Study on Surface Vibration Characteristics of Composite Shallow-buried Tunnel Blasting Construction

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Abstract: Based on the background of the construction of the mining section at the southern end of Yangli Station of Fuzhou Metro Line 2 project, in order to study the ground surface vibration law during the blasting construction of tunnels in the upper soft and lower hard composite strata, the vibration velocity data were obtained through field tests, and the traditional and modified Sadowski formulas were used to fit and analyze the vibration velocity respectively, which were verified by numerical simulation. The results show that under the condition of composite stratum, the peak value of radial vibration velocity of blasting construction on the surface of cave-forming area is the largest, and the peak value of vertical vibration velocity on the surface of non-cave-forming area is the largest; the ground vibration of shallow-buried tunnel excavation area in composite stratum has void effect, and the larger the distance between the blasting centers, the more obvious the void effect; the fitting degree of traditional Sadowski formula \( V = KQ^aR^b \) is lower than that of modified Sadowski formula because of the existence of soft-hard interface, the attenuation rate of vertical vibration velocity is the sharpest relative to the radial and tangential vibration velocities on the surface of composite shallow-buried tunnels. At the same time, the feasibility of numerical software to simulate such engineering blasting construction is verified.

1. Introduction

In recent years, with the rapid development of China's national economy, in the tunnel construction of high-speed railway, urban rail transit, intercity railway and other projects, it is often encountered that the tunnel underpasses strata with two or more different physical and mechanical properties, the most typical of which is the upper soft stratum and the lower hard stratum. With the continuous expansion and extension of high-speed railway, it will be more and more common to tunnel under soft and hard strata.

Based on the project of No. 7 underground crossing Beihuan avenue of Shenzhen metro, Wu Ke et al. [1] analyzed the settlement characteristics of the existing road surface under the tunnel and the settlement rules of the upper soft and lower hard strata by combining numerical simulation and field monitoring. Zheng Baocai [2] studied the control deformation of upper soft and lower hard strata with Nanjing Ninghe intercity railway tunnel as the background. Wu Bo et al. [3] used numerical simulation and strength reduction method to discuss the quantitative standard of surrounding rock stability of tunnel...
in upper soft and lower hard stratum. It can be seen that the current research on the influence of the upper soft and lower hard tunnel construction mainly focuses on the analysis stage of the subsidence deformation and surrounding rock stability.

The main means of studying the propagation law of blasting velocity in tunnel are field monitoring and numerical simulation. Zhang Yan et al. [4] analyzed the vibration attenuation rules of blasting seismic waves under different rock mass conditions by using statistical and regression methods through on-site blasting vibration tests in mines. Zhai Caiya et al. [5] took the construction project of Qingdao metro line 3 as the background, and used numerical simulation to analyze the propagation rules of blasting vibration of subway tunnels in granite area. Xu Jiangbo et al. [6], relying on the deep buried soft rock tunnel project of Majiashan on the Lanyu line and through on-site vibration monitoring, obtained the Sadowski empirical formula for the deep buried soft rock tunnel.

The study of single layer tunnel blasting vibration propagation law is more, for the formation of soft and hard on existing lines tunnel blasting ground vibration characteristics and the study of cavity effect is relatively limited, therefore to the formation of soft and hard on the tunnel blasting construction of the law of vibration transmission research has important engineering significance. Based on the construction of the mining section at the south end of Yangli station of Fuzhou metro line 2 project, this paper studies the propagation law of the blasting surface vibration wave of this special stratum tunnel by means of field monitoring, numerical simulation and fitting analysis.

2. Project Overview
South mining section of Yangli station, Fuzhou rail transit line 2 project, left line ZDK38+098.444 ~ZDK38+170.378, the total length is 71.934m. The right line YDK38+100.176 ~ YDK38+173.427, with a total length of 73.251m. Pump house and air duct are set in the mine method interval at ZDK38 +160.741 (YDK38 +163.849). The clear distance between the two tunnels is only 1.6 ~3.5m, which is a small clear distance tunnel, and the mutual influence degree of the double-hole blasting construction is relatively high. Tunnel overburden soil thickness is about 9.0 m to 11.2 m, a relatively shallow, level of surrounding rock is VI ~ V, again there is a soft soil rock interface, the mining method in the period of formation are mainly from the top to the bottom of weathered rock and the breeze, construction difficulty is great.

