Research Article

Hollow Effect of Ground Vibration Induced by Electronic Detonator in Shallow Tunnel

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Blasting excavation is extensively used in tunnel construction, and the adverse effect of ground vibration induced by blasting on surrounding structures and inhabitants is a critical problem. This study aims to investigate the tunnel hollow effect on triaxial peak particle velocities (PPV) and dominant frequencies induced by electronic detonator. Field experiments were conducted in a shallow tunnel construction site and the ground vibration waveforms were recorded. Variational mode decomposition (VMD) was applied to denoise and correct the zero-drift phenomenon, and the proposed method of selecting the optimal parameter was verified. A series of statistical analyses and tests were performed to evaluate the differences of peak particle velocity and dominant frequency among various monitoring points. The results showed that the hollow effect on Z-axis PPV is significant, and triaxial PPV is also affected when the horizontal distance exceeds 30 m. The hollow effect on dominant frequency could not be identified since the hollow of tunnel is a free face, and the dominant frequency of reflected wave remains unchanged. An augmented factor of 1.229 is determined carefully as the hollow effect factor on PPV. Therefore, blasting vibration induced by electronic detonator of the excavated zone should be attached with greater importance, and hollow effect on PPV should be considered in the blasting design of tunnel excavation.

1. Introduction

With the economy development and urbanization acceleration in China, underground space utilization has grown rapidly. As a highly efficient and economical excavation method, blasting is widely used in tunnel constructions. However, studies show that only up to 30% of blasting energy is directly applied to rock fragmentation. If not controlled well, the rest energy may cause adverse effects such as ground vibration, flying rocks, noise, and air blasts [1].

Among the above side effects of blasting, ground vibration has long been considered as the primary problem since its amplitude, dominant frequency, and duration might cause damage to nearby structures and nuisance to inhabitants [2]. Ground vibration, in general, can be measured as ground displacement, acceleration, and velocity. Conventionally, peak particle velocity (PPV) is used to assess the amplitude of ground vibration, and many regulations are designed based on PPV and dominant frequency [3, 4].

Mainly, the charge per delay and the distance from the surface are the two factors which determine the value of PPV, and investigations on factors affecting PPV have been conducted comprehensively by numerical simulations and field experiments [5–11]. Based on these investigations, millisecond blasting has been verified as a valid approach to mitigate ground vibration. The crucial idea of a successful millisecond blasting is that energy could be dissipated maximally when the adjacent seismic waves interfere with each other [12–14], which are fundamentally determined by delay time.

During tunnel blasting construction, another factor affecting PPV is the hollow effect of excavated zone, which leads to the fact that the collapse area always appears in the excavated zone close to the tunnel face. The failure mechanism, loads, and fracture characteristics in the excavated zone have changed [15–20] due to blasting excavation. Wang et al. [21] discovered that PPV generated from the excavated zone was 1.2 to 1.4 times greater than that induced ahead of
the tunnel face. Besides, Zhao et al. [22] evaluated the ground vibration signals by combing wavelet analysis and adaptive optimal kernel time-frequency distribution method. The authors’ result verified the existence of hollow effect and further illustrated that not only PPV but also the dominant frequency increases due to the hollow in the excavated zone. Furthermore, Cai et al. [23] derived a calculation equation for PPV in the excavation and non-extraction zones based on the energy attenuation law and seismic wave propagation. The numerical simulation showed that the hollow effect is proportional to the blasting load, and the average quotient is 1.2. These previous researches conducted field blasting experiments by nonel detonators, and the delay times were at least 50 ms. Here is a scheme to assess the band width of an IMF is as follows:

1. For each IMF \( u_m \), first, compute the analytic signal by applying the Hilbert transform to obtain a unilateral frequency spectrum. Let \( u_m(t) \) be the intrinsic mode function:

\[
u_m(t) = A_m(t) \cos(\varphi_m(t)),\]

where the envelope \( A_m(t) \geq 0 \), the phase \( \varphi_m(t) \) is a non-decreasing function, \( \varphi_m'(t) \geq 0 \).

