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## Study on Vibration of Tunnel Blasting Construction in Upper Soft and Lower Hard Ground

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Abstract. Based on the construction of Wufengshan Tunnel on Jintai Railway, in order to study the propagation law of vibration wave when the tunnel meets the special stratum of upper soft and lower hard, the obtained vibration velocity is fitted and analyzed by field monitoring and numerical simulation. The analysis results show that the traditional Sadowski formula is suitable for the study of vibration velocity law in single stratum and has a good fit. For the study of vibration velocity propagation law in complex stratum such as upper soft and lower hard, the modified Sadowski formula  $V = KQ^aR^b$  is more suitable; through tunnels in upper soft and lower hard stratum, the peak value of vertical vibration velocity of blasting is higher. Because of the existence of soft-hard interface, the attenuation velocity of vertical vibration velocity is the sharpest relative to the radial and tangential vibration velocities. 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 construction of tunnels for high-speed railway, urban rail transit and inter-city railway projects, two or more strata with different physical and mechanical characteristics are often encountered in the tunnel excavation section, the most typical of which is the upper soft and lower hard strata, i.e. the upper part of the tunnel section. Soft stratum or soft rock, the lower part is hard rock stratum.With the continuous expansion and extension of high-speed railway, tunnel engineering in upper soft and lower hard strata will become more and more popular.

Wu K et al.[1] relying on the project of Shenzhen Metro Line 7 crossing Beihuan Avenue, using the method of numerical simulation and on-site monitoring, this paper analyzed the settlement characteristics of the existing road pavement under the tunnel and the settlement law of the upper soft and lower hard strata. Zheng B C[2] Based on Nanjing Ninghe Intercity Railway Tunnel, the control deformation of upper soft and lower hard strata is studied. Wu B et al.[3] Quantitative criteria for surrounding rock stability of tunnels in upper soft and lower hard strata are discussed by numerical simulation and strength reduction method. It can be seen that at present, the research on the influence

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of upper soft and lower hard tunnel construction mainly concentrates on the analysis stage of stratum settlement deformation and surrounding rock stability.

There are two main methods to study the propagation law of blasting vibration velocity in tunnel: on-site monitoring and numerical simulation. Zhang Y et al.[4] Through field blasting vibration test in mines, the law of vibration attenuation of blasting seismic wave under different rock mass conditions is analyzed by statistical and regression methods. Zhai C Y et al.[5] Based on the construction project of Qingdao Metro Line 3, the propagation law of blasting vibration of metro tunnel in granite area was analyzed by numerical simulation. Xu J B et al.[6] relying on the Majiashan deep-buried soft rock tunnel project of Lanzhou-Chongqing Railway, through on-site vibration monitoring, obtained the Saxhlet empirical formula for deep-buried soft rock tunnel.

The above-mentioned scholars have done more research on the propagation law of blasting vibration in single stratum tunnel, but less on the characteristics of blasting vibration and void effect in soft and hard tunnels adjacent to existing lines. Therefore, the research on the propagation law of blasting vibration in soft and hard stratum tunnel has important engineering significance. Based on the Wufengshan Tunnel Project of Jintai Railway, this paper studies the propagation characteristics of blasting vibration waves in tunnels with special strata by means of on-site monitoring, numerical simulation and fitting analysis.



Figure 1 The Rock formation of the tunnel face

#### 2. Project overview

The total length of Wufengshan Tunnel is 532m. It mainly passes through the upper soft and lower hard strata as shown in Figure 3. The tunnel is parallel to the Jinlingtou Tunnel of the existing business line as shown in Figure 2. The distance between the entrance of the tunnel and the existing business line is 57m, and the distance between the exit and the existing business line is 35m. The stratum lithology of Wufengshan tunnel site is mainly as follows: Quaternary Holocene residual slope (Q4el+dl) silty clay; underlying bedrock is Jurassic upper series (J3z) tuff; the regional structure of tunnel crossing is mainly fissure, fold structure is not developed, the fault is mainly NW, and the NW faults are mostly tensional and torsional faults, which are subjected to faults. As well as the influence of dike intrusion, the geological structure is more complex, the joints and fissures of rock mass are developed, and most of them are closed, the rocks are fragmented and easy to collapse and fall. Therefore, the potential safety hazards of blasting construction are very great whether the tunnel passes through the upper soft and lower hard strata or the excavation of adjacent existing lines. Therefore, it is necessary to study the propagation law of vibration wave in such special strata. Fig. 1 is the face rock stratum of Wufengshan Tunnel. The corresponding relationship between Wufengshan Tunnel and the existing line is shown in Fig. 2.

