



Vibration control of blasting excavation of large cross-section highway tunnel over metro line

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Abstract

The blasting excavation of the new tunnel may cause damage to the adjacent tunnel. Taking the Hongshi road tunnel in Chongqing as a research object, the paper analyzed the influence of the maximum charge on the vibration speed of the existing tunnel by comparing the influence of adjacent tunnel blasting team on the existing tunnel simulated by ANSYS/LS-DYNA with the actual monitoring results. The results show that when adopting the “three steps + invert” four steps excavation, the maximum charge quantity of each excavation step is 56.8 kg, 40.2 kg, 37.1 kg, and 21.6 kg, and the combined vibration velocity of the control measuring points is less than 1.5 cm/s. All meet the design requirements. The vibration velocity of the blasting side of the existing subway tunnel is mainly in the horizontal direction and relatively small in the vertical direction. With the increase of distance from the blasting point, the maximum vibration velocity is the charge quantity of large sections and can be increased gradually.

Keywords Large-section tunnel · Adjacent tunnel · Finite element method · Numerical simulation · Blasting vibration

Introduction

As urban infrastructure expanding continuously and rapidly, the construction of new structures will inevitably affect existing ones. The excavation causes blasting vibration and the redistribution of surrounding rock stress, thus leading to the potential structural safety issue of the existing tunnel during the construction process. The closer the distance is, the more prominent the influence is.

Relevant research points out that when the vibration velocity caused by blasting occurs on the sidewall of the existing tunnel, it reaches the largest level. The more stable the surrounding rock is, the smaller the vibration velocity is. When the spacing is less than one time of the tunnel diameter, the vibration velocity of the tunnel lining may exceed the allowable value, while the relationship between the vibration

velocity of the surrounding rock and the distance to the blasting source is nonlinear (Bi and Zhong 2004). Sidewall, arch foot, arch crown, and other parts of the blasting side of the built tunnel are the most severely impacted parts of the built adjacent tunnel when conducting the upper loose blasting. During the construction, it is important to monitor the blasting side of the tunnel (Ouyang and Shuai 2009). The maximum blasting charge remains unchanged, the better the surrounding rock quality, and the greater the thickness of the intermediate rock, the smaller the vibration speed of each measuring point will be, which means the smaller the impact of blasting vibration may cause, and vice versa (Chen 2010). The peak value of vibration velocity in the vertical direction is larger than that in the other two directions, but the main tensile stress of vault and base plate element is horizontal. Thus, the vertical vibration velocity does not fully represent the stress state of the surrounding rock (Zhong et al. 2010). Under blasting vibration, the maximum tensile stress, vertical displacement, and vibration velocity of the second lining of the existing metro tunnel are all located in the center of the inverted arch. The maximum vertical displacement and vibration velocity are successively reduced from the inverted arch, the arch foot to the sidewall, and the arch crown. If the excavation footage reaches 1 m, the vibration velocity on the inverted arch center exceeds the blasting safety control

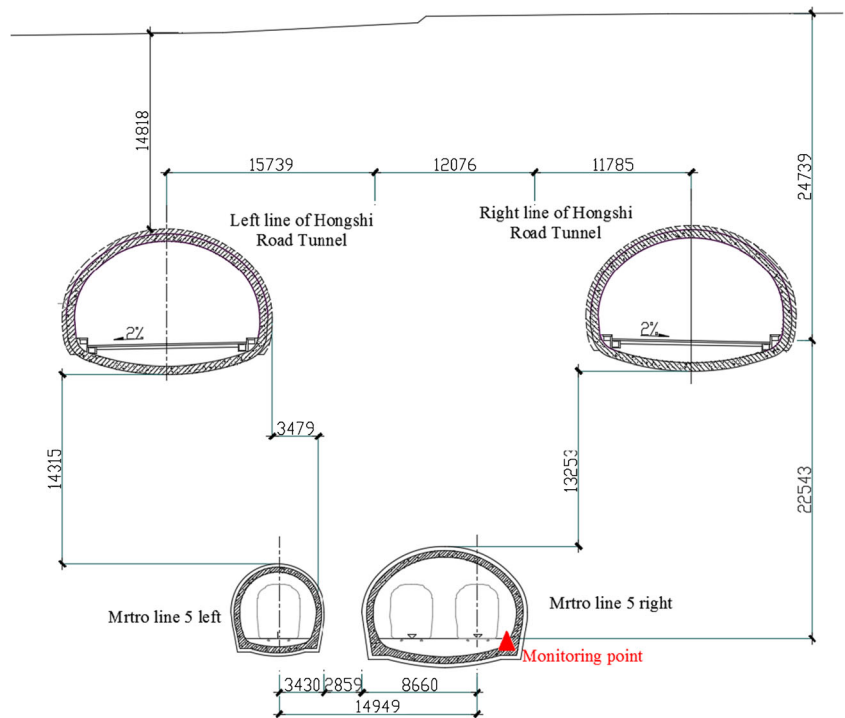
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Fig. 1 Cross section of location relationship between Hongshi road tunnel and Metro Line 5 section tunnel (unit: mm)