In particular, for IMF, the analytic form of IMF by applying Hilbert transformation is

\[
u_{m,A}(t) = A_m(t) \cos(\phi(t)) + j \sin(\phi(t))
= A_m(t) e^{j \phi(t)}.
\]

2. Shift the IMF’s spectrum to the baseband by applying an exponential tuned to the estimated center frequency:

\[
\left[ \left( \delta(t) + \frac{j}{\pi t} \right) u_m(t) \right] e^{-jwt}.
\]

3. Estimate the bandwidth by calculating the squared \( L^2 \)-norm of the demodulated signal gradient, and the resulting constrained problem is

\[
\min_{\{u_m,\{w_m\}\}} \left\{ \sum_{m=1}^{k} \left\| \frac{d}{dt} \left[ \left( \delta(t) + \frac{j}{\pi t} \right) u_m(t) \right] e^{-jwt} \right\|_2^2 \right\}
\]

s.t., \( \sum_{m=1}^{k} u_m(t) = f(t) \).

To solve this problem, a quadratic penalty term and Lagrangian multiplier \( \lambda \) were used to render the unconstrained problem:

\[
M(u_m, w_m, \lambda) = a \sum_{m=1}^{k} \left\| \left[ \left( \delta(t) + \frac{j}{\pi t} \right) u_m(t) \right] e^{-jwt} \right\|_2^2 + \left\| f(t) - \sum_{m=1}^{k} u_m(t) \right\|_2^2 + \langle \lambda, f(t) - \sum_{m=1}^{k} u_m(t) \rangle
\]

multipliers (ADMM) [25]. The updating process is calculated in the spectral domain and summarized as follows:
\[
\tilde{u}_{m}^{n+1}(w) = \frac{\tilde{f}(w) - \sum_{i,m} \tilde{u}_{i}^{n+1}(w) - \sum_{i,m} \tilde{u}^{n}_{i}(w) + (\tilde{\lambda}^{n}(w)/2)}{1 + 2\alpha(w - u_{m}^{n})^{2}}, \quad m \in \{1,k\},
\]

\[
\tilde{u}_{m}^{n+1}(w) = \int_{0}^{\infty} w|\tilde{u}_{m}^{n+1}(w)|^{2} dw \quad \int_{0}^{\infty} |\tilde{u}_{m}^{n+1}(w)|^{2} dw, \quad m \in \{1,k\}.
\]

Use the dual ascent to update the Lagrangian multiplier \(\lambda\) for all \(w \geq 0\):

\[
\tilde{\lambda}^{n+1}(w) = \tilde{\lambda}^{n}(w) + \tau \left( \tilde{f}(w) - \sum_{m=1}^{k} \tilde{u}_{m}^{n+1}(w) \right). \tag{8}
\]

Until the calculation is converged,

\[
\sum_{m=1}^{k} \frac{\|\tilde{u}_{m}^{n+1} - \tilde{u}_{m}^{n}\|^{2}}{\|\tilde{u}_{m}^{n}\|^{2}} < \epsilon. \tag{9}
\]

2.2 Determination of VMD Parameters. In the VMD computing algorithm, two major parameters are required to be set in advance, namely, the penalty weight \(\alpha\) and number of IMF \(k\). As the penalty weight \(\alpha\) grows larger, the bandwidth of IMF would be smaller, which might lead to a fall in an infinite recursive loop. The appropriate penalty weight \(\alpha\) is suggested as 10 times the signal length.

The number of IMF \(k\) plays a more salient role since it directly determines the accuracy of decomposition. As VMD is equivalent to a set of adaptive filters, if the number of IMF is small, significant information within the signal would be filtered. On the other hand, if the number of IMF is relatively large, the noise would be added into the signal. Therefore, both overbinning and underbinning affect the VMD precision. However, there is still no conclusion on how to set the value of \(k\). Therefore, a new method is proposed based on Hilbert transform instantaneous energy:

1. For an input signal \(z(t)\), Hilbert transform is performed to obtain the analytical form:

\[
z_{H}(t) = z(t) + jH[z(t)]
\]

\[
A(t) = e^{j\phi(t)},
\]

\[
\phi(t) = \arctan \left( \frac{H[z(t)]}{z(t)} \right).
\]

2. Then, \(z(t)\) can be written as

\[
z(t) = Re[z_{H}(t)]
\]

\[
= Re[A(t)e^{j\phi(t)}] = Re \left( A(t)e^{2\pi \int_{0}^{\infty} f(t)dt} \right).
\]

where \(Re\) takes the real part of a complex number; \(d\phi(t) = 2\pi f(t)dt\). \(z(t)\) could be represented as a function of time \(t\) and instantaneous frequency \(f(t)\); then the Hilbert transform instantaneous energy can be defined as

\[
IE_{z}(t) = \int f \left( \text{Re}[A(t)e^{2\pi \int f(t)dt}] \right)^{2} df.
\]