Fig. 1 Tunnel section

3. Field Test Analysis
3.1. Monitoring Scheme
The mileage monitored on site is ZDK38+098.444 ~ZDK38+170.378. Level due to the double line
tunnel surrounding rock is VI ~ V, and interval is small, vibration speed control is very strict, so the up and down the steps excavation blasting. The on-site measuring points were arranged on the ground directly above the arch of the left line tunnel. The blasting palm surface of the left line tunnel was taken as the symmetrical surface, and 9 measuring points were arranged in sequence along the axis direction of the left line tunnel, with the spacing of measuring points being 6m. The specific arrangement of measuring points is shown in Fig 2.

![Fig. 2 Layout of survey points](image)

The monitoring equipment adopts the new type vibrometer TC-4850 from Chengdu Zhongke measurement and control co., LTD., which can trigger the instrument with weak vibration. The instrument is portable and easy to operate, and can accurately record the vibration time, vibration value and other related parameters. Fig 3 shows the entrance of the tunnel at the southern end of Yangli station. Fig 4 shows the field instrument layout.

![Fig. 3 Tunnel entrance](image)  ![Fig. 4 Instrument layout](image)

### 3.2. Analysis of Monitoring Results

In this field test, the upper step blasting of the left line tunnel was performed. The length of the palm surface of the upper step reached ZDK38+124.444, the distance from the left line hole was 26m, and the excavation footage of the upper step was 1.4m. The blasting scheme adopted in the field is arranged with step holes as shown in Fig. 5. The maximum loading capacity is 3 stages, and the loading capacity is 4.8kg. Table 1 shows the monitoring data of blasting vibration. Some measured blasting vibration
waveforms are shown in Fig. 5.

### Table 1 Partial monitoring data of blasting vibration

| Maximum dose/kg | The constraints of the left line and the hole distance/m | Detonation distance /m | Peak velocity (cm·s⁻¹) |
|-----------------|--------------------------------------------------------|------------------------|------------------------|
|                 |                                                        | radial                 | tangential             | vertical               |
| 4.8             | 26                                                     | 1.99                   | 1.59                   | 2.89                   |
| 2               | 21.4                                                   | 2.21                   | 1.62                   | 3.54                   |
| 3               | 16.6                                                   | 2.98                   | 1.80                   | 3.89                   |
| 4               | 13.0                                                   | 3.81                   | 2.04                   | 3.94                   |
| 5               | 11.5                                                   | 4.05                   | 2.31                   | 5.20                   |
| 6               | 13.0                                                   | 2.56                   | 1.56                   | 2.68                   |
| 7               | 16.6                                                   | 1.80                   | 0.99                   | 1.46                   |
| 8               | 21.4                                                   | 1.28                   | 0.61                   | 0.97                   |
| 9               | 26.6                                                   | 1.05                   | 0.25                   | 0.69                   |

![Figure 6: Partial measured vibration velocity waveform](image)

According to Table 1, it can be found that in the upper soft and lower hard composite strata, the peak value of radial vibration velocity produced by surface blasting in the area formed by the hole behind the tunnel palm surface is the largest, while the peak value of tangential vibration velocity is the smallest. The peak value of vertical vibration velocity is the largest in the uncaved area.