standard. It is recommended to design the excavation footage at 0.1 m (Wang et al. 2011). Xiao et al. (2011), Xiao et al. (2012), and Liu and Ming (2012) believe that the forming tunnel can amplify the surface vibration speed to several degrees. Different types of blasthole blasting on the excavation face follow different attenuation laws. As the blasting initiation section increases, the *K* value in the attenuation formula

decreases gradually (Xue et al. 2012). When the distance between adjacent blasting loads is too narrow, the front blasting side shows triangular failure, while the back blasting side displays crack growth at the starting point and bottom angle. The degree of failure decreases as the distance broadens (Guo et al. 2018; Wu et al. 2020), taking the newly built Linjiatun tunnel of the Jintai railway line as the engineering background, used

Fig. 2 Blasting construction of Hongshi road tunnel



Table 1 Parameters used in the calculation of wall rock and concrete

Materials	Young’s modulus /Pa	Poisson’s ratio	Density/(kg m ⁻³)
Grade IV surrounding rock	3.657E+09	0.13	2490
Initial support of metro tunnel	2.10E+10	0.2	2200
Secondary lining of metro tunnel	3.100E+10	0.2	2500
Initial support of Hongshi road tunnel	2.50E+10	0.2	2200
Secondary lining of Hongshi road tunnel	3.10E+10	0.2	2500

Table 2 Parameters of emulsion explosive and state equation

Explosive density (g/cm ³)	Detonation velocity (m/s)	Burst pressure/ GPa	Parameters of JWL equation of state for explosives					
			A/ Gpa	B/ Gpa	R ₁	R ₂	ω	E ₀
1.05	5500	10	741	18	5.56	1.65	0.35	3.6

the AHP-GRA method to analyze the influencing factors of the vibration caused by the adjacent operating tunnel. The main factors affecting the vibration frequency generated by the operating tunnel are the maximum charge amount and the distance between the blasting centers. Yu and Wen (2007) analyzed the impact of a blasting excavation of the subway tunnel on surface buildings. Wu et al. (2009) carried out a blasting vibration test and evaluate the safety level of the subway tunnel when having construction blasting under densely populated residential areas. Jiang et al. (2013) analyzed the vibration monitoring value of the subway tunnel near the blasting excavation. Liu et al. (2014) and Qian and

Wang (2014) analyzed the impact of blasting excavation on adjacent buildings through numerical simulation of tunnel safety. Li et al. (2014) conducted a more in-depth study on the blasting deformation and control method in the construction of a short distance metro tunnel.

Through the analysis of the monitoring statistics, blasting vibration, and safety impact of the blasting excavation on the adjacent tunnel, it shows that less research has been conducted on blasting vibration control of operating subways, especially in terms of the blasting construction of the existing operation subway that close to the new long-span highway tunnel. It is necessary,