The total energy is

\[
TE_{z} = \int IE_{z}(t)dt.
\]

3. Calculate the total energy of input signal as \(TE_{z}\); then for each number of \(k\), VMD was performed on the input signal and the total energy of reproduced signal calculated as \(TE_{k}\). The energy loss is defined as

\[
Loss_{k} = (TE_{z} - TE_{k})^{2}.
\]

Plot the list of \(Loss_{k}\) versus the number of \(k\), as shown in Figure 1. It is desirable to find a sharp reduction in the size of \(Loss_{k}\), which means that when the \(Loss_{k}\) drops dramatically in size, an additional IMF would add relatively little to the information already extracted.

2.3 Calculation and Statistical Evaluation for Hollow Effect. After performing VMD on the input signal, a reconstructed waveform is generated, which is denoted as \(Z_{k}(t)\). Triaxial PPV and dominant frequencies could be calculated based on \(Z_{k}(t)\) by applying Fast Fourier Transform. Accordingly, the differences between excavated and unexcavated zones could be analyzed.

PPV \(_{D}\) and \(f_{D}\) are the PPV and dominant frequency of the excavated zone, with a distance of \(D\) which is the absolute horizontal distance between the tunnel face and vibration monitoring point. PPV \(_{D}\) and \(f_{D}\) are the PPV and dominant frequency of the unexcavated zone, with a distance of \(D\). For each distance \(D\), a list of pairwise PPV and dominant frequency could be collected by vibration monitoring, namely, \([PPV_{-D},PPV_{D}]\) and \([f_{-D},f_{D}]\).

At a given constant \(D\), in order to evaluate the significance of differences between PPV \(_{D}\) and \(PPV_{D}\), \(f_{D}\) and \(f_{D}\), the Wilcoxon rank-sum test [26] is applied, which is a nonparametric alternative to the two-sample \(t\)-test for assessing whether the means of these two populations are equal. The two-sample \(t\)-test requires that the two groups of observations are sampled from two independent and normally distributed populations with equal variance, but these
requirements are barely met in engineering scenarios. While the Wilcoxon rank-sum test does not assume known distributions, it is based solely on the order in which the observations from the two samples fall.

If the Wilcoxon rank-sum test verifies any significant differences, the magnitudes of the differences are of interest as they can be seen as quantifications of the hollow effect, and the ratio of excavated zone to unexcavated zone can be applied as a measurement.

Define $V_R$ as the PPV ratio of excavated zone to unexcavated zone, and $f_R$ as the dominant frequency ratio of excavated zone to unexcavated zone:

$$V_R = \frac{PPV_{-D}}{PPV_{D}}$$

$$f_R = \frac{f_{-D}}{f_{D}}$$

where $V_R$ and $f_R$ are two statistical parameters to quantify the hollow effect on PPV and dominant frequency. The Wilcoxon rank-sum tests were performed again to assess whether the ratios $V_R$ and $f_R$ have statistical difference as the absolute horizontal distance $D$ changes. By this means, the pattern of hollow effect can be discovered. The analysis flow charts of the present study are shown in Figure 2.

3. Methodology Implementation

3.1. Monitoring Experiment of Blasting Vibration. The Winter Olympic branch line of Beijing Metro Line 11 is an important transportation facility of the 2022 Beijing Olympic Winter Games. The field vibration monitoring experiments were conducted in the Jinding Street Station construction section of the Winter Olympic branch line, with a total construction length of 1896.8 m. The project layout of this tunnel construction section is shown in Figure 3.

The overburden depth of the tunnel ranges from 19 m to 24 m. The rock along the tunnel is mainly the slightly weathered basalt, and its uniaxial compressive strength is 108.4 MPa. Hence, the drilling and blasting technique is applied. As can be seen in the project layout (Figure 3), extensive residential neighborhoods are located in the vicinity of the tunnel. Since the blasting vibration is likely to cause damage to nearby structures and influence the residents, millisecond blasting technique using electronic detonator is adopted. The electronic detonator can provide an accurate delay time controlled by an integrated chip from 1 ms to 15 s, and the delay time can be set arbitrarily according to various surrounding rock and blasting conditions. Figure 4 shows a typical blasthole layout of the tunnel face, and the numbers denote its detonation sequence. This tunnel adopted a three-bench blasting excavation method, with a width of 12.3 m, a height of 8.7 m, and excavation footage of 2 m. Three benches were initiated separately according to in-site working conditions. As shown in the figure, blastholes were detonated in turn, and the charge per delay was charge per hole. A delay time of 10 ms was set to mitigate the blasting vibration.

