Influence of free face numbers on energy distribution characteristics of blast vibration signal in underwater drilling blasting

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Abstract. Aiming to the problem of free face not only affect the blasting effects but also the blasting vibration affects, an analytical method of exploring the free face' influences of the blasting vibration and the attenuation law of seismic wave is proposed. Taking the field monitoring data of underwater blasting seismic wave between the river reach of the Three Gorges Dam and Gezhouba Dam as the study object, utilize the wavelet analysis and decompose method to research the blasting vibration signal’s total energy and energy distribution characteristics in variety of frequency band on different free face. The results indicated that underwater drilling blasting vibration has the characteristic of low frequency, short duration and fast attenuation. Most of the energy of the explosion will be consumed as seismic energy in the slotted blasting due to the restricted of a single free face. However, after the subsequent excavation blasting, the free face number increases but the total energy of blasting vibration and PPV decreases. Therefore, in addition to the usual seismic mitigation measures of underwater drilling and blasting, the number of free faces can be increased to achieve the effect of shock absorption control without reducing section charge.

1. Introduction

In recent years, with the promotion of China's "One Belt And One Road" national strategy and the booming development of the water transportation industry, underwater blasting technology has been widely used in all kinds of life. Underwater blasting not only brings great convenience to engineering construction, but also brings some harmful effects to the surrounding environment and structures. Especially, the harm of blasting vibration has become the focus of people's attention[1].

At present, domestic and foreign scholars have carried out extensive and in-depth studies on land rock blasting theory[2], numerical simulation calculation[3-4] and safety criteria[5]. However, due to the difficulty of underwater blasting operation, complexity of construction environment and coupling of vibration medium, on the viewpoint of energy[6], the research on the influence of free face vibration in underwater drilling blasting is not deep enough[7,9].

Thus, in this paper, the influence of the number of free face on the energy distribution characteristics of underwater drilling blasting vibration signal is discussed based on the measured data of the three gorges reservoir area regulation project and wavelet analysis method, which provides a theoretical basis for the optimal design parameters of underwater blasting and the active control of blasting vibration.
2. Blasting vibration test of different numbers of free face

2.1 Project profile

The junction section between the three gorges and Gezhouba (referred to as the "two DAMS") is the throat of connecting the middle and upper reaches of the golden waterway of the Yangtze river. The obstructing rocks and shallow areas in up channel need to be repaired and cleared by means of underwater drilling and blasting. The blasting reef of the project locates in the channel of letianxi anchorage and liantuo section in Yichang city. As shown in Figure 1, the surrounding environment of the construction is complex.

![Figure 1. The river reach between two dam and rapids distribution map](image)

The rocks in the blasting area are moderately weathered granite with an average compressive strength of 89.2Mpa. The first blasting is grooved blasting, in which 3 rows of holes with 5 holes in each row and 1~3 stage second delay detonator are arranged. First row of holes in the first blasting has only one free face on the top. The other two rows of holes detonated subsequently gradually have another relative adequate free face in flank.

Another blasting is a typical underwater bench blasting of 5 stage delay detonator in the 3 rows with 6 holes in each stage. When the first group blasted, there are only two free face distributed on the top and the side of the rock. After the first group of detonations, one side free face is newly generated, which makes the subsequent group of detonations become three free face blasting. The layout of the hole is shown in Figure 2.

The charging structure of the twice blasting is same. The hole aperture is 90mm and depth of bedrock drilling is 7m with 1m of blocking. 2# rock emulsified explosive is used and the maximum charge are 200kg in the first-time blasting and 120kg in the second-time blasting, respectively.

![Figure 2. The plan view of two blasting hole layout](image)

2.2 Fourier analysis of measured blasting seismic signal

A total of 8 measuring points were arranged along the blasting shoreside and its detail conditions are in Table 1. TC-4850 blasting vibration measuring instrument was used to monitor the different segment blasting signal. Combined with the autocorrelation function method, the power spectrum estimation was obtained from the Fourier transform of the autocorrelation function of each blasting signal. Figure 3 is the vertical velocity-time curves of blasting vibration and its power spectral density diagram.
Table 1. Conditions of different numbers of free face and monitoring points

| Blasting signal | 1-1* | 1-2* | 2-1* | 2-2* | 1-a | 1-b | 1-c | 1-d | 2-a | 2-b | 2-c | 2-d |
|-----------------|------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Free face number| 1    | 2    | 2    | 2    | 1   | 1   | 1   | 1   | 2   | 2   | 2   | 2   |
| Segment charge(kg) | 200  | 180  | 120  | 120  | 200 | 200 | 200 | 200 | 120 | 120 | 120 | 120 |
| Distance between explosion source and measuring point(m) | 142  | 142  | 153  | 153  | 142 | 267 | 392 | 517 | 153 | 278 | 403 | 528 |

* Signal 1-1 and signal 1-2 are respectively I and II segment blasting signal in the first blasting.
* Signal 2-1 and signal 2-2 are respectively I and II segment blasting signal in the second blasting.
* Signal 1-a, 1-b, 1-c, 1-d, 2-a, 2-b, 2-c, 2-d are I segment blasting signal of the twice blasting by eight different distance monitoring point

Figure 3. The vertical velocity-time curves and its power spectral density diagram

3. Wavelet analysis of blasting seismic signal

For underwater blasting vibration signals, the low frequency signal usually attracts more attention. Thus, utilizing the characteristic of the Daubechies wavelet, which have the better compact support, smoothness, and approximately symmetry, the low-frequency part of the signal can be elaborately analyzed. The measured blasting seismic wave was decomposed and reconstructed by 7 layers of sym8 wavelet basis[10]. The bandwidth of each frequency band is shown in Table 2.

