 78.4 Hz, 67.1 Hz. The main vibration frequencies of blasting vibration in spreading area 2 are 73.5 Hz, 66.8 Hz, 76.3 Hz, 71.2 Hz. From the above comprehensive analysis, it can be seen that the main vibration frequencies of blasting vibration in cutting area is less than 50 Hz, and the main vibration frequencies of blasting vibration in spreading area 1 and spreading area 2 distribute within a scope of 50 Hz ~ 100 Hz, which is because the stress wave happens to reflect when it transmits to the free face, and the superposition of the reflected sparse wave and the original stress wave shortens the rising time and the continuous acting time of the load pressure in the distant area, and so resulting in the increase of the load frequency[14]. The amplitude of blasting vibration in cutting area is the greatest, and the amplitude value is concentrated within a scope of 50 Hz; while the amplitude spectrum curve of blasting vibration in spreading area moves towards a scope of 50~100 Hz.

3.2. The energy variation law of blasting vibration signal in cutting area

The energy spectrum of blasting vibration signal in cutting area is obtained by wavelet package analysis technique. The main frequency band is defined as the frequency range composed of each

![Figure 4 Amplitude spectral curve of vibration signals directly above the blasting face](image)

(a) Cutting area

(b) auxiliary area 1

(b) auxiliary area 2
sub-band whose energy percentage is greater than 10%. The energy spectrum of typical vibration signal of 3 channels in cutting area and spreading area is shown in Fig 5, and the energy distribution is shown in Tables 2 and Table 3, in which A-1(0m), A-4(3m), A-7(8m) indicate the three measuring points from the near to the distant. The measuring point B is the same as point A.

The monitored points in front of the cutting area.

(a) Horizontal radial          (b) Horizontal tangential            (c) Vertical direction

The monitored points behind of the cutting area.

(a) Horizontal radial          (b) Horizontal tangential            (c) Vertical direction

The monitored points in front of the auxiliary area.

(a) Horizontal radial          (b) Horizontal tangential            (c) Vertical direction

The monitored points behind of the auxiliary area.

(a) Horizontal radial          (b) Horizontal tangential            (c) Vertical direction

Fig 5 Energy spectrum of blasting vibration in cutting area and auxiliary area

Tab 2 Main frequency band distribution table of blasting vibration signals in cutting area
Within the horizontal distance of 0-8m in front of blasting face, this area is mainly affected by stress wave. From Figure 5 and Table 2, it can be seen that: (1) In the horizontal radial and tangential direction, the main frequency band gradually moves to high frequency with the increase of horizontal distance, and the energy percentage increases from 68.6\% to 93.1\%, and from 63.6\% to 66.2\% respectively. The proportion of high frequency energy increases and the frequency band becomes wide, where in a scope of 100~200Hz, the energy proportion of measuring point A-7 increases 1.13 times and 1.76 times greater than those of measuring point A-1 respectively. 2. In the vertical direction, the main frequency band of measuring point A-1 over the blasting face is 0~31.25Hz + 62.5Hz~93.75Hz, the frequency band is narrow, and the energy percentage is only 37.8\%. It can be seen that the energy distribution of each frequency band is comparatively balanced in the scope of 0~300Hz. The main frequency band gradually moves towards low frequency with the increase of horizontal distance and the energy percentage rises from 37.8\% to 72.1\%. And the proportion of low frequency energy rises, in a scope of 0~31.25Hz, the energy ratio of measuring point B-7 in the three directions increases 0.25 times, 0.60 times and 1.08 times greater than that of B-1 in the three directions. It can be seen that stress wave mainly carries high frequency energy, and after it declines into seismic wave, the energy ratio of high frequency falls, while the ratio of low frequency energy carried by seismic wave rises.