In this study, vibrations induced by middle bench blasting were investigated because its designed charge per hole of easier hole was the same as the cutting hole of upper bench, which may cause larger vibration magnitude and duration. The detailed blasting parameters of the middle bench are shown in Table 1.

The ground vibrations were monitored by triaxial vibration velocity transducers, as shown in Figure 5, and the schematic diagram of vibration monitoring is shown in Figure 6. The coordinates $X$, $Y$, and $Z$ represent the longitudinal, transverse, and vertical axis, respectively. In this experiment, the absolute horizontal distance $D$ was taken as 0 m, 10 m, 15 m, 20 m, and 30 m, and nine monitoring points were placed on the ground rock surface to monitor the ground vibration velocity. The overburden depth was 19 m, and a total of 108 records were collected. The typical time history curves of vibration velocity are shown in Figure 7. According to Figure 7(b), the phenomenon of zero-drift exists, which indicates that the original signals need to be corrected.

3.2. Analysis of Hollow Effect. In order to correct the zero drift and denoise signals, VMD method and the proposed method to determine the optimal number of $k$ were applied. Figure 8 displays a typical plot of $Loss_\alpha$ versus the number of $k$. By the rule of sharp reduction in the size of $Loss_\alpha$, the optimal number of $k$ of each signal can be identified. Time history curves of vibration velocity with $k$ IMFs are shown in Figure 9. As it can be seen from this figure, VMD method decomposes the signal into several IMFs based on the value of $k$, with different center frequencies. Figure 10 shows the results of VMD, and the Y-axis waveform of monitoring point 5 evidently demonstrates the effect of VMD on eliminating the zero drift, while the general trends remain the same.

Figures 11 and 12 display boxplots and kernel density plots of PPV and dominant frequency calculated from the reconstructed waveforms. The boxplots and kernel density plots show that PPV distributions vary noticeably with the monitoring point distance. In contrast, the distributions of dominant frequency are relatively similar and concentrated, which implies that the differences among dominant frequencies might be insignificant. Even though the monitoring devices were set carefully, some distinct outliers were...
Figure 2: Analysis flowcharts: (a) reconstructed signal generation; (b) hollow effect evaluation.

Figure 3: Project layout of the Winter Olympic branch line of Beijing Metro Line 11.
Figure 4: Layout of typical blasthole for electronic detonators of the tunnel.

Table 1: Blasting parameters of the middle bench.

| Blasting event | Blasthole type  | Blasthole number | Blasthole length (m) | Blasthole spacing (m) | Blasthole diameter (mm) | Charge diameter (mm) | Charge weight per hole (kg) | Delay time (ms) |
|----------------|-----------------|-------------------|----------------------|-----------------------|------------------------|------------------------|---------------------------|----------------|
| Middle bench   | Easer hole      | 24                | 2.2                  | 1.0                   | 42                     | 32                     | 1.1                       | 10             |
|                | Periphery hole  | 10                | 2.2                  | 0.25                  | 42                     | 32                     | 0.5                       | 10             |
|                | Bottom hole     | 13                | 2.2                  | 1.0                   | 42                     | 32                     | 1.1                       | 10             |

Figure 5: Triaxial vibration velocity transducer TC-4850.
still introduced by the internal measuring error of triaxial vibration velocity transducer and geological defects, which are required to be excluded. Table 2 lists the averages and standard deviations of PPV with different monitoring distances, and the dominant frequency results are shown in Table 3. The largest PPV occurs right above the tunnel face in Z-axis, which is 1.143 cm/s on average. Table 2 informs that PPV\(_D\) is generally larger than PPV\(_{-D}\), while Table 3 does not tell much difference between \(f_{-D}\) and \(f_D\). To statistically compare the difference between PPV\(_{D}\) and PPV\(_{-D}\), \(f_{-D}\) and \(f_D\), the Wilcoxon rank-sum test is performed, and the test results are listed in Table 4. At a given confidence level \(\alpha = 0.05\), only the Z-axis peak particle velocities of excavated and unexcavated zones are significantly different regardless of the absolute horizontal distance. When the absolute horizontal distance is greater than 30 m, the hollow effect on PPV exists in three directions. The dominant frequencies are not statistically different across all the absolute horizontal distances and directions. This result is because the hollow of tunnel mainly plays a role of free face, and the frequencies of reflected waves do not change. These results also inform that when a tunnel is excavated below a residential area, more attention should be paid to the excavated zone, especially within a horizontal distance of 30 m from the tunnel face, since the Z-axis PPV of excavated zone is usually larger than that of the unexcavated zone, and human beings are more sensitive to vertical vibrations [27].
Figure 8: Typical plot of Loss$_k$ versus the number of $k$: (a) monitoring point 2 at +10 m; (b) monitoring point 5 at −10 m.