### Table 2 Cavity amplification factor

| Detonation distance /m | Radial velocity amplification factor $\varphi_x$ | Tangential velocity amplification factor $\varphi_y$ | Vertical velocity amplification factor $\varphi_z$ |
|------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 11.5                   | 1.000                                         | 1.000                                         | 1.000                                         |
| 13.0                   | 1.488                                         | 1.308                                         | 1.470                                         |
| 16.6                   | 1.656                                         | 1.818                                         | 2.664                                         |
| 21.4                   | 1.727                                         | 2.656                                         | 3.649                                         |
| 26.6                   | 1.895                                         | 6.360                                         | 4.188                                         |

The cavity amplification factor $\psi$ is introduced to obtain the ground vibration law of cave-forming area. $\psi$ is expressed as the ratio of the peak value of the vibration of the ground building above the tunnel to the peak value of the point whose distance is equal to the face of the tunnel and the face of the tunnel is symmetrical. The expression of $\psi$ is:

$$\psi = \frac{v_c}{v_{uc}}$$  \hspace{1cm} (1)

In the formula, $v_c$ denotes the peak vibration velocity of the surface building above the tunnel excavation area; $v_{uc}$ denotes the peak vibration velocity of the surface building above the tunnel excavation area. The cavity magnification coefficients of No. 1 and No. 5 measuring points on the surface of hollow area corresponding to the corresponding measuring points on the surface of unhollow area.
area are shown in Table 2. Fig. 7 and 8 are the fitting curves of magnification coefficient \( y \) and \( z \), respectively.

From Tables 2 and 7 and 8, it can be found that the cavity amplification coefficient of each direction increases with the increase of the detonation center distance, and the tangential and vertical velocity amplification coefficient increases with the increase of the detonation center distance as a power function.

### 3.3. Traditional Sadowski Regression Analysis

According to the Sadowski empirical formula [7] in China's Blasting Safety Regulations, the monitoring data of blasting vibration can be regressed and analyzed. According to the literature [8], the ground vibration law behind the tunnel blasting face can not be fitted by the traditional Sadowski formula. Therefore, only the ground vibration law in front of the blasting face is fitted and analyzed, and its expression is as follows:

\[
V = K \left( \frac{\sqrt[3]{Q}}{R} \right)^\alpha
\]

(2)

Let \( y = V, x = Q^{1/3}/R, a = K, b = \alpha \), then the equation (2) becomes:

\[
y = ax^b
\]

(3)

In formula (2): \( V \) means particle velocity (cm/s); \( R \) means distance between measuring point and explosion source (m); \( K \) and \( \alpha \) mean site coefficient and attenuation coefficient respectively; \( Q \) means maximum charge (kg). As can be seen from Fig. 3, the measuring point No. 5 is located behind the tunnel face. Fitting analysis is made on the vibration velocities of 5-9 measuring points in each direction, and the fitting results are shown in Fig. 9.

| Direction   | \( K \)  | \( \alpha \) | Modified \( R^2 \) |
|-------------|---------|-------------|------------------|
| Radial      | 118.4   | 1.802       | 0.840            |
| Tangential  | 150.1   | 2.137       | 0.873            |
| Vertical    | 314.9   | 2.231       | 0.825            |

Table 3 Regression results of attenuation law

![Fig. 9 Fitting results of velocity in each direction](image-url)
The original data processing software is used to fit the data obtained from field monitoring, and the corresponding attenuation law of vibration velocity in different directions under different layout schemes of measuring points is obtained. After fitting, the values of \( K \), and revised \( R^2 \) are shown in Table 3.

From Table 3, it can be found that the fitting effect of traditional Sadowski formula is general, and the correlation coefficients are below 0.90. The vertical velocity attenuation coefficients perpendicular to the soft-hard interface of composite strata are larger than the radial and tangential velocity attenuation coefficients parallel to the soft-hard interface of composite strata. When the stress wave passes through the interface, the existence of two different interfaces increases the friction between rock particles, intensifies the energy dissipation of stress wave, and consequently increases the attenuation of vibration velocity. This indicates that the existence of soft-hard interface intensifies the attenuation of blasting vibration wave.