Comparison of blasting vibration signal energy in front of working face with that of in rear of
working face. Within the horizontal distance of 0-8m, the main frequency band of blasting vibration signal in the horizontal radial, tangential and vertical directions moves gradually towards high frequency range of \( 100 \sim 200 \text{Hz} \), and the ratio of high frequency energy rises. It can be seen that under the action of stress wave, the frequency of vibration signal is higher, the ratio of high frequency energy is greater. In this scope, the energy of blasting vibration signal in front of working face is generally greater than that of in rear of working face.

3.3. The energy variation law of blasting vibration signal in spreading area

It’s found in wavelet packet energy spectrum that the energy variation law of blasting vibration signal in spreading area 1 is basically the same as that in spreading area 2, which can be regarded as the law of blasting vibration in the case of two free faces. Therefore, the energy variation law of spreading area can be explained by the blasting vibration energy spectrum (Figure 5) of spreading area 1. The distribution of blasting vibration energy in the horizontal radial, tangential and vertical directions are shown in Table 3.

Within the horizontal distance of 0-8m in front of blasting face, this area is mainly affected by stress wave. From Figure 5 and Table 3, it can be seen that: (1) In the horizontal radial, tangential and vertical direction, the main frequency band gradually moves to high frequency with the increase of horizontal distance, and the energy percentage decreases from 78.0\% to 54.9\%, 62.9\% to 26.0\% and 83.7\% to 30.0\%, respectively. It reveals that the vibration energy distribution in the distant measuring points becomes wide and balanced. And the energy proportion of high frequency rises. In the range of 150-250Hz, the energy proportion of measuring point A-7 in the three directions increases 1.04 times, 0.60 times and 0.57 times greater than that of measuring point A-1, respectively.

Within the horizontal distance of 0-8m in the rear of blasting face: (1) In the horizontal radial, tangential and vertical directions, the main frequency band gradually moves to low frequency with the increase of horizontal distance, and the percentage of energy rises from 83.6\% to 95\%, 83.2\% to 95\%, and 52\% to 86.8\%, respectively. The energy proportion of low frequency rises and frequency band becomes narrow. In the range of 0-62.5Hz, the energy ratio of measuring point B-7 in the three directions increases 0.77 times, 2.73 times and 1.78 times greater than that of B-1. Therefore, the harm brought by low frequency energy of distant blasting vibration should be watched out. In the same distance, the energy of blasting vibration signal in front of working face is generally greater than that of in rear of working face, which reveals the same law as blasting vibration in cutting area.

3.4. The law of partitioned blasting vibration energy varying with distance

The blasting vibration energy of each measuring point is obtained by wavelet packet analysis. It is found in research that the trend of blasting vibration energy varying with distance in spreading area is basically the same as that of blasting vibration energy varying with distance in cutting area. But energy attenuation velocity is different when energy varies with distance. The law of partitioned blasting vibration energy varying with distance in the horizontal direction is identical with that in the tangential direction. Therefore, the energy-distance curve of blasting vibration in cutting area (Figure 6, Figure 7) is drawn to illustrate the variation law.

![Fig 6 Blasting vibration energy-distance curve of cutting area in Horizontal radial](image-url)
From Figure 6, it can be seen that in the horizontal distance of 0-8m ahead of working face, the energy-distance curve shows an upward trend, and the energy comparatively increases 0.2-0.4 times; In the horizontal distance of 0-8m in the rear of working face, the energy-distance curve shows an downward trend, and the energy comparatively decreases 1.5-3 times.

From Figure 7, it can be seen that in the horizontal distance of 0-8m ahead of the working face, the energy-distance curve shows an downward trend, and the energy comparatively decreases 1.0-1.5 times; In the horizontal distance of 0-8m behind of working face, the energy-distance curve shows an downward trend, and the energy comparatively decreases 3-6 times.

The declined energy curve of proportioned blasting is drawn as shown in Figure 8 and Figure 9.