Figure 9: Typical time history curves of vibration velocity with (k) IMFs. Each line represents an IMF. $k = 0$ is the original signal. (a) Monitoring point 2 at +10 m; (b) monitoring point 5 at −10 m.
Figure 10: Typical time history curves of original waveform and reconstructed waveform: (a) monitoring point 2 at +10 m; (b) monitoring point 5 at −10 m.

Figure 11: PPV and dominant frequency box plots: (a) PPV; (b) dominant frequency.
The results of significance tests are listed in Table 4, from which it can be seen that the hollow effect does not influence the dominant frequency but substantially affects the PPV in some circumstances. To quantify the hollow effect on PPV, VR\textsubscript{D} is defined as the ratio of PPV of excavated zone and unexcavated zone. Only VR\textsubscript{D} of Z-axis across all the pair monitoring points are calculated, along with the VR\textsubscript{D} of X- and Y-axis with an absolute horizontal distance of 30 m, and the results are shown in Table 5. Apparently, these VR\textsubscript{D} averages seem to vary with each other, but due to the relatively large standard deviations, the conclusion of remarkable difference cannot be drawn. To further investigate whether these VR\textsubscript{D} values are significantly different from each other, Wilcoxon rank-sum test was applied again to evaluate the difference among Z-axis VR\textsubscript{D} and triaxial VR\textsubscript{30}, as listed in Table 6. Unlike the tests results in Table 5, here each VR\textsubscript{D} involves multiple comparisons. In order to maintain a family-wise type-I error rate when conducting

| Monitoring distance | X-axis average (cm/s) | X-axis standard deviation | Y-axis average (cm/s) | Y-axis standard deviation | Z-axis average (cm/s) | Z-axis standard deviation |
|---------------------|-----------------------|--------------------------|-----------------------|--------------------------|-----------------------|--------------------------|
| 0                   | 0.755                 | 0.183                    | 0.806                 | 0.226                    | 1.143                 | 0.419                    |
| −10                 | 1.005                 | 0.301                    | 0.722                 | 0.204                    | 1.025                 | 0.070                    |
| +10                 | 0.689                 | 0.140                    | 0.701                 | 0.166                    | 0.978                 | 0.140                    |
| −20                 | 0.715                 | 0.315                    | 0.469                 | 0.078                    | 0.873                 | 0.027                    |
| +20                 | 0.378                 | 0.038                    | 0.455                 | 0.046                    | 0.470                 | 0.147                    |
| −30                 | 0.558                 | 0.038                    | 0.408                 | 0.068                    | 0.642                 | 0.054                    |
| +30                 | 0.341                 | 0.040                    | 0.378                 | 0.093                    | 0.471                 | 0.125                    |
multiple hypothesis tests at once, Benjamini–Yekutieli [28] correction method is applied to adjust the p values. At the given family-wise confidence level $\alpha = 0.05$, it is shown that no significant difference could be found based on the adjusted p values, which indicates that VR should be identical for these directions and absolute horizontal distances. By

| Monitoring distance (m) | X-axis average (Hz) | X-axis standard deviation | Y-axis average (Hz) | Y-axis standard deviation | Z-axis average (Hz) | Z-axis standard deviation |
|------------------------|---------------------|--------------------------|---------------------|--------------------------|---------------------|--------------------------|
| 0                      | 84.523              | 16.460                   | 80.868              | 16.459                   | 95.971              | 28.262                   |
| −10                    | 66.572              | 1.155                    | 88.036              | 31.370                   | 88.297              | 31.185                   |
| +10                    | 66.939              | 0.529                    | 65.989              | 0.372                    | 66.430              | 0.964                    |
| −20                    | 67.381              | 1.407                    | 65.899              | 0.664                    | 66.667              | 0.291                    |
| +20                    | 67.751              | 0.718                    | 65.954              | 0.547                    | 66.065              | 0.478                    |
| −30                    | 68.808              | 0.768                    | 66.856              | 0.714                    | 66.105              | 0.516                    |
| +30                    | 67.221              | 0.437                    | 66.962              | 1.367                    | 67.027              | 1.899                    |