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Figure 2 Correspondence with existing lines

#### **3. Field test and analysis**

#### 3.1 Monitoring scheme

The monitoring mileage of Wufengshan Mountain Tunnel is LDgK11+452-LDgK11+532. Because the surrounding rock at the exit of Wufengshan Tunnel is relatively fragmented, short bench excavation blasting is adopted. The upper step is composed of soft rock and the lower step contains soft rock and hard rock. There are three schemes for site monitoring. Five measuring points are arranged in sequence along the axis direction of the tunnel in the soft rock area of the upper step side wall with 5 meters apart; five measuring points are arranged along the axis direction of the tunnel in the hard rock area of the lower step arch waist with 5 meters apart; and three schemes are arranged separately in the soft rock area of the upper step side wall with 5 meters apart from the lower step arch waist with 5 meters apart. Two measuring points are arranged along the tunnel axis in the waist hard rock area, one at the interface of soft and hard rock mass, and the horizontal distance between the five measuring points is 5 m. Fig. 3 shows the layout of the site survey points.



Figure 3 Tunnel survey point layout

The monitoring equipment adopts TC-4850 new type vibrometer of Chengdu Zhongke Measurement and Control Company. The weak vibration can trigger the instrument to measure. The instrument is portable and easy to operate. It can accurately record the relevant parameters such as vibration time, vibration value and so on. Fig. 4 shows the exit of Wufengshan Tunnel at the beginning of detonation. Fig. 5 is a field mounted vibrometer.

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Figure 4 Tunnel exit



Figure 5 Monitoring instruments

#### 3.2 Monitoring results analysis

Three blasting vibration velocity tests were carried out on the site. The blasting excavation face was all upper step part, and the three excavation footages were 2.0m. The blasting hole layout of the blasting scheme adopted in the site was 7.5kg as shown in the figure. The mileage piles of excavation face are LDgk11+472, LDgk11+470 and LDgk11+468 respectively. Table 1 shows some monitoring data of blasting vibration. The measured blasting vibration waveform is shown in Fig. 6 Table 1 Partial monitoring data of blasting vibration

			8	8				
Maximum	Milaaga Dila	Monitoring point	Detonation – distance /m	Peak velocity /(cm.s <sup>-1</sup> )				
segment	Number			Radial	Tangential	Vertical		
dose /kg	Number			direction	direction	direction		
		1	30.0	2.03	1.49	2.05		
	LDgk 11+472	2	25.0	2.12	2.16	2.69		
7.5		3	20.0	2.56	2.87	3.52		
		4	15.0	4.12	4.49	5.27		
		5	10.0	7.71	8.09	8.84		
	LDgk 11+470	1	32.3	2.23	2.64	3.24		
		2	27.3	3.47	3.17	3.87		
		3	22.4	4.51	3.70	4.63		
		4	17.5	6.12	4.80	5.74		
		5	12.7	8.72	9.03	9.72		





According to Table 1, it can be found that in the upper soft and lower hard strata, the vertical peak vibration velocity produced by blasting is larger, and there is no obvious difference between the radial and tangential peak vibration velocities; under the same lithological conditions, the ratio of the peak vibration velocities in each direction to the distance between the blasting centers is proportional; under

different lithological conditions, the peak vibration velocities in each direction are not absolutely proportional to the distance between the blasting centers, and the measuring points are not absolutely proportional. The lithological conditions have a great influence on the blasting vibration velocity.

#### 3.3 Traditional Sadowski regression analysis

According to Sadowski's empirical formula[7] in China's Blasting Safety Regulations, the monitoring data of blasting vibration can be regressed and analyzed. The expression is as follows:

$$V = K \left(\frac{\sqrt[3]{Q}}{R}\right)^{\alpha} \tag{1}$$

In the formula, V - the particle velocity (cm/s); R - the distance between the measuring point and the explosion source (m); K - the site coefficient and attenuation coefficient; Q - the maximum charge volume (kg).