Fig. 3 ANSYS calculation model

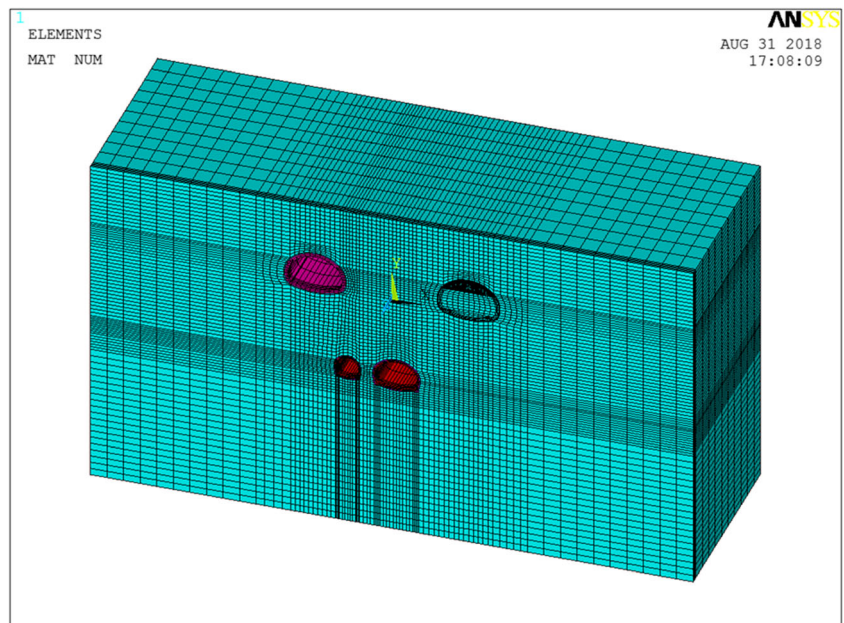
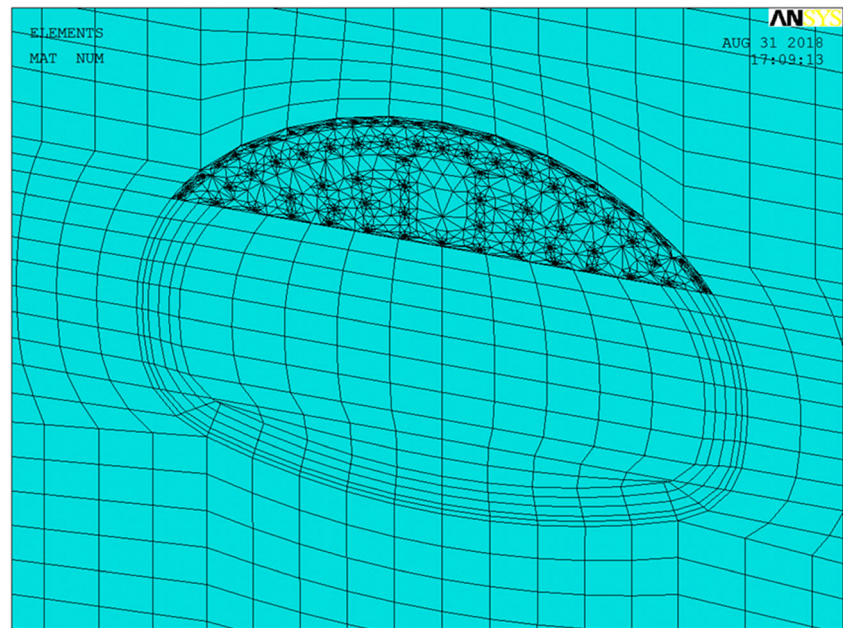


Fig. 4 Mesh model of upper bench blasting



therefore, to study in this area. Based on the method of numerical simulation analysis and field test verification, this paper studies the vibration control of the blasting excavation of the highway tunnel over the existing metro line with a large-span highway tunnel under construction in Chongqing as study cases.

Project overview

Hongshi road tunnel is an integral part of the north bank approach of Hongyancun Bridge. It is an urban

expressway, with a design speed of 80 km/h, two-way six lanes, and two-way up and down separated double holes. The starting and ending pile number of the left tunnel is $zk0 + 125.058 \sim zk0 + 684.108$, with a total length of 559.050 m; the starting and ending pile number of the right tunnel is $yk0 + 191.601 \sim yk0 + 741.162$, with a total length of 549.561 m. The axis of both tunnels is 27.9–51.3 m, the standard clear span of the tunnel is 14.286 m, and the tunnel height is 7.713 m. The track section tunnel under the Hongshi road tunnel is in operation (Fig. 1). In order to ensure the structural safety of the metro section tunnel in operation, the left line $zk0 + 145 \sim zk0 + 280$ and the right

