Study on Drilling and Blasting Construction of a Small-Spacing Tunnel and Vibration Characteristics of Intermediate Rock Strata

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Abstract. The dynamic response of rock stratum in a small-spacing tunnel under a blasting load is studied based on field vibration monitoring of the drilling and blasting excavation of a small-spacing tunnel in the WenLing city railway S1 section. The vibration velocity spectrum, amplitude distribution of surrounding rock particles, and vibration blasting of the left and right face under a blasting seismic wave are analyzed. This paper focuses on the vibration characteristics and propagation law of rock stratum and the blasting face in a small-spacing tunnel. The results show that, in the same cross section, the blasting side of the middle-intercalated strata is the area with the maximum particle vibration velocity and its horizontal radial vibration velocity is largest. Additionally, the vibration velocity of cut-hole blasting is dominant and is about 1.5–2 times that of the auxiliary hole. The influence of the blast center distance on the blasting action can be reduced by reducing the charge amount of the cut hole and increasing the number of free surfaces. The main frequency of the vibration velocity is distributed at ~15–110 Hz and the attenuation of a high frequency seismic wave is fast. The tunnel cyclic blasting damages the surrounding rock in the middle rock layer such that the peak velocity of particles in front of the tunnel are generally larger than those in the rear. With a reasonable arrangement of the amount of dosage, the blasting vibration in the far rock of the tunnel face is greater than that in the near rock, which weakens the influence of the blasting center distance on blasting vibration.
1. Introduction
With the rapid development of China's transportation industry, shallow and buried small-spacing tunnels have become an important part of mountain tunnels. A small-spacing tunnel is a new type of tunnel structure, different from ordinary separated and multi-arch tunnels, that plays an important role in tunnel construction.

The drilling and blasting method has advantages, such as wide application range, high excavation efficiency, mature technology, and low economic cost, that make it the main construction method of small-spacing tunnels\(^{[1-2]}\). The blasting vibration generated by the drilling and blasting method will cause damage to surrounding rock, especially the middle rock wall of a small-spacing tunnel, which is frequently disturbed by vibration during blasting construction, affecting its stability. During tunnel construction, the middle rock layer plays an important role in controlling the stability of the surrounding rock\(^{[3]}\) as well as in the safety of the tunnel structure and surface buildings.

At present, tunnel drilling and blasting construction technology primarily reduces blasting vibration by controlling the surrounding hole spacing\(^{[4]}\), the thickness of the smooth blasting layer\(^{[5-6]}\), the surrounding hole density coefficient, charging concentration, by reducing the blasting layer thickness\(^{[7-9]}\), etc. In numerical simulation studies of the drilling and blasting method for small-spacing tunnel construction, it has been concluded that the maximum tensile stress of the later part of the tunnel appears after blasting in the blast wall, arch foot, vault, bottom plate\(^{[10-12]}\), etc. The reflected tensile damage of the surrounding rock-free surface is caused by an explosion stress wave and damage of the blast wall, arch foot, and vault of the first tunnel is obvious\(^{[13-14]}\). At present, there are few studies on the internal vibration velocity law and the surrounding rock stability of the middle rock layer in a small-spacing tunnel. Therefore, it is of great practical significance to research the blasting construction method of a small-spacing tunnel and the vibration response characteristics of the middle rock wall for the protection of the structural stability of the tunnel.

Based on the TengLing tunnel project in WenLing city, this study develops a construction method of left and right-part blasting, tests the internal vibration velocity of the middle-intercalated strata, and reveals the influence of drilling and blasting construction on the vibration characteristics of the middle-intercalated strata by analyzing the amplitude distribution and variation law of the vibration velocity curve.

2. Monitoring and analysis of blasting vibration signal

2.1. Project overview
The studied tunnel is located in Taizhou City, Zhejiang Province, and belongs to the double-tunnel single section of TengLing City railway line S1. The tunnel is located in grade II and III surrounding rock, which is relatively hard. The design excavation area is 56.06 m\(^2\) and the excavation deformation is 3 cm. The total lengths of the first and second tunnels are 878 and 872 m, respectively. The width, height, and flattening ratio of the single tunnel excavation is 7.24 m, 9.20 m, and 0.79, respectively, and the thickness of the middle rock layer is \(\sim 2.7\text{--}4.9\) m, which increases gradually along the tunnel excavation direction. The maximum buried depth is \(\sim 22\text{--}30\) m and belongs to a shallow tunnel with small spacing.