Table 2. Frequency bandwidth partition

| Frequency band | bandwidth(Hz) | Serial number |
|----------------|---------------|--------------|
| a7             | 0~7.8125      | 1            |
| d7             | 7.8125~15.625 | 2            |
| d6             | 15.625~31.25  | 3            |
| d5             | 31.25~62.5    | 4            |
| d4             | 62.5~125      | 5            |
| d3             | 125~250       | 6            |
| d2             | 250~500       | 7            |
| d1             | 500~1000      | 8            |

The blasting vibration signal \( s(t) \) is decomposed and reconstructed by wavelet with the level of \( N \), and the formula of total energy \( E \) of the corresponding signal is that:

\[
E = \int_{-\infty}^{\infty} s^2(t) dt = \sum_{i=0}^{N} \int_{-\infty}^{\infty} g_i^2(t) dt + \sum_{i=0}^{N} \int_{-\infty}^{\infty} g_i g_i(t) g_i(t) dt
\]  (1)

According to the orthogonality of the wavelet function, the second part that on the right of the equal sign of the above equation is zero, and the above equation can be simplified as:

\[
E = \sum_{i=0}^{N} \int_{-\infty}^{\infty} g_i^2(t) dt = \sum_{i=0}^{N} E_i
\]  (2)

Where \( E_i \) is frequency band energy of blasting vibration component, \( g \) is the high frequency part of
the decomposition of vibration signal $s(t)$ and the subscale corresponds to the level of decomposition.

The energy of blasting vibration components in each frequency band can be figure out by formula (3)–(4) and the proportion $E_j$ of the energy of each frequency band to the total energy can be obtained by formula (5).

$$E_n = \sum_{n=1}^{M} |a_n(n)|^2 \cdots i = 1,2,\cdots,N$$  \hspace{1cm} (3)

$$E_d = \sum_{n=1}^{M} |d_n(n)|^2 \cdots i = 1,2,\cdots,N$$  \hspace{1cm} (4)

$$E_j = (E_j / E) \times 100\%$$  \hspace{1cm} (5)

Where $M$ is sampling number, $a_n(n)$ is approximation coefficient of wavelet decomposition of blasting vibration signal, $d_n(n)$ is detail coefficient of wavelet decomposition of blasting vibration signal.

4. Characteristics of frequency band energy distribution of blasting vibration signals

4.1 The relationship between free face and total energy of blasting vibration signal

According to the formula (1)–(5) and MATLAB software, the energy values of each frequency band and their percentages in blasting vibration signals are shown in Table 3.

| Frequency band | Wavelet Frequency band energy |
|----------------|--------------------------------|
|                | Signal 1-1 | Signal 1-2 | Signal 2-1 | Signal 2-2 |
|                | energy     | percentage | energy     | percentage |
| 0–7.8125       | 2.6287     | 0.1        | 0.1087     | 0.04       |
| 7.8125–15.625  | 24.4471    | 0.93       | 0.1631     | 0.06       |
| 15.625–31.25   | 2147.6642  | 81.7       | 194.0952   | 71.4       |
| 31.25–62.5     | 312.8177   | 11.9       | 64.6168    | 23.77      |
| 62.5–125       | 105.4117   | 4.01       | 8.9708     | 3.3        |
| 125–250        | 26.2872    | 1          | 3.2621     | 1.2        |
| 250–500        | 7.0975     | 0.27       | 0.5709     | 0.21       |
| 500–1000       | 2.3658     | 0.09       | 0.0054     | 0.02       |
| summation      | 2628.7     | 271.842    | 169.2      | 34.253     |

(1) Comparing the two different blasting process, the vibration energy of grooved blasting is much larger than that of general bench blasting. The segment charge capacity of signal 1-1 is only 1.6 times of that of signal 2-1, but the total energy of signal 1-1 is 15.53 times that of signal 2-1. That is because the underwater grooved blasting is limited by a single free face, and explosive blasting energy is mostly consumed in the form of seismic energy.

(2) Comparing the same blasting, for example, the blasting vibration energy of single free face is much higher than that of multiple free face. Signal 1-1 has the same charge of signal 1-2, but has the 9.7 times total vibration energy of signal 1-2. Also, signal 2-1 has the 4.97 times total vibration energy of three-free face blasting vibration signal 2-2. Hence specific vibration energy $\lambda_E$ is introduced, which means the ratio of the total vibration energy produced by unit mass explosive to its charge. The $\lambda_E$ of single free face blasting signal 1-1 is 13.14, while two free face blasting signal 1-2 is 1.355 and three free face blasting signal 2-2 is 0.28. It can be obviously seen that the more numbers of free face are, the fewer specific vibration energy is.