Fig. 5 Mesh model of middle bench blasting

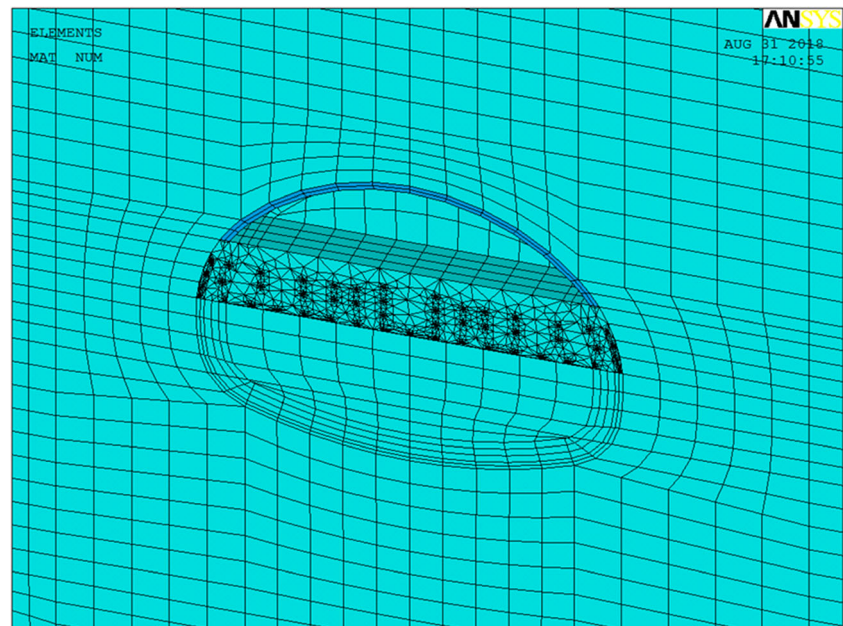


Fig. 6 Mesh model of lower bench blasting

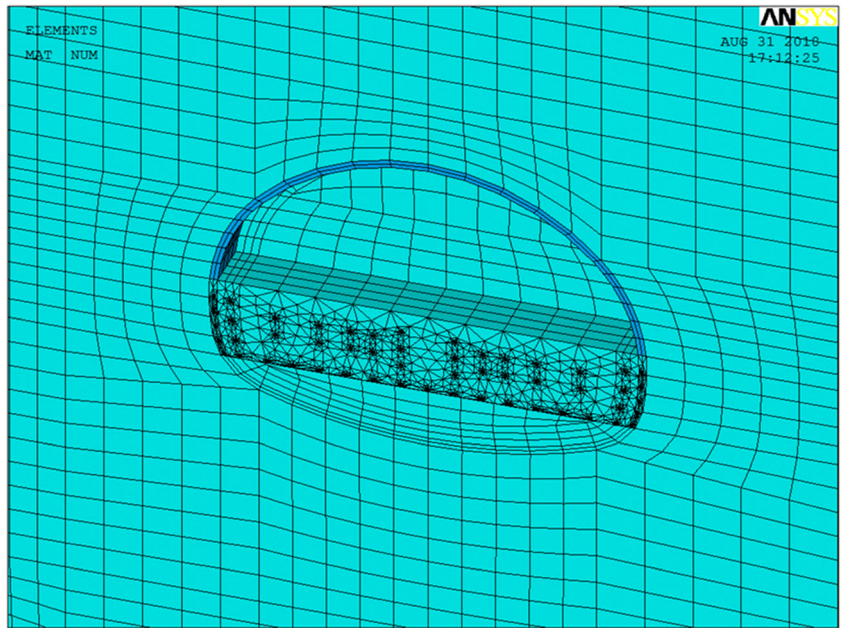


Fig. 7 Mesh model of inverted arch blasting

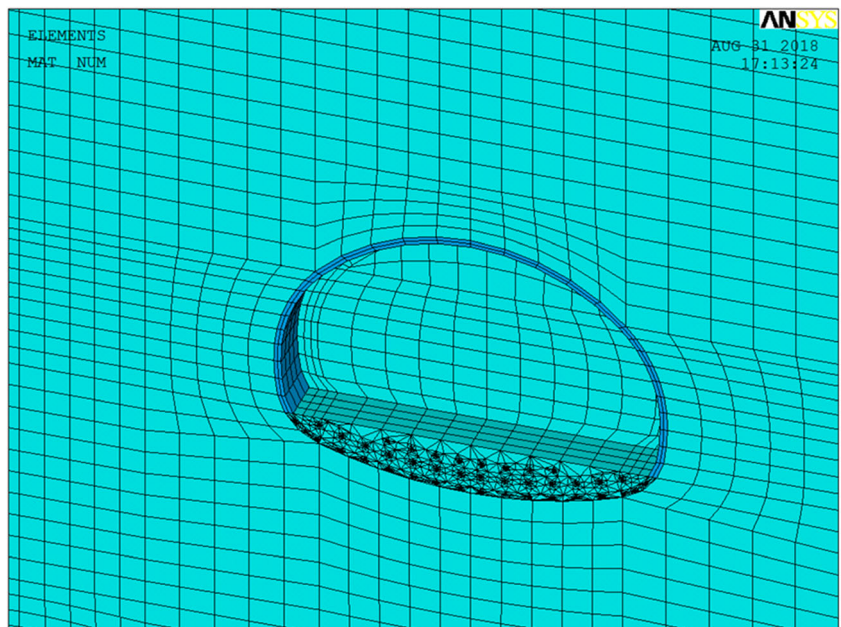
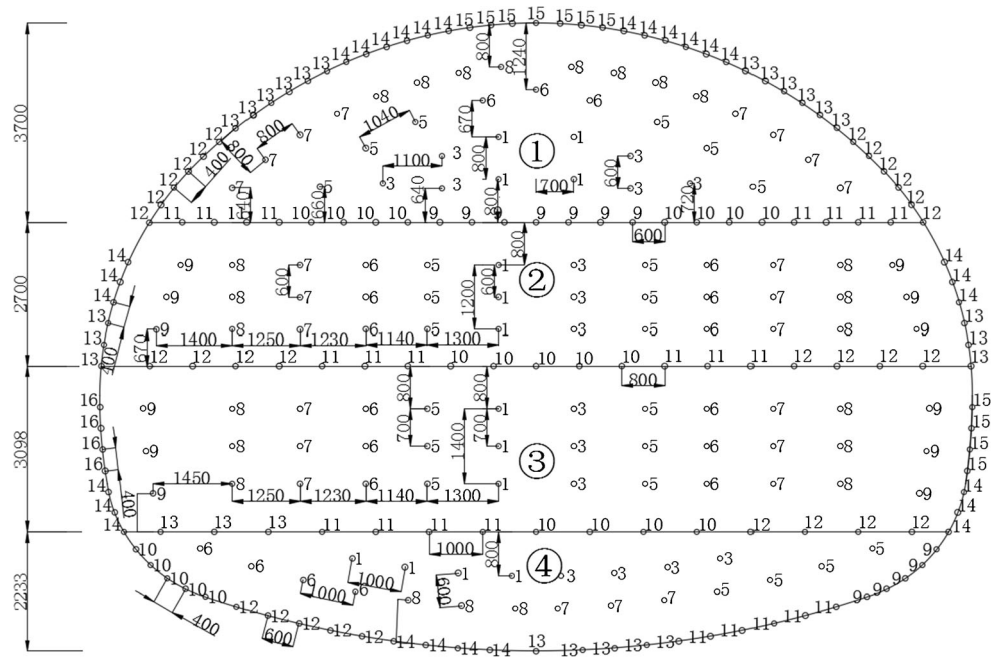