Table 2 Regression results of attenuation faw							
Direction	Layout of measuring points	Κ	α	Correlation coefficient R			
D - 1' - 1	Scheme 1	200.3	1.420	0.984			
direction	Scheme 2	223.7	1.270	0.989			
direction	Scheme 3	463.1	1.679	0.825			
Tangential direction	Scheme 1	274.7	1.532	0.985			
	Scheme 2	353.4	1.455	0.990			
	Scheme 3	440.9	1.749	0.806			
Vertical direction	Scheme 1	334.6	1.582	0.986			
	Scheme 2	391.9	1.474	0.990			
	Scheme 3	446.7	1.892	0.812			

The original data processing software is used to fit the data obtained from field monitoring, and the corresponding attenuation law of vibration velocity in all directions under different layout schemes of measuring points is obtained. the K fitted and the related data R are shown in Table 2.

Through Table 2, it can be found that scheme 1 and 2 are well fitted by Sadovsky formula, and the correlation coefficients are above 0.98. Traditional Sadovsky formula is used in scheme 3 to fit the correlation coefficient of about 0.8, and the fitting effect is general. The main reason is that there are measuring points at the interface of hard and soft rock mass in scheme 3. During the process of stress wave transferring from upper soft rock to interface and then from interface to lower hard rock, whether it is tension wave, shear wave or compression wave, stress wave will be caused by the reflection of interface and friction between rock mass at interface. The acceleration of energy dissipation makes the vibration velocity attenuate sharply. Moreover, it can be seen from the figure that the vibration velocity of the measured points arranged at the interface deviates from the fitting curve, which shows that it is not appropriate to use the traditional Sadovsky formula to fit the blasting vibration velocity in the upper soft and lower hard strata.



From Table 2, it can be found that the attenuation coefficients of the fitting vibration velocities in all directions of the upper soft rock are larger than those of the lower hard rock. At the same time,

from Figure 7, it is known that the vibration velocities in all directions of the soft rock are smaller than those of the hard rock. The main reasons are that the soft rock is relatively fragmented, there are many voids between the rock blocks, which are very incomplete, and the stress wave reflects and transmits continuously in the process of propagation. The attenuation speed is fast and the vibration speed is relatively small.

#### 3.4 Traditional Sadowski regression analysis

Considering the complexity of the stratum condition of the tunnel, the modified Sadovsky formula  $V = KQ^aR^b$  is used to fit and analyze the vibration velocity of the three measurement points of the scheme[8,9]. By taking logarithms on both sides of the revised formula, we can get the result:

$$\ln V = \ln K + a \ln Q + b \ln R$$
(2)

Assume  $z = \ln V$ ,  $x = \ln Q$ ,  $y = \ln R$ ,  $C = \ln K$ , then be expressed as: z = ax + by + c(3)

In the formula, V - the peak particle velocity (cm/s); R - the distance between the measuring point and the explosion source (m); K, a, b - the coefficients and attenuation index related to the geological conditions, stratigraphic lithology and topography of the explosion point; Q - the maximum charge quantity (kg). Table 3 shows the velocity and converted data of all directions at the three measuring points of the scheme.

 Table 3 Measured point vibration velocity in scheme 3

Mileage pile	Loading	Monitoring	D/m	1m D	$V/(cm.s^{-1})$			$\ln V$		
number	capacity Q/kg	point	<b>K</b> /III	IIIK	$V_x$	$V_y$	$V_z$	$\ln V_x$	$\ln V_y$	$\ln V_z$
		1	34.0	3.53	2.03	1.49	2.05	0.71	-0.34	0.72
		2	29.0	3.37	2.12	2.16	2.69	0.75	0.77	0.99
LDgk11+468	7.5	3	24.1	3.18	2.56	2.87	3.52	0.94	1.05	1.26
-		4	19.4	2.97	4.12	4.49	5.27	1.42	1.50	1.66
		5	14.6	2.68	7.71	8.09	8.84	2.04	2.09	2.18



Fig 8 Regression analysis of vibration velocity in scheme 3

Fitting results of all directions of vibration velocities at scheme 3 are shown in Fig. 8. The empirical regression formula fitted by modified Sadovsky formula is shown in Table 4.

Table 4 Fitting	results of	modified	Sadovsky	formula

Direction	Modified Sadovsky formula	Correlation coefficient R
Radial direction	$V = 325.8Q^{1.6978}R^{-2.5963}$	0.8882
Tangential	$V = 287.1 Q^{0.3184} R^{-1.6288}$	0.9211

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direction		
Vertical direction	$V = 292.3Q^{0.3093}R^{-1.7161}$	0.9973

Comparing Fig 7, Table 2 with Fig 8, Table 4, The vibration velocity of the measuring point in the third scheme is fitted by the modified Sadowski formula, and the fitness is higher than that of the traditional Sadowski formula. Therefore, it is more reasonable to use modified Sadowski formula  $V=KQ^aR^b$  to characterize the propagation law of blasting vibration wave in upper soft and lower hard complex strata.