| 1st variable (m) | 2nd variable (m) | Variable tested | Wilcoxon rank-sum test p value | Benjamini–Yekutieli adjusted p value |
|------------------|------------------|-----------------|-------------------------------|-------------------------------------|
| −10              | +10              | X-axis $PPV_{-10}$ and $PPV_{10}$ | 0.116                          |                                     |
| −10              | +10              | Y-axis $PPV_{-10}$ and $PPV_{10}$ | 0.935                          |                                     |
| −10              | +10              | Z-axis $PPV_{-10}$ and $PPV_{10}$ | 0.008                          |                                     |
| −10              | +10              | X-axis $f_{-10}$ and $f_{10}$ | 0.257                          |                                     |
| −10              | +10              | Y-axis $f_{-10}$ and $f_{10}$ | 0.830                          |                                     |
| −10              | +10              | Z-axis $f_{-10}$ and $f_{10}$ | 0.525                          |                                     |
| −20              | +20              | X-axis $PPV_{-20}$ and $PPV_{20}$ | 0.347                          |                                     |
| −20              | +20              | Y-axis $PPV_{-20}$ and $PPV_{20}$ | 0.522                          |                                     |
| −20              | +20              | Z-axis $PPV_{-20}$ and $PPV_{20}$ | 0.011                          |                                     |
| −20              | +20              | X-axis $f_{-20}$ and $f_{20}$ | 0.522                          |                                     |
| −20              | +20              | Y-axis $f_{-20}$ and $f_{20}$ | 0.121                          |                                     |
| −20              | +20              | Z-axis $f_{-20}$ and $f_{20}$ | 0.136                          |                                     |
| −30              | +30              | X-axis $PPV_{-30}$ and $PPV_{30}$ | 0.004                          |                                     |
| −30              | +30              | Y-axis $PPV_{-30}$ and $PPV_{30}$ | 0.002                          |                                     |
| −30              | +30              | Z-axis $PPV_{-30}$ and $PPV_{30}$ | 0.035                          |                                     |
| −30              | +30              | X-axis $f_{-30}$ and $f_{30}$ | 0.134                          |                                     |
| −30              | +30              | Y-axis $f_{-30}$ and $f_{30}$ | 0.830                          |                                     |
| −30              | +30              | Z-axis $f_{-30}$ and $f_{30}$ | 0.439                          |                                     |

| Variable | Average value | Standard deviation |
|----------|---------------|--------------------|
| Z-axis VR$_{10}$ | 1.278 | 0.223 |
| Z-axis VR$_{20}$ | 1.776 | 0.574 |
| X-axis VR$_{30}$ | 1.277 | 0.541 |
| Y-axis VR$_{30}$ | 0.841 | 0.240 |
| Z-axis VR$_{30}$ | 0.940 | 0.463 |

| 1st variable | 2nd variable | Wilcoxon rank-sum test p value | Benjamini–Yekutieli adjusted p value |
|--------------|--------------|-------------------------------|-------------------------------------|
| Z-axis VR$_{10}$ | Z-axis VR$_{20}$ | 0.129                          | 0.730 |
| Z-axis VR$_{10}$ | Z-axis VR$_{30}$ | 0.104                          | 0.730 |
| Z-axis VR$_{10}$ | Z-axis VR$_{30}$ | 0.037                          | 0.365 |
| X-axis VR$_{30}$ | Y-axis VR$_{30}$ | 0.522                          | 1.000 |
| X-axis VR$_{30}$ | Z-axis VR$_{30}$ | 0.337                          | 1.000 |
| Y-axis VR$_{30}$ | Z-axis VR$_{30}$ | 0.749                          | 1.000 |
| Z-axis VR$_{30}$ | X-axis VR$_{30}$ | 0.914                          | 1.000 |
| Z-axis VR$_{10}$ | Y-axis VR$_{30}$ | 0.009                          | 0.135 |
| Z-axis VR$_{20}$ | X-axis VR$_{30}$ | 0.150                          | 0.730 |
| Z-axis VR$_{20}$ | Y-axis VR$_{30}$ | 0.007                          | 0.135 |
calculating the average of these VRD values, the overall VRD is 1.229, which means that the hollow effect causes the Z-axis PPV of excavated zone 22.9% higher than the unexcavated zone, regardless of the horizontal distance. When the absolute horizontal distance is greater than 30 m, the hollow effect influences the PPV of X-, Y-, Z-axis with an augmented factor of 1.229.