Table 3 Maximum charge of single blasting

Excavation steps	Excavation location	Control vibration speed (cm/s)	K	α	Blasting distance (m)	Maximum charge of single section (kg)
①	Upper step	1.5	250	1.8	30	4.8
②	Middle step	1.5	250	1.8	27	3.6
③	Lower step	1.5	250	1.8	25	3.0
④	Inverted arch	1.5	250	1.8	22	2.0

Fig. 8 Layout of each excavation step blast hole (unit: mm)



line $y_k0 + 211.5 \sim y_k0 + 340$ of the tunnel are excavated through controlled blasting. The lithology of the surrounding rock of the tunnel in the blasting excavation section is mainly sandy mudstone with sandstone of various thicknesses. The rock mass is relatively complete, and the surrounding rock is classified as grade IV. The tunnel adopts a composite lining structure.

The scope of the Hongshi road tunnel across the operation subway section requires a lower than 1.5 cm/s speed of controlled blasting vibration. Thus, the excavation should be carried out by a three-step excavation method, which is divided

into four steps: upper, middle, lower, and invert excavation (Fig. 2).

Model building and field monitoring

Material model and equation of state

The project uses no. 2 rock emulsion explosives in the construction. ANSYS/LS-DYNA is used for explosion simulation, and the JWL equation of state is used to simulate the

Fig. 9 Layout of monitoring points for numerical simulation blasting

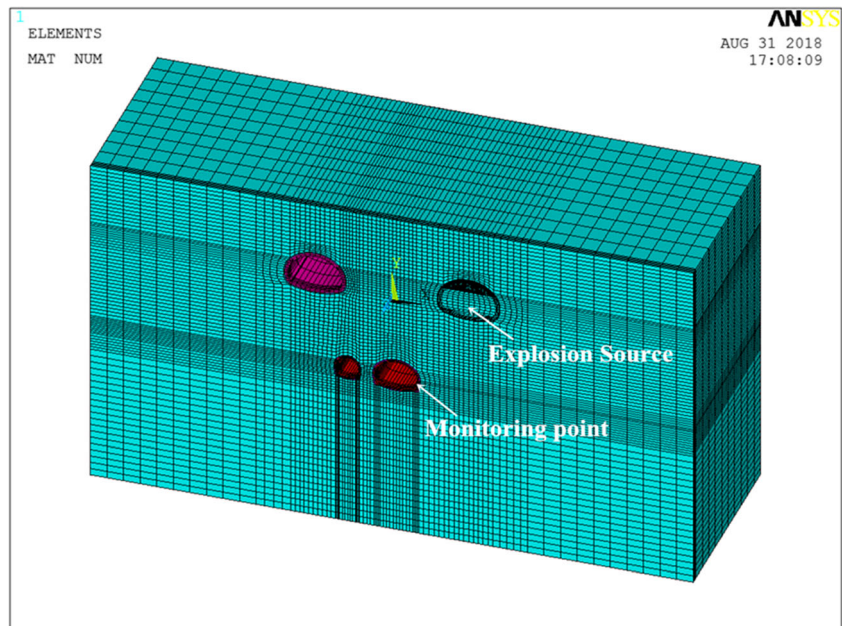


Table 4 The main parameters of TC-4850N blasting vibration tester

Item	Parameter
Sampling rate	100 sps~100 Ksps, with multi-gear adjustable
A/D resolution	16 bit
Frequency response	0~10 kHz
Recording method	Single record, automatic repeat record, continuous record
Recording time	1~5000 s adjustable
Trigger mode	Internal trigger, external trigger, synchronous trigger, timing trigger
Range	±1 V, ±10 V, maximum input value ±10 V (±35 cm/s)
Recording accuracy	0.01 cm/s
Reading accuracy	1‰
Adaptive environment	-10~75 °C, 0~95% RH (no condensation)
Size	168 mm × 200 mm × 80 mm (4 channels)
Weight	1.5 kg

relationship between pressure and specific volume in the detonation process.

$$p = A \left(1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V} \quad (1)$$

where A , B , R_1 , R_2 , and ω are material constants, P is pressure, V is relative volume, and E_0 is initial specific internal energy. Table 1 shows relevant parameters of surrounding rock and concrete, while Table 2 displays parameters of no. 2 rock emulsion explosive.