### 3.4. Modified Sadowski Regression Analysis

Considering the complexity of the stratum condition of the tunnel, the modified Sadowski formula \( V = K Q^a R^b \) is used to fit and analyze the vibration velocity of the 5-9 measuring point [9,10]. The logarithm of the two sides of the modified formula is obtained:

\[
\ln V = \ln K + a \ln Q + b \ln R
\]  

Let \( y = \ln V \), \( x_1 = \ln Q \), \( x_2 = \ln R \), \( c = \ln K \), then (4) is transformed into:

\[
y = a x_1 + b x_2 + c
\]  

In the formula, \( V \) is the peak particle velocity (cm/s); \( R \) is the distance between the measuring point and the explosion source (m); \( K \), \( A \) and \( B \) are the coefficients and attenuation indices related to the geological conditions, stratigraphic lithology and topography of the explosion point; \( Q \) is the maximum section charge (kg). Table 4 shows the measured velocity and the converted data.

| \( Q \)/kg | lnQ | Monitoring point | R/m  | lnR | \( V \)/(cm.s\(^{-1}\)) | lnV | lnV' |
|-----------|-----|-----------------|------|-----|----------------|-----|-----|
|           |     |                 |      |     | \( V \) |       |      |
| 4.8       | 1.57| 5               | 11.5 | 2.44| 4.05 | 2.31 | 5.20 | 1.40 | 0.84 | 1.65 |
|           |     | 6               | 13.0 | 2.56| 2.56 | 1.56 | 2.68 | 0.94 | 0.44 | 0.99 |
|           |     | 7               | 16.6 | 2.81| 1.80 | 0.99 | 1.46 | 0.59 | -0.01| 0.38 |
|           |     | 8               | 21.4 | 3.06| 1.28 | 0.61 | 0.97 | 0.25 | -0.49| -0.03 |
|           |     | 9               | 26.6 | 3.28| 1.05 | 0.25 | 0.69 | 0.05 | -1.39| -0.37 |

Fig. 10 Regression results of velocity in all directions of measured points

Fitting results of velocity in each direction of measured points are shown in Fig. 10. The empirical regression formula fitted by modified Sadowski formula is shown in Table 5.
Table 5 Fitting results of modified Sadowski formula

| Direction   | Modified formula               | Modified $R^2$ |
|-------------|--------------------------------|----------------|
| Radial      | $V = 271.9Q^{0.7923} R^{-2.4634}$ | 0.96466        |
| Tangential  | $V = 500.4Q^{0.9646} R^{-2.708}$  | 0.93228        |
| vertical    | $V = 87.1Q^{0.3093} R^{-1.5216}$ | 0.93517        |

By comparing and analyzing Figs. 10, 11 and Table 3, 5, it is found that the modified Sadowski formula is better than the traditional Sadowski formula in fitting the surface vibration law of composite strata. Therefore, it is more reasonable to use the modified Sadowski formula $V = KQ^a R^b$ to characterize the propagation law of blasting vibration wave in the upper soft and lower hard composite strata.

4. Numerical Analysis

4.1. Computational model and parameters

Using FLAC3D explicit finite difference program and selecting the south end of Yangli Station of Fuzhou Metro Line 2 to build a three-dimensional model. The whole length of the model is 72m, the thickness of upper weathered rock is 8m, and the thickness of lower weathered rock is 22m. The simulated excavation method is the excavation of upper and lower steps. The width and height of double-track tunnel floor are 7.2m and 8.4m respectively. The distance between the two tunnels is 1.6~3.5m. Considering that the influence range of tunnel on surrounding rock disturbance is 3.5 times of tunnel diameter, the X-direction sizes of the model rock mass are 48m, and the Mohr-Coulomb elastic-plastic constitutive model is adopted for the rock mass. The non-reflective viscous boundary is adopted for the surrounding and bottom boundary of rock mass, and the general Rayleigh damping is adopted for this calculation. The material parameters are shown in Table 6. The three-dimensional mesh model is shown in Fig 11.