From Figure 8, it can be seen that in the horizontal distance of 0-8m, the curve slope of vibration energy in front of blasting face in cutting area is 0.088, which is less than 0.103, the curve slope of vibration energy in rear of blasting face in cutting area; The curve slope of vibration energy in front of blasting face in spreading area is 0.027, which is less than 0.041, the curve slope of vibration energy in rear of blasting face in spreading area. This reveals that the change of rock properties in the excavated area of the tunnel, and together with the influence of the excavated space leads to the attenuation of the vibration energy in this area faster than that in the unexcavated area.
The slope of vibration energy curve before blasting in cutting area is 0.088, which is greater than that in auxiliary area. That of vibration energy in front of blasting face in spreading area, and the above two curve slopes of vibration energy in rear of the above two working faces shows the same law. This reveals that the vibration energy attenuation of two free faces both in front and rear of spreading area is slow, compared with that of one free face both in front and rear of cutting area. The energy curve of blasting vibration in spreading area is below the energy curve of blasting vibration in cutting area, and vibration energy is low. It can be explained from energy point view that adding free face is beneficial to reducing vibration harm.

It can be seen from Figure 9 that in the range of 0~17m behind the blasting face, when blasting in the cutting area and auxiliary area, the energy in three directions gradually tends to be consistent with the increase of horizontal distance. The slope of energy curve in vertical direction of blasting in cutting area is 0.056 less than 0.103 (Figure 8). This shows that the vibration is mainly affected by stress wave in the range of 0~8m, and the energy decays quickly. In the range of 8~17m, stress wave attenuates into seismic wave, and energy attenuation is relatively slow.

4. Conclusion

The innovation of this paper lies in that not only is the blasting vibration law taken into account, but also the wavelet packet analysis technology is applied into the research a scope of 10m in cutting area and spreading area. Limited by current research cases, the influences on the test of surrounding rock properties and charging quantity is not considered in this research scheme. Therefore, this scheme can be taken as a reference for the related numerical simulation.

The main influence of vibration signal frequency and vibration energy in this paper lies in the difference of free faces (one free face in cutting area and two faces in spreading area). In the scholar Yang’s paper, the wavelet packet technology is also applied to analyze the blasting vibration frequency and the vibration energy under the circumstances of one free face and two free faces respectively, but his measuring points is respectively placed at 28m, 35m, 48m and 81m away behind of explosion center. In this paper, the same law of blasting vibration frequency and vibration energy in the rear of the working face as Yang’s revealed by wavelet packet analysis: the blasting vibration frequency and vibration energy of two free faces is greater than those of one free face. However, in this paper, the blasting vibration frequency and vibration energy in front of working face are also studied and the main results are as follows:

1) Over the blasting surface, the main frequency of blasting vibration in cutting area is concentrated on a scope of 0-50Hz, and the main vibration frequency in spreading area is concentrated on a scope of 50-100Hz.

2) The law of blasting vibration in cutting area: Within the horizontal distance of 0-8m in front of working face, in the horizontal radical and tangential direction, the main frequency band gradually moves to high frequency with the increase of horizontal distance, and the proportion of high frequency energy increases 1.0-1.7 times. In the vertical direction, the main frequency band moves to low frequency, and the low frequency energy increases about 2.5 times. In the distance of 0-8m in the rear of the working face, the main frequency bands in three directions all move to low frequency with the increase of horizontal distance, and the low frequency energy ration increases 0.2-1.0 times.

3) The law of blasting vibration in spreading area: Within the horizontal distance of 0-8m in front of working face, the main frequency bands in three directions gradually move to high frequency with the increase of horizontal distance, and the high frequency energy ratio increases 0.5-1.0 times. In the horizontal distance of 0-8m in the rear of the working face, the main frequency bands in three directions all move to low frequency with the increase of horizontal distance, and the low frequency energy ratio increases 1.5-3.0 times.

4) In the construction, the influence of low frequency energy from distant blasting on the tunnel should be watched out. Compared with the unexcavated area in front of working face, the attenuation of the vibration energy in the excavated area in rear of working face is much faster. The vibration energy attenuation of blasting two free faces in spreading area is slower than that of blasting one free
face in cutting area.

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