Construction of the 3D computing model

ANSYS/LS-DYNA is used to analyze the influence of blasting construction on the existing subway tunnel which is under the new Hongshi road tunnel. The shortest vertical distance from the Hongshi road tunnel to the operating Metro Line 5 is selected for three-dimensional modeling. The modeling adopts a three-step method + inverted arch four-step excavation and 2.0-m excavation footage by calculation. Assuming the second lining of the left line of the Hongshi

Fig. 10 TC-4850N blasting vibration meter

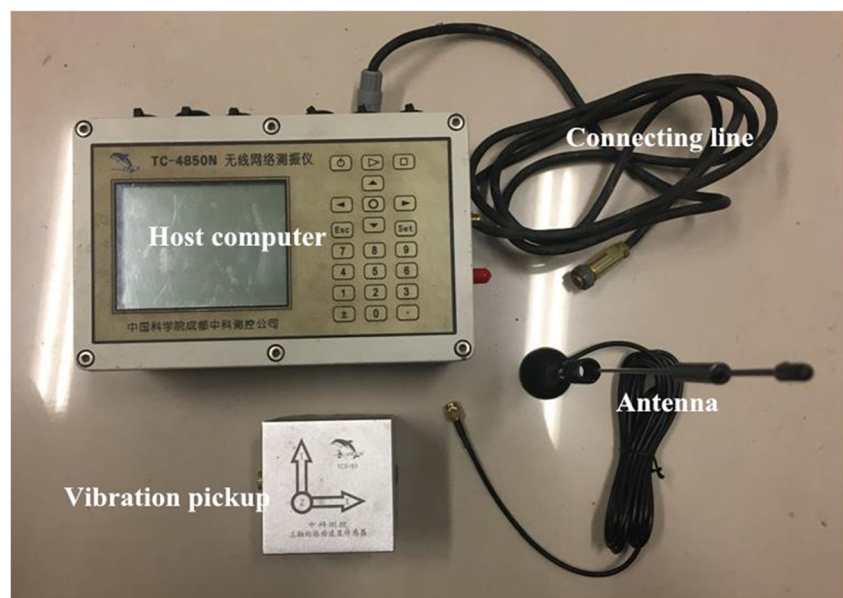




Fig. 11 Device power connection



Fig. 13 Equipment installation

road tunnel is completed during the modeling process, only the right line is used for blasting numerical simulation to analyze the influence of back tunnel blasting on the second lining of the first tunnel. The right line spans a large-span tunnel with the shortest vertical distance. To reduce the boundary effect and optimize the accuracy of calculation, the model size is 160-m left and right bound-

ary in the X direction, 90-m up and down boundary in the Y direction, 51-m front and back boundary in the Z direction. The non-reflection boundary conditions (ednb, add, nonr, 1,1) are used in front of and behind the model, on the left and right side, and at the bottom of it. The cm-g- μ s unit system is used for modeling. The calculation model is as shown in Figs.3, 4, 5, 6, and 7.