Table 6 Material parameters

| Materials        | $r/\text{(kN.m}^3\text{)}$ | $E/\text{GPa}$ | $\mu$ | $\phi/^{(\circ)}$ | $c/\text{MPa}$ | $t/\text{MPa}$ |
|------------------|-----------------------------|---------------|-------|-------------------|----------------|---------------|
| Upper soft rock  | 17                          | 18.4          | 0.40  | 23.5              | 0.12           | 0.15          |
| Lower hard rock  | 24                          | 37.2          | 0.50  | 33                | 0.45           | 0.35          |

Fig. 11 Mesh model

According to the theoretical analysis of blasting vibration, blasting load can be simplified to triangular load with linear ascending and descending sections. The formulas for calculating $t_r$ and total action time $t_s$ [11,12] are respectively:

$$t_r = 12r^{3/2}Q^{0.05} / K(s)$$

$$t_s = 84r^{3/2}Q^{0.2} / K(s)$$

Among them, $K$ is the bulk modulus of elasticity (10^5 Pa), $V$ is the Poisson's ratio of rock mass and $R$ is the contrast distance. The blasting load $P_{\text{max}}$ is solved by the following empirical formula according
to reference [13-15]:

\[
P = \frac{139.97}{Z} + \frac{844.81}{Z^2} + \frac{2154}{Z^3} - 0.8034 \text{(kPa)} \tag{7}
\]

In formula (7): \( Z = R/Q^{1/3} \) means the proportional distance, \( R \) means the distance from the detonation center to the loading surface (m), \( Q \) is the amount of explosive (kg), the total charge is taken in the simultaneous blasting, and the maximum charge is taken in the sectional initiation. According to reference [16-18], it is advisable that the duration of the equivalent blasting load curve rising and falling is 100 ms and 600 ms. In order to observe the attenuation process of vibration waveform, the total time is 1s.

4.2. Comparison of simulated and measured vibration velocities

In order to verify the correctness of the model and the reasonableness of the equivalent blasting load applied, the vibration velocity of the measured points 1-9 on the ground surface is simulated when the upper step palm face mileage reaches ZDK38+124.444. In view of the space limitation, the vertical vibration velocity of No. 1 measuring point in the excavated cave area is compared with that measured in the field, and the error is analyzed. Fig 12 shows the simulated and measured vibration waveforms.

![Simulated vibration wave](image1)

![Measured vibration wave](image2)

Fig. 12 Simulated and measured velocity waveforms

From Fig. 12, it can be seen that the simulated vibration velocity curve is quite different from the measured one, which is mainly manifested in the fact that the measured vibration velocity frequency is relatively large and the measured vibration velocity waveform has obvious piecewise peaks. However, the basic trend and peak velocity of the simulated blasting vibration waveform are not much different from the actual waveform. The vertical velocity of the measured point 1 is 2.89cm/s, while the simulated vertical velocity is 3.15cm/s. Because the dissipation of tunnel support and explosive energy in air is not considered in numerical simulation, the simulated vibration velocity is larger than the measured one, and the relative error between them is 9.0%. It can be concluded that the numerical software is feasible to study the propagation characteristics of blasting vibration wave in tunnel, and the calculation results are credible.

5. Conclusions

(1) Through on-site monitoring, the maximum vertical peak vibration velocity is generated in the excavated area, while the maximum radial peak vibration velocity is generated in the excavated area; the cavity magnification factor of each direction will increase with the increase of the distance between the blasting centers, and the tangential and vertical magnification coefficients show a power function growth law.

(2) Combining the fitting results of the traditional Sadowski formula and the modified Sadowski formula, the attenuation coefficient of vertical velocity is the largest and the attenuation speed is the fastest in the upper soft and lower hard composite strata.

(3) By comparing and analyzing the fitting results of the traditional Sadowski formula and the
modified Sadowski formula $V=KQ^aR^b$, it is found that the modified Sadowski formula has a higher fitting degree, which indicates that it is more reasonable to use the modified Sadowski formula $V=KQ^aR^b$ to characterize the propagation law of blasting vibration wave in the upper soft and lower hard complex strata.