As shown in Fig. 1, a smooth blasting excavation method of the left and right parts of the whole section was adopted and the cut hole was arranged in the lower part of the center of the palm face. The right half begins the blasting, the arch bottom is checked and the gravel is removed to create a good
free face, then the left half is excavated by blasting. The support, invert filling, concrete laying, and other procedures are carried out successively to form a closed section. The next section of blasting construction and excavation are then carried out.

![Figure 1. Blast hole layout.](image)

A design borehole diameter $\varphi = 40$ mm, resistance line $w = 65$ cm, cutting-hole spacing $a = 100$ cm, auxiliary hole spacing $a = 75$ cm, peripheral hole spacing $a = 45$ cm, auxiliary hole row spacing $B = 65$ cm, blast hole depth of $\sim 2.5$–3 m, and explosive consumption $Q \approx 0.3$–0.45 kg/m$^3$ are selected according to the requirements of smooth blasting layout. Rock emulsion explosive is also selected, along with vertical wedge cutting wherein the bottom of the peripheral hole is located on the design contour line, the bottom of the bottom hole is located 10-cm beyond the design contour line, the excavation cycle depth is 2–2.5 m, and the explosive loading mode is continuous forward.

2.2. Blasting vibration monitoring
A TC-4850N vibrometer and large range triaxial vibration velocity sensor are used in the blasting vibration tests. The sensor can measure the vibration velocity of three mutually perpendicular components at the measuring point. That is, the vibration velocity in the $X$-direction perpendicular to the tunneling direction, the vibration velocity in the $Y$ direction along the tunneling direction, and the vibration velocity in the $Z$-direction perpendicular to the measuring point. The measurement range included a vibration speed range of 391 mm/s; a sampling frequency of 5 K/s for the No. 1 and No. 2 instruments and a sampling frequency of 8 K/s for the No. 3, 4, and 5 instruments; a negative delay of $-100$ ms; a sensitivity of 26.19–30.00 V/cm·s$^{-1}$; and a range of 10 V. The system can continuously monitor and store 1000 vibration wave patterns.
As shown in Fig. 2, the measuring points are arranged at the arch waist of the blasting side of the first tunnel. The distance between measuring point (1) and the starting position of the intermediate rock layer is 5 m. The distances between measuring points (1) and (2), (2) and (3), (3) and (4), and (4) and (5) are 5, 10, 15, and 25 m, respectively. The elevation of the five measuring points is the same. In order to ensure the accuracy of the test data, when installing the TC-4850N vibrometer, an anchoring agent is used to anchor the sensor at the arch waist position of the blasting side of the advance tunnel. Meanwhile, the vibrometer is fixed below the sensor and connected to it.

2.3. Blasting vibration signal analysis
According to the test condition and construction progress requirements, 40 blasting vibration tests were carried out for the blasting excavation of the small-spacing tunnel in the TengLing section of WenLing city. The vibration waveform diagram and blasting parameter table under part of the mileage of a typical measuring point, C, in a blasting vibration were selected, as shown in Figs. 3 to 5 and Table 1.

Table 1. Maximum vibration velocity in each direction of each construction cycle at measuring point C.