#### 4. Numerical analysis

#### 4.1 Traditional Sadowski regression analysis

Using FLAC3D explicit finite difference program and selecting the mileage K477+796~K477+876 of the exit section of Wufeng Mountain Tunnel, a three-dimensional model is established. The floor of the new tunnel section is 9m wide and 11m high. The simulated excavation mode is short steps. The cross-section floor of existing railway tunnel is 15m wide and 12m high. The distance between the two tunnels is 35 40m, and the upper soft rock layer is 37 M. Considering that the influence range of tunnel on surrounding rock disturbance is 3.5 times of tunnel diameter, the dimensions of X, Y and Z directions of the model rock mass are 120 m, 80 m and 80 m, respectively. Among them, Mohr-Coulomb elastic-plastic constitutive model is used for rock mass and linear elastic model is used for existing tunnel lining. 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[10] The material parameters are shown in Table 5. The three-dimensional mesh model is shown in Figure 10.

Table 5 Material parameters								
Material Science	$r/(kN.m^3)$	E/GPa	$\mu$	$arphi/(^\circ)$	c/MPa	t/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		
Lining	22	15.0	0.16	-	-	12		





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 given:

$$t_{r} = \frac{12\sqrt{r^{2-\nu}}Q^{0.05} / K(s)}{t_{s} = \frac{84\sqrt{r^{2-\nu}}Q^{0.2} / K(s)}$$
(4)

In the formula: K - the bulk modulus of elasticity (10<sup>5</sup>Pa); V - the Poisson's ratio of rock mass ; R - the contrast distance. The blasting load  $P_{max}$  is solved by the following empirical formula according to reference[13-15]:

$$P = \frac{139.97}{Z} + \frac{844.81}{Z^2} + \frac{2154}{Z^3} - 0.8034 (\text{kPa})$$
(5)

In the formula:  $Z=R/Q^{1/3}$  - proportional distance; R - the distance from the detonation center to the loading surface (m); Q - 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[16-19], 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 the vibration waveform, the total time is 1 s.

#### 4.2 Comparison of simulated and measured vibration velocities

Because of the particularity of the upper soft and lower hard composite strata, the velocity curve of the measured point is simulated when the excavation face mileage is LDgk11+468. In view of the space limitation, the partial directional velocity of the No. 5 measuring point in the third scheme is selected for numerical calculation, and the error is analyzed by comparing it with the measured velocity in the field. Figure 10 shows the simulated and measured vibration waveforms.



From Fig. 10, it can be seen that there are obvious differences between the simulated velocity curve and the measured curve, which is mainly manifested in the larger frequency of the measured velocity. However, the basic trend and peak value of vibration wave after simulation blasting are not different from those of actual wave. The measured radial velocity is 8.72 cm/s, while the simulated radial velocity is 8.25 cm/s with a relative error of 5.4%. The measured vertical velocity is 9.72 cm/s, and the simulated vertical velocity is 8.96 cm/s with a relative error of 7.8%. It can be concluded that the numerical software is feasible to study the propagation characteristics of blasting vibration wave in tunnels, and the calculation results are credible.

#### 5. Conclusion

(1) Through on-site monitoring, the vertical peak vibration velocity produced by blasting is larger, and there is no significant difference between the radial and tangential peak vibration velocities. In the upper soft and lower hard strata, the blasting vibration velocity is not absolutely proportional to the distance between the blasting centers, and is closely related to the lithological conditions of the excavation face.

(2) According to the fitting analysis of traditional Sadowski formula, the attenuation coefficient of vibration velocity in each direction of upper soft rock is larger than that of lower hard rock, and the peak vibration velocity in each direction of soft rock is smaller than that of hard rock. The main reason is that soft rock is relatively fragmented, which increases the reflection times of stress wave in the propagation, thus leading to the rapid attenuation of vibration wave in soft rock.

(3) In single stratum, it is more suitable to use traditional Sadowski formula to fit the propagation law of vibration wave, but it is more reasonable to use modified Sadowski formula  $V=KQ^aR^b$  to characterize the propagation law of blasting vibration wave in upper soft and lower hard complex stratum.

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

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