4.2 Relation between free face and energy distribution of blasting vibration signal in different frequency bands

(1) Based on the data of monitoring points with different distance from the detonation center (signal 1-a~signal 2-d), it can be found that the blasting vibration energy attenuates faster in the vicinity of the
The general trend shows an exponential decreasing trend. As shown in Figure 4, the blasting near field has a high frequency vibration energy, while the propagation to the far end is mainly the low frequency vibration energy.

![Figure 4. Blasting vibration total energy attenuation of one free face and two free face](image)

![Figure 5. Three-dimensional distribution of blasting vibration energy](image)

(2) Figure 5 shows that the signal energy of each segment is mainly concentrated in the low frequency band (15.625~31.25Hz), while the high frequency band accounts for a small proportion. In the first blasting, with the increase of the number of free faces, the percentage of energy distribution in the range of 15.625~31.25Hz decreased from 81.7% to 71.4%. While the percentage of energy distribution in the range of 31.25~62.5Hz increased from 11.9% to 23.77%. To the similar discipline, during the second blasting, 15.625~31.25Hz frequency band energy percentage decreased from 69.3% to 50.8%, while 31.25~62.5Hz frequency band increase from 22.33% to 29.53%. Hence, increasing the number of free face can make the blasting vibration energy concentrate to high frequency.

4.3 Distribution characteristics of frequency bands energy and particle peak vibration velocity (PPV) in different free face blasting vibration signal

Figure 6 is the time history curve of vibration components of blasting signal 1-1 extracted by wavelet analysis. It can be found that the duration of low-frequency vibration component a7 and d7 is longer, but the PPV value is lower; The duration of d6 and d5 is shorter, but the PPV value is the highest. The duration of high-frequency vibration component is the shortest.

Taking the similar methods can figure out the other PPV of different free face numbers. As shown in Figure 7, the distribution law of PPV is basically consistent with that of energy. Generally, PPV value increase sharply at first and then decrease slowly with the frequency band from low to high. What’s more important is that the PPV value is significantly decrease with the free face number increase.

![Figure 6. Blasting vibration component of signal 1-1 at different frequency bands](image)

![Figure 7. Distribution of each band PPV of blasting vibration signal](image)

5. Conclusion

(1) When a single free face is used in underwater drilling, most of the energy produced by the explosive convert into vibration energy. When the charge structure and section charge is same, as the increase of
free face numbers, the total vibration energy decreases, and the more blasting energy is used for rock mass breaking and overcoming water resistance and throwing. Therefore, increasing the number of free faces can effectively reduce blasting vibration.

(2) The energy generated by underwater drilling blasting is mainly concentrated in the low frequency band (15.625Hz ~ 31.25 Hz). With the increase of free face numbers, the main frequency tends to be middle and high frequency, which can avoid the natural vibration frequency of other facilities.

(3) The free face of underwater drilling blasting significantly affects the PPV value. The PPV value first increases sharply and then slowly decreases with the frequency band from low to high. With the increase of the number of free face, the PPV value presented a nonlinear decreasing trend. Therefore, in the process of predicting the PPV of underwater drilling blasting, the influence of free face numbers should be mainly considered.

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References
[1] Zhong, G. Fang, Y. Xu, H. (2008) Study on blasting vibration effect assessment of structure based on wavelet transform. Journal of Vibration and Shock, 27: 121-124.
[2] Li, H. Yang, X. Shu, D. (2010) Characteristics of blasting seismic energy distribution in different explosion sources. Journal of Sichuan University(Engineering Science Edition), 42: 30-34.
[3] Gu, W. Wang, Z. Chen, J. (2016) Influence of charge structure on the energy transfer of blasting vibration and explosive effect. Journal of Vibration and Shock, 35: 207-211.
[4] Wang, W. Leng, Z. Lu W. (2018) Effect of free face numbers of blasting vibration in rock blasting. Mine and Metallurgical Engineering, 38: 17-22.
[5] Zhang, S. Liu, L. Zhong, Q. (2019) Energy distribution characteristics of blasting seismic wave on open pit slope. Journal of Vibration and Shock, 38: 224-232.
[6] Gu, W. Wang, Z. Liu, J. (2017) Research and application of underwater blasting vibration testing technology. Journal of Ordnance Equipment Engineering, 38: 256-260.
[7] Wu, C. Xu, C. Zhang, Q. (2017) Influence of free face on energy distribution characteristics of blasting vibration. Journal of Vibration and Shock, 37: 907-914.
[8] Chi, M. Zhao, M. Liang, K. (2013) Influence of number of free face on time-frequency characteristics on blasting seismic wave. Blasting, 30: 16-20.
[9] Yang, J. Lu, W. Yang, P. (2016) Influences of blast-created free surfaces on blasting vibration frequencies during full-face excavation. Journal of Vibration and Shock, 35: 193-197.
[10] Yan, Y. Xing, H. (2018) Sea clutter de-noising based on wavelet packet multi-threshold method. Journal of Electronic Measurement and Instrumentation, 24: 172-178.