| Serial number | Position       | Distance between blasting centers | X Maximum vibration velocity/(cm/s) | Y Maximum vibration velocity/(cm/s) | Z Maximum vibration velocity/(cm/s) |
|--------------|----------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
|              |                | left right                        | left right                        | left right                        | left right                        |
| 1            | DK48+328.7     | 8.0709 10.397                     | 4.68 7.26                        | 6.03 9.02                        | 5.50 7.02                        |
| 2            | DK48+326.1     | 6.0877 8.945                     | 20.93 23.66                     | 16.83 17.07                     | 14.14 10.50                     |
| 3            | DK48+324       | 4.9244 8.1977                    | 21.46 10.19                     | 11.91 6.73                      | 14.74 11.10                     |
| 4            | DK48+321.3     | 4.5541 7.9808                    | 33.39 34.23                     | 13.19 10.03                     | 14.14 18.93                     |
| 5            | DK48+318.6     | 5.64 8.6465                     | 15.99 28.89                     | 16.38 12.01                     | 13.18 22.72                     |
| 6            | DK48+316.5     | 7.1063 9.6671                    | 8.38 6.08                       | 10.76 7.44                      | 5.94 5.05                       |
| 7            | DK48+314.1     | 9.0918 11.208                    | 3.11 5.04                       | 6.10 7.61                       | 3.17 4.22                       |
| 8            | DK48+311.4     | 11.516 13.25                     | 3.35 3.18                       | 3.82 5.95                       | 2.54 3.71                       |
| 9            | DK48+309.4     | 13.379 14.898                    | 1.54 3.04                       | 2.49 7.02                       | 1.67 2.84                       |
By using a non-electric millisecond detonator to delay initiation, the vibration waveform generated by the blasting of different holes in each section can be obtained. The velocity wave property of the cut hole is 0–50 ± 10 ms and that of the auxiliary hole and the surrounding hole are −460 ± 40 and 460–880 ± 60 ms, respectively. In the vibration wave diagram, the blasting vibration velocity produced by the cutting hole is the largest because the single-section charge of the cutting hole is the largest; it can produce greater blasting vibration when the distance between the blasting centers is the same. The vibration velocity is decomposed into three mutually perpendicular component vibration velocities: the vibration velocity in the X direction of vertical tunneling, the vibration velocity in the Y direction of tunneling, and the vibration velocity in the Z direction of the measuring point. The longitudinal wave generated by blasting is parallel to or intersects with the X direction in the propagation process\cite{15}. This makes the vibration velocity in the X direction the maximum.

3. Study on the vibration characteristics of medium rock stratum

The back tunnel of the TengLing section tunnel project in WenLing city adopts the construction method of full-section left and right blasting excavation. In order to study the blasting vibration characteristics of the middle rock layer and verify the vibration reduction effect of left and right blasting construction, a vibration test of the middle rock layer in back-tunnel blasting construction is carried out. The test results are then analyzed and studied. According to the site construction conditions, the area within ~0–10 m from the front and rear of the tunnel is regarded as the near area of tunnel blasting. The area within ~10–50 m is regarded as the medium and far area of tunnel blasting. The working face of the construction site is shown in Fig. 6.

Figure 6. Site construction drawing.

3.1. Propagation law of blasting vibration velocity in different sections
In the process of blasting excavation, reducing the impact of blasting vibration on surrounding rock is the key to construction. Therefore, amplitude, vibration velocity, and frequency are the main research subjects of blasting excavation. Through data analysis and summary, it is found that the three important factors affecting the blasting vibration speed and frequency are terrain conditions (site coefficient, $K$, and attenuation coefficient, $a$), the single-section charge of the blast hole, and the blasting center distance. Through field monitoring of the blasting vibration, the peak velocity of a particle under different conditions is used as the reference variable. The calculation and analysis are carried out using the Sadowski formula:

$$V = K (\sqrt[3]{Q} / R)^a, \ (1)$$

where $V$ is the blasting vibration velocity of the measuring point, $K$ is the site coefficient, $Q$ is the charge corresponding to the blasting vibration velocity of the measuring point, $R$ is the distance between the blasting centers, and $a$ is the attenuation coefficient.

Taking the excavated part of the tunnel face as the front, the propagation law of blasting vibration velocity in the $X$, $Y$, and $Z$ directions of the surrounding rock in the medium rock stratum caused by cutting-hole blasting is obtained through regression analysis. The fitting curve is shown in Fig.7-12. The propagation law of blasting vibration velocity in the $X$-direction, $V_x$, for cutting-hole blasting is given by:

$$V_{chx} = 113.43 \times (\sqrt[3]{Q} / R)^{1.56} \ (R^2 = 0.856) \text{ for the front}$$

and

$$V_{chx} = 330.12 \times (\sqrt[3]{Q} / R)^{1.69} \ (R^2 = 0.907) \text{ for the rear.}$$