(4) Through comparative analysis of monitoring data and numerical calculation, the feasibility of using numerical calculation method to study the propagation law of blasting vibration wave in tunnels in upper soft and lower hard composite strata is verified.

References

[1] Wu Ke, Zhang Wen, WU Haotian, et al. Deformation law of a metro tunnel underneath an existing urban road in combination soft/hard stratum[J]. Modern Tunnelling Technology, 2017, 54(6): 126-135.

[2] Zheng Baocai. Controlled blasting technique for tunnel in upper-soft and lower-hard stratum crossing existing railway[J]. Railway Engineering, 2018, 58(06): 90-92.

[3] Zhao Wenjuan, Wu Bo. Study on stability quantitative evaluation standard of surrounding rock along tunnel with top soft and bottom hard stratum[J]. Mine Construction Technology, 2017, 38(1): 35-38.

[4] Zhang Yan, Guo Lianjun, Zhang Daning. Research on attenuation laws of blasting vibration under different rock masses[J]. Mining Research and Development, 2015, 35(09): 97-99.

[5] Zhai Caiya, Li Anlong, Liu Tao, et al. Vibration propagation of tunnel blasting in granite areas[J]. Journal of Engineering Geology, 2014, 22(05): 824-831.

[6] Xu Jiangbo, Yan Changgen, Bao Han, et al. Research on blasting vibration of soft rock tunnel entrance[J]. Highway, 2016, 61(08): 222-228.

[7] State administration of safety in production. GB6722-2014 Blasting Safety Regulations [S]. Beijing: China Standard Press, 2014.

[8] Chen Xuejun, Yu Sizhe, Song Yu, et al. Analysis of factors influencing the propagation of mining blasting vibration wave in karst area[J]. Journal of Geomechanics, 2018, 24(05): 692-698.

[9] Ye Zhouyuan, Ma Jianjun, Cai Lujun, et al. An optimized calculation of particle vibration velocity by means of the vibration data form blasting monitoring[J]. Mining Research & Development, 2003, 23(4): 48-51.

[10] Chen Yumin, Xu Dingping. FLAC/FLAC3D foundation and engineering examples [M]. Beijing: China Water Conservancy and Hydropower Press, 2013.

[11] Liu Guohua, Wang Zhenyu. Dynamic response and blast-resistance analysis of a tunnel subjected to blast loading[J]. Journal of Zhejiang University(Engineering Science), 2004, 38(02): 77-82.

[12] Shi Yaxin, Wang Mingnian, Li Qiang. Analysis of influence of blasting vibration on middle wall of a double-arch tunnel[J]. Rock and Soil Mechanics, 2007, 28(6): 1275-1279.

[13] Low H Y, Hao H. Reliability analysis of reinforced concrete slabs under explosive loading[J]. Structural Safety, 2001, 23(2): 157-178.

[14] YA B, OJ F, GJ D. A blast-tolerant sandwich plate design with a polyurea interlayer[J]. International Journal of Solids and Structures, 2006, 43(25/26): 7644-7658.

[15] Olmati, Pierluigi, Petrini, et al. Fragility analysis for the performance-based design of cladding wall panels subjected to blast load[J]. Engineering Structures, 2014, 78(Nov.1): 112-120.

[16] Shi Hongchao, Ding Ning, Zhang Jichun. Analysis of vibration effects on surrounding rock for small clear distance tunnel under the dynamic action of blasting[J]. Blasting, 2008,25(1):74-78.

[17] Li Yunpeng, Ai Chuanzhi, Han Changling, et al. Study on dynamics effect caused by blasting construction by numerical simulation for tunnels with small spacing[J]. Explosion and Shock Waves, 2007,27(1):75-81.

[18] Bi Jihong, Zhong Jianhui. Study on influence of blasting vibration from excavation of a new tunnel on existed tunnel[J]. Engineering Blasting, 2004,10(4):69-73.