4. Conclusions

For the purpose of studying the influence of hollow effects on PPV and dominant frequency induced by electronic detonator, field experiments were conducted at a tunnel construction site which is close to a residential area by using electronic detonators. Within the framework of this study, the following conclusions can be drawn.

(1) The proposed method of selecting the optimal number of intrinsic mode function k for VMD successfully eliminates the zero-drift phenomenon in the original waveforms. The reconstructed waveforms are less volatile.

(2) By applying the Wilcoxon rank-sum test, the Z-axis PPV of excavated and unexcavated zones are statistically different regardless of the absolute horizontal distance. Triaxial hollow effect on PPV also exists when the absolute horizontal distance is greater than 30 m. Hollow effect on the dominant frequency could not be identified for all the absolute horizontal distances and directions.

(3) The PPV ratios of excavated to unexcavated zones are calculated, and the significance tests show no remarkable difference among PPV ratios. An augmented factor of 1.229 is determined as the hollow effect factor on PPV, and this factor is suitable for applying to Z-axis PPV and triaxial PPV when the absolute horizontal distance is larger than 30 m. The PPV augmented factor calculated in this study is in accord with Wang et al. [21] and Cai et al. [23], which illustrates that the hollow effect on PPV induced by short delay hole-by-hole blasting with electronic detonator is the same as nonel detonator with greater delay time.

(4) During tunnel construction, the excavated zone should be monitored carefully. Hollow effect should be considered in blasting design since the PPV of excavated zone might exceed the dangerous threshold and cause damage to the surrounding structures and nuisance to inhabitants.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

References

[1] R. Trivedi, T. N. Singh, and A. K. Raina, “Prediction of blast-induced flyrock in Indian limestone mines using neural networks,” Journal of the Institute of Rock and Soil Mechanics, vol. 6, no. 5, pp. 447–454, 2014.

[2] G. G. U. Aldas, “Explosive charge mass and peak particle velocity (PPV)-frequency relation in mining blast,” Journal of Geophysics and Geotechnical Engineering, vol. 7, no. 3, pp. 223–231, 2010.

[3] M. Monjezi, M. Ahmadi, M. Sheikhan, A. Bahrami, and A. R. Salimi, “Predicting blast-induced ground vibration using various types of neural networks,” Soil Dynamics and Earthquake Engineering, vol. 30, no. 11, pp. 1233–1236, 2010.

[4] J. H. Yang, W. B. Lu, Z. G. Zhao, P. Yan, and M. Chen, “Safety distance for secondary shotcrete subjected to blasting vibration in Jinping-II deep-buried tunnels,” Tunnelling and Underground Space Technology, vol. 43, no. 7, pp. 123–132, 2014.

[5] M. Jun, L. Xianglong, W. Jianguo et al., “Experimental study on vibration reduction technology of hole-by-hole presplitting blasting,” Geofluids, vol. 2021, Article ID 5403969, 10 pages, 2021.

[6] A. I. Lawal, S. Kwon, O. S. Hammed, and M. Adebayoldris, “Blast-induced ground vibration prediction in granite quarries: an application of gene expression programming, ANFIS, and sine cosine algorithm optimized ANN,” International Journal of Mining Science and Technology, vol. 31, no. 2, pp. 265–277, 2021.

[7] Z. Leng, Y. Fan, Q. Gao, and Y. Hu, “Evaluation and optimization of blasting approaches to reducing oversize boulders and toes in open-pit mine,” International Journal of Mining Science and Technology, vol. 30, no. 3, 2020.

[8] L. Sambuelli, “Theoretical derivation of a peak particle velocity–distance law for the prediction of vibrations from blasting,” Rock Mechanics and Rock Engineering, vol. 42, no. 3, pp. 547–556, 2009.

[9] I. Vennes, H. Mitri, D. R. Chinnasane, and M. Yao, “Large-scale destress blasting for seismicity control in hard rock mines: a case study,” International Journal of Mining Science and Technology, vol. 30, no. 2, pp. 141–149, 2020.