The propagation law of blasting vibration velocity in the $Y$-direction, $V_y$, for cutting-hole blasting is given by:

$$V_{chy} = 132.38 \times (\sqrt[3]{Q} / R)^{1.45} \ (R^2 = 0.926) \text{ for the front}$$

and

$$V_{chy} = 138.75 \times (\sqrt[3]{Q} / R)^{1.59} \ (R^2 = 0.896) \text{ for the rear.}$$

The propagation law of blasting vibration velocity in the $Z$-direction, $V_z$, for cutting-hole blasting is given by:

$$V_{chz} = 123.34 \times (\sqrt[3]{Q} / R)^{1.49} \ (R^2 = 0.857) \text{ for the front}$$

and

$$V_{chz} = 163.26 \times (\sqrt[3]{Q} / R)^{1.55} \ (R^2 = 0.856) \text{ for the rear.}$$
As shown in Figure 7-12, it can be seen that the site coefficient, $K$, and attenuation coefficient, $\alpha$, caused by cutting-hole blasting are greater behind the tunnel face than in front of the tunnel face, which also makes the vibration velocity of the front in the $X$, $Y$, and $Z$ directions smaller than that of the rear. In the near area of tunnel blasting, the ratio of the maximum single charge quantity, $Q_{\text{max}}$, to the distance between blasting centers, $R$, is greater than one and the vibration velocity of particles in front and behind the tunnel face is quite different. In the $X$ direction, the vibration velocity of particles in the rear is 1.91, 1.26, and 1.41 times that in the front, the $Y$ direction, and the $Z$ direction, respectively. In the middle and far region of tunnel blasting, the ratio of $Q_{\text{max}}$ to $R$ is less than one, which means the vibration velocity caused by the cutting-hole blasting exhibits little difference between the front and back of the tunnel.

| Law parameters | Cut hole (in front of tunnel face) | Cut hole (behind tunnel face) |
|----------------|-----------------------------------|-------------------------------|
| $K$            | 113.43                            | 330.12                        |
| $\alpha$       | 1.56                              | 1.69                          |

Through regression analysis, the propagation law of blasting vibration velocity in the $X$, $Y$, and $Z$ directions
of the surrounding rock caused by auxiliary and peripheral hole blasting is obtained as follows.

The propagation law of blasting vibration velocity in the $X$-direct, $V_x$, for auxiliary and peripheral hole blasting is given by:

$$V_{apx} = 96.43 \times (\sqrt[3]{Q} / R)^{1.32} \ (R^2 = 0.856) \ \text{for the right}$$

and

$$V_{apx} = 101.74 \times (\sqrt[3]{Q} / R)^{1.52} \ (R^2 = 0.963) \ \text{for the left.}$$

The propagation law of blasting vibration velocity in the $Y$-direction, $V_y$, for auxiliary and peripheral hole blasting is given by:

$$V_{apy} = 83.38 \times (\sqrt[3]{Q} / R)^{1.39} \ (R^2 = 0.926) \ \text{for the right}$$

and

$$V_{apy} = 134.38 \times (\sqrt[3]{Q} / R)^{1.21} \ (R^2 = 0.936) \ \text{for the left.}$$

The propagation law of blasting vibration velocity in the $Z$-direction, $V_z$, for auxiliary and peripheral hole blasting is given by:

$$V_{apz} = 113.34 \times (\sqrt[3]{Q} / R)^{1.45} \ (R^2 = 0.857) \ \text{for the right}$$

and

$$V_{apz} = 95.24 \times (\sqrt[3]{Q} / R)^{1.44} \ (R^2 = 0.964) \ \text{for the left.}$$
According to Table 3, no matter if in front or behind the tunnel face, $K$ and $\alpha$ produced by blasting for the auxiliary and surrounding holes are smaller than the cut hole. The peak vibration velocity of the rock mass in the middle rock layer caused by the cut-hole blasting is $\sim 1.5$–2 times that of the auxiliary and surrounding holes. This is because the single-section charge of the cut hole is the largest and the proportional distance in the tunnel blasting near this area is largest; the blasting vibration effect is the most obvious. $K$ and $\alpha$ of the left and right auxiliary holes and the surrounding holes indicate little difference. When the charge amount is the same, the blasting vibration is almost the same and is far less than that of the cut hole, which verifies the rationality of left- and right-part blasting of the tunnel face. This method effectively protects the intermediate rock stratum.