Fig. 12 Cable crossing



Fig. 14 Equipment fixing

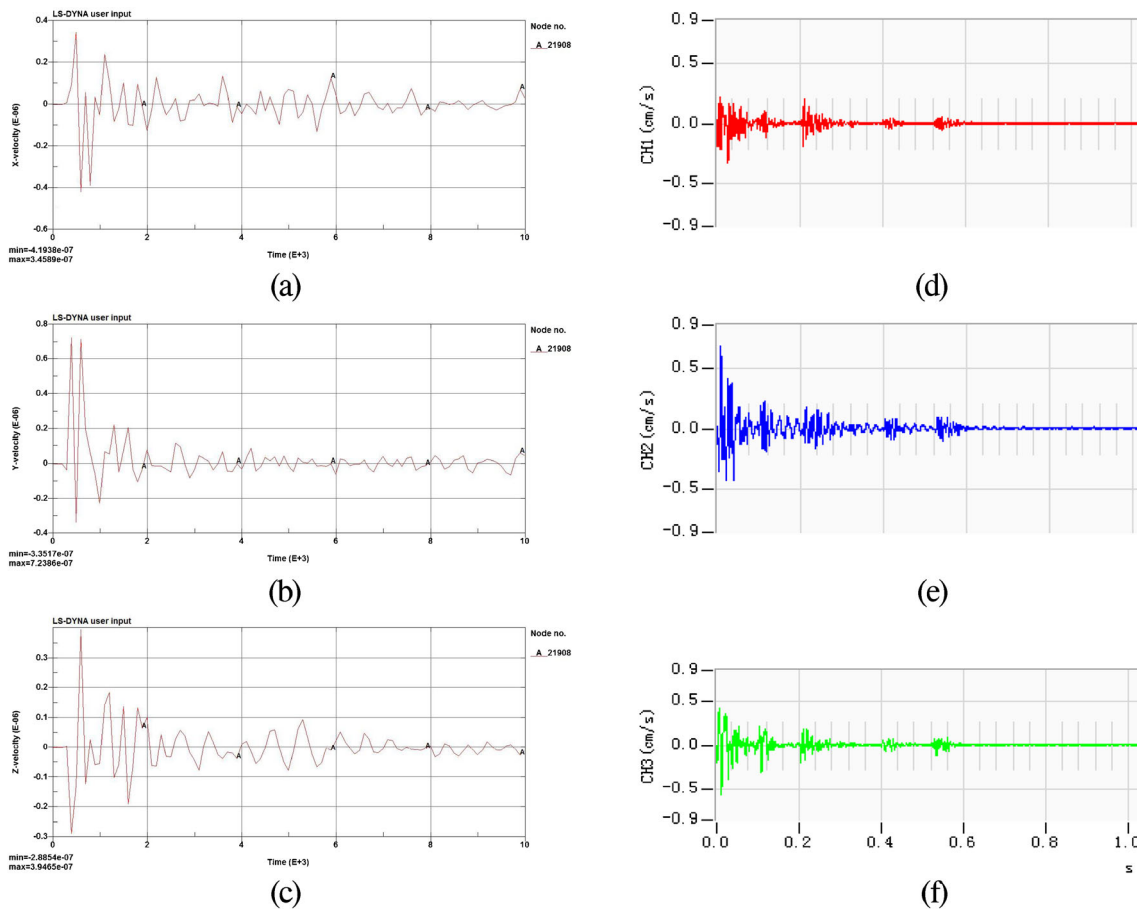


Fig. 15 Comparison between numerical simulation results and field monitoring results during upper bench excavation. **a** Numerical simulation of vibration velocity in the X direction of measuring point. **b** Numerical simulation of vibration velocity in the Y direction of measuring point. **c** Numerical simulation of vibration velocity in the Z direction of measuring point.

d Vibration velocity in the X direction of the field monitoring point. **e** Vibration velocity in the Y direction of the field monitoring point. **f** Vibration velocity in the Z direction of the field monitoring point

During the numerical calculation of tunnel blasting (as shown in Fig. 8 and Table 3 for the layout and charge quantity of each excavation step), the vibration impact of the blasting excavation in Hongshi road tunnel on the lining structure while Metro Line 5 is operating is thus analyzed.

In order to simulate the impact of blasting vibration on the structure of the operating tunnel, the blasting time interval of cutting hole, driving hole, bottom hole, and the surrounding hole is assumed to be 100 ms. The blasting control points are shown in Fig. 9. The measuring points are arranged on the right wall of the right line of the tunnel in the Metro Line 5 in operating.

Field tests

TC-4850N remote blasting acquisition system is used to monitor the blasting velocity (Fig. 10). Table 4 demonstrates the main parameters of the instrument, Fig. 1 shows the layout of

measuring points in the operating subway tunnel, and Figs. 11, 12, 13, and 14 display the layout of on-site monitoring points.

Results and discussion

Figures 15, 16, 17, and 18 show the comparison between the simulation results and the measured values of vibration velocity during the excavation of upper bench, middle bench, lower bench, and invert of Hongshi road tunnel. The maximum vibration velocity is 0.6750 cm/s and the numerical simulation result is 0.723 cm/s; the maximum vibration velocity is 0.3610 cm/s and the numerical simulation result is 0.488 cm/s; the maximum vibration velocity is 0.7947 cm/s and the numerical simulation result is 0.825 cm/s; during the blasting construction of the inverted arch, the maximum vibration velocity is