[10] Z. Zhang, C. Zhou, A. Remennikov, T. Wua, S. Lud, and Y. Xia, “Dynamic response and safety control of civil air defense tunnel under excavation blasting of subway tunnel,” Tunnelling and Underground Space Technology, vol. 112, no. 6, Article ID 103879, 2021.

[11] Y. Zhao, R. L. Shan, H. L. Wang, X. Tong, and Y.-he Li, “Regression analysis of the blasting vibration effect in cross tunnels,” Arabian Journal of Geosciences, vol. 14, no. 18, 2021.

[12] W. Jianguo, Z. Ting, L. Xianglong, T. Zihao, and Ma Jun, “Study on the fractal characteristics of the pomegranate biotite schist under impact loading,” Geofluids, vol. 2021, Article ID 1570160, 8 pages, 2021.

[13] X. Liu, S. Song, Y. Tan et al., “Similar simulation study on the deformation and failure of surrounding rock of a large section chamber group under dynamic loading,” International Journal of Mining Science and Technology, vol. 31, no. 3, pp. 495–505, 2021.

[14] Y. Zhou, D. Zhao, B. Li, H. Wang, Q. Tang, and Z. Zhang, “Fatigue damage mechanism and deformation behaviour of granite under ultrahigh-frequency cyclic loading conditions,” Rock Mechanics and Rock Engineering, vol. 54, pp. 4723–4739, 2021. (prepublish).

[15] J. Yang, H. Lian, and L. Li, “Investigating the effect of confining pressure on fracture toughness of CO2-saturated
[16] Z. Yu, Z. Yongfa, Y. Haiqing, L. Qiang, and T. Guodong, “Experimental study on relationship between fracture propagation and pumping parameters under constant pressure injection conditions,” *Fuel*, vol. 307, 2022.

[17] R. Kumar, P. K. Mandal, A. Narayan, and D. Arka Jyoti, “Evaluation of load transfer mechanism under axial loads in a novel coupler of dual height rock bolts,” *International Journal of Mining Science and Technology*, vol. 31, no. 2, pp. 225–232, 2021.

[18] Y. Zhao, J. Bi, C. Wang, and L. Pengfei, “Effect of unloading rate on the mechanical behavior and fracture characteristics of sandstones under complex triaxial stress conditions,” *Rock Mechanics and Rock Engineering*, 2021, (prepublish).

[19] Y. Wu, X.-Z. Li, Z. Huang, and X. Sen, “Effect of temperature on physical, mechanical and acoustic emission properties of Beishan granite, Gansu Province, China,” *Natural Hazards*, vol. 107, 2021 (prepublish).

[20] M. He, Z. Zhang, J. Zhu, and L. Ning, “Correlation between the constant mi of hock-Brown criterion and porosity of intact rock,” *Rock Mechanics and Rock Engineering*, 2021.

[21] H. L. Wang, Z. S. Wang, R. C. Bao, and S. X. Li, “Hollow effect induced by vibration in cross-harbor tunnel,” in *Proceedings of the 2nd International Conference on Manufacturing Science and Engineering*, Guilin, China, April 2011.

[22] M. S. Zhao, E. A. Chi, Q. Kang, and T. J. Tao, “Analysis about effect of hollow on time-frequency characteristic of surface vibration signal,” in *Proceedings of the International Forum on Materials Processing Technology (IFMPT)/International Conference on Sensors, Instrument and Information Technology (ICSIIT)*, Guangzhou, China, January 2014.

[23] C. Jun, Q. Xiuli, and S. Ying, “Influence of hollow effect on PPV of wall rock under blasting load,” *IOP Conference Series: Earth and Environmental Science*, vol. 719, no. 3, 2021.

[24] K. Dragomiretskiy and D. Zosso, “Variational mode decomposition,” *IEEE Transactions on Signal Processing*, vol. 62, no. 3, pp. 531–544, 2014.

[25] D. Bertsekas, *Constrained Optimization and Lagrange Multiplier Methods*, Elsevier Science, New York, NY, USA, 1982.

[26] R. Hogg, *Probability and Statistical Inference*, Pearson Education, London, UK, 1988.

[27] N. E. Afnor, *Mechanical Vibration and Shock: Evaluation of Human Exposure to Whole Body Vibration - I. General Requirements; II. Risks for Health*, International Organization for Standardization, Geneva, Switzerland, 1990.

[28] Y. Benjamini and D. Yekutieli, “The control of the false discovery rate in multiple testing under dependency,” *Annals of Statistics*, vol. 29, no. 4, 2001.