### 3.2. Analysis of vibration velocity in front of and behind the tunnel face
As shown in Figs. 19 and 20, the vibration velocity is quite different in front of and behind the tunnel face, and left and right blasting presents different variation rules. According to the derived rules, under the condition of the same charge, the smaller the distance between blasting centers, the greater the vibration velocity. For the right half of tunnel-face blasting, because the right half of the tunnel face is the first to detonate, the single-section charge of the cut hole is the largest so that the vibration velocity of the blast can reach 38.3 cm/s when the measuring point and the tunnel face are in the same section. In the area near the tunnel blasting, when the proportional distance is greater than one, $Q_{\text{max}}$ of a single section occupies the dominant position affecting the blasting vibration velocity. Therefore, the vibration velocity of the right half of the tunnel blasting is greater than that of the left half. In the middle and far area of tunnel blasting, the proportional distance decreases gradually and the left-half $K$ and $a$ are greater than those of the right half. Therefore, the vibration velocity of the left half of the tunnel blasting is significantly greater than that of the right half and the vibration velocity behind the tunnel blasting face is significantly greater than that of the front, with a peak value of the rear vibration velocity of 33.9 cm/s. The peak value of the front vibration velocity is 21.5 cm/s, 12.4 cm/s less than that of the rear.

As shown in Figs. 21 and 22, within a range of 5 m from the horizontal face of tunnel blasting near the
tunnel affected by the charge amount of the cut hole, the vibration speed generated by the right half of the blasting is much higher than that of the left half, with a difference of 21.5 cm/s. The right half is nearly four times the vibration speed of the left half. In the middle and far region of tunnel blasting, the vibration velocity produced by left-half blasting is generally greater than that of the right half, which is different from the vibration velocity law in the $X$ direction. The vibration velocity produced by right-half blasting in the $Y$ direction presents a symmetrical distribution and gradually decreases with the increase of distance, while the vibration velocity produced by left-half blasting in front of the tunnel is much greater than that in the rear, with a difference of 6.5 cm/s.

![Figure 23. Analysis of vibration velocity in front of and behind the Z-direction tunnel](image1)

![Figure 24. Comparison of vibration velocity of left and right half in the Z direction](image2)

As shown in Figs. 23 and 24, within the range of 5 m from the horizontal face to the tunnel blasting near the tunnel due to the largest single-section charge of the cut hole, the vibration speed of the right half of the tunnel blasting is much higher than that of the left half, with a difference of 26.5 cm/s. The vibration speed of the right half is nearly four times that of the left half. In the middle and far area of tunnel blasting, different from the $X$ and $Y$ directions, the $Z$ direction is in front of the tunnel face and the vibration velocity curves of its left and right parts are approximately equal. However, behind the tunnel face, the vibration velocity of the left part is larger than that of the right part and the maximum difference is 11.5 cm/s. The vibration velocity curves of the right-part are generally symmetrical and the vibration velocity gradually decreases with the increase of distance. The vibration velocity of the left part is larger than that of the front part and the difference reaches 7.6 cm/s.

The results show that the variation of the particle vibration velocity in the $X$, $Y$, and $Z$ directions caused by drilling and blasting are similar. In the near area of tunnel blasting, the peak vibration velocity of the particle in the right half of the tunnel blasting is much higher than that in the left half. In the middle and far area of tunnel blasting, the vibration produced by the left and right half of the tunnel blasting is similar and the peak vibration velocity of the particle on the left and right half of the tunnel face is slightly higher in the rear than in the front.

### 3.3. Main frequency analysis

In the blasting vibration process, the frequency corresponding to the peak velocity of particle vibration is the main vibration frequency of blasting vibration. When the main vibration frequency is equal to or close
to the natural frequency of the surrounding rock, it will cause resonance. This resonance will multiply the blasting vibration and easily lead to structural damage. Therefore, it is very important to study the main vibration frequency of the blasting earthquake in the process of studying the blasting seismic effect. The blasting seismic wave collected in the WenLing small-spacing tunnel is edited and filtered by the ZhongKe vibration measurement platform software. The filtering mode is high pass, with an upper limit frequency of 100 and lower limit frequency of 10. A typical spectrum analysis diagram of a vibration wave in the X-Y-Z direction is obtained. It can be seen from the figure that the frequency distribution of blasting seismic wave is relatively uniform, and the main vibration frequency is mainly concentrated between 60-120Hz. The distribution of the main vibration frequency in the X, Y, and Z directions caused by blasting construction of the small-spacing tunnel in the TengLing section of WenLing versus blasting center distance is shown in Figs. 25–27.

![Figure 25](image_url) **Figure 25.** Analysis chart of main frequency of X-direction vibration

The main vibration frequency in the X-direction perpendicular to the tunnel excavation is between 5.15 and 138.6 Hz and is mostly concentrated in the low frequency band below 100 Hz. The main vibration frequency caused by left-half blasting is evenly distributed and the main vibration frequency is concentrated near 100 Hz. The main vibration frequency caused by the blasting vibration in the right half increases with the increase of the distance between blasting centers. Generally speaking, the main vibration frequency of the blasting vibration in the left half is greater than that in the right half.

The main vibration frequency along the Y direction of tunnel excavation is between 23.5 and 119.5 Hz. There is no obvious change rule with the increase of blasting center distance. There are nine occurrences above 100 Hz and 25 below 100 Hz. The main vibration frequencies caused by the left and right half blastings are approximately equal and there is no obvious difference.

The frequency distribution of the main vibration in the Z-direction perpendicular to the measuring point is between 3.6 and 140 Hz. There is no obvious change rule with the increase of distance between blasting centers. The frequency of the main vibration higher than 100 Hz (occurring 14 times) is not different from that lower than 100 Hz (occurring 16 times). Near the blasting near, with ~0–25 m blasting center distance, the dominant frequency of the left half blasting vibration is greater than that of the right half. Far from the blasting area, with ~25–50 m blasting center distance, the dominant frequency of the left and right half blasting vibration have little difference and the overall distribution is uniform.

From the analysis of the main vibration frequency of the small-spacing tunnel in the TengLing section of WenLing, it can be concluded that the main vibration frequency of the left and right half caused by drilling
and blasting construction is around 100 Hz and that of each direction is between 3.6 and 140 Hz. The results show that the main vibration frequency of the left half is larger than that of the right half when the distance between the blasting centers is ~0–25 m. With the increase of blasting distance, the main vibration frequency of the left and right half tends to be equal when the distance between the blasting centers is ~25–55 m.

4. Conclusion

(1) According to the field test results, the blasting vibration produced in this paper by the full-tunnel-face cutting and left and right section blasting construction method is small. Under the condition of ensuring safety and construction progress, the influence of blasting center distance on the intermediate rock stratum is weakened, which can popularize this method for similar projects.

(2) Through the classification and regression analysis of the test data, the propagation law of the vibration velocity in different areas of the middle sandwich strata caused by different sections of blasting is obtained. The increase of free surface makes the site coefficient, $K$, and attenuation coefficient, $a$, decrease. The peak value of the particle vibration velocity caused by cutting blasting is ~1.5–2 times that of the auxiliary and surrounding holes. The correlation coefficient is ~0.8–1.0, which is a high degree of fitting. These results provide an important reference to the prediction of vibration velocity of rock stratum in a tunnel.

(3) Through the analysis of the vibration velocity of different blasting areas, it is concluded that the maximum vibration velocity of a particle in tunnel blasting is affected by many factors. In the area near the tunnel blasting, the peak vibration velocity of the right half is ~3–4 times that of the left half and the difference of vibration velocity between the front and rear of the tunnel face can reach 12.4 cm/s; on the whole, the rear is larger than the front. In the middle and far zone of tunnel blasting, the difference of vibration velocity is small.

(4) Through the analysis of the main vibration frequency in the process of a blasting earthquake, it is concluded that the main vibration frequency of the left and right parts is around 100 Hz and the main vibration frequency of each direction is between 3.6 and 140 Hz. In the vicinity of tunnel blasting, the main vibration frequency caused by blasting in the left half of each direction is generally greater than that in the right half. In the far zone of tunnel blasting, the dominant frequencies of the left and right parts of the tunnel tend to be equal.

5. References

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