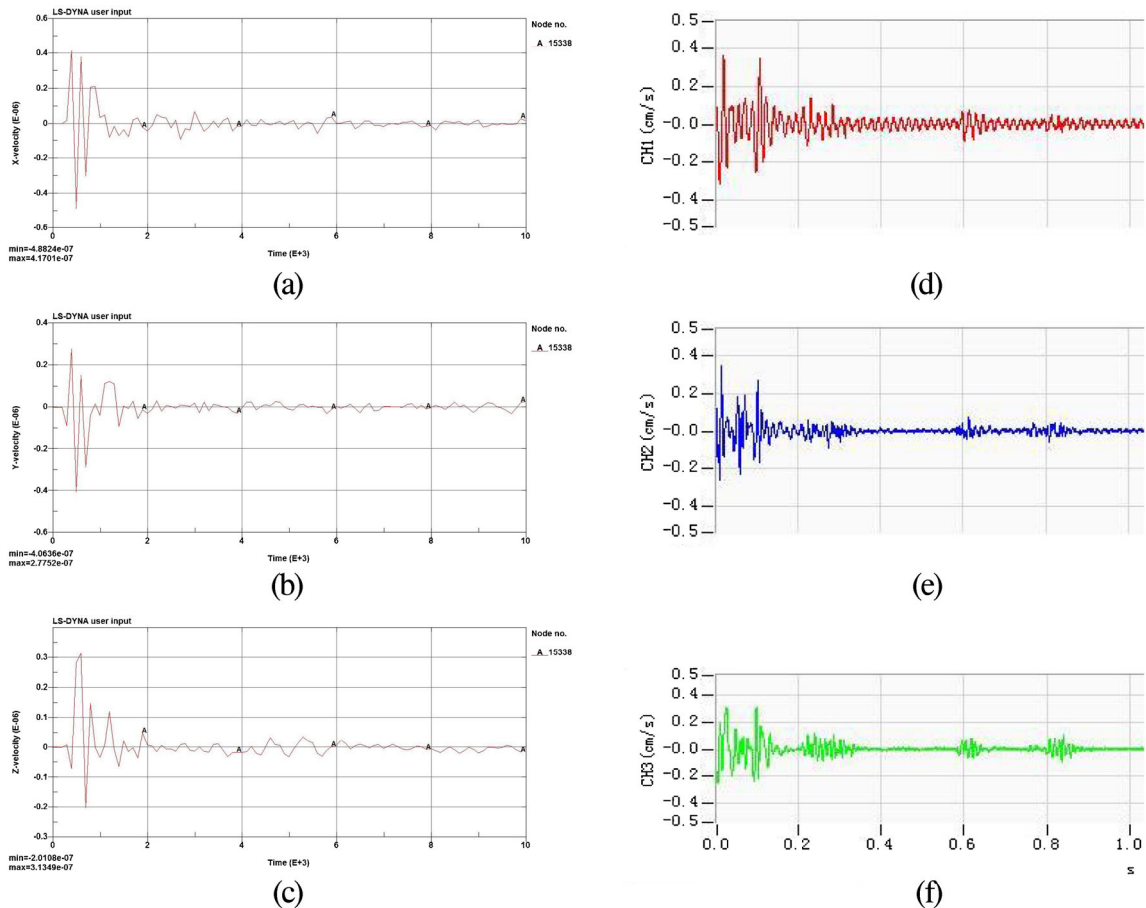


Fig. 16 Comparison between numerical simulation results and field monitoring results during bench excavation. **a** Numerical simulation of vibration velocity in the X direction of measuring point. **b** Numerical simulation of vibration velocity in the Y direction of measuring point. **c** Numerical simulation of vibration velocity in the Z direction of

measuring point. **d** Vibration velocity in the X direction of the field monitoring point. **e** Vibration velocity in the Y direction of the field monitoring point. **f** Vibration velocity in the Z direction of the field monitoring point

0.8370 cm/s and the result of numerical simulation is 0.655 cm/s; the vibration velocity does not exceed the upper limit value (1.5 cm/s) required by the design.

The simulation collects the vibration velocity in X, Y, and Z directions of the sidewall of the blasting face with the maximum charge quantity of the upper step at 4.8 kg, the maximum charge quantity of the middle step at 3.6 kg, the maximum charge quantity of the lower step at 3.0 kg, and the maximum charge quantity of the inverted arch at 2.0 kg. Figures 15, 16, 17, and 18 show the vibration curve. According to the simulation results (as shown in Table 5), the vibration speed is less than the upper limit of the design requirements, so it will not have a great impact on the existing Metro Line 5 tunnel.

Figures 19, 20, and 21 show the change curves of numerical simulation results in X, Y, and Z directions compared with the field measured results, and the

change rules between the two are consistent. It can be seen from Figs. 19 and 20 that the numerical simulation results of blasting vibration velocity in X and Y directions are less than the field measured results during the excavation of inverted arch and lower bench, which indicates that the excavated part of the upper bench and middle bench creates a free surface, which has the effect of vibration reduction; when excavating the upper and middle steps, the numerical simulation results are larger than the field measured results, and the analysis reason is that during the numerical simulation, the blasting vibration can be reduced. The surrounding rock is regarded as isotropic without considering the factors such as joints and fissures. However, the surrounding rock on site actually contains joints and fissures, including groundwater, which can reduce blasting vibration to a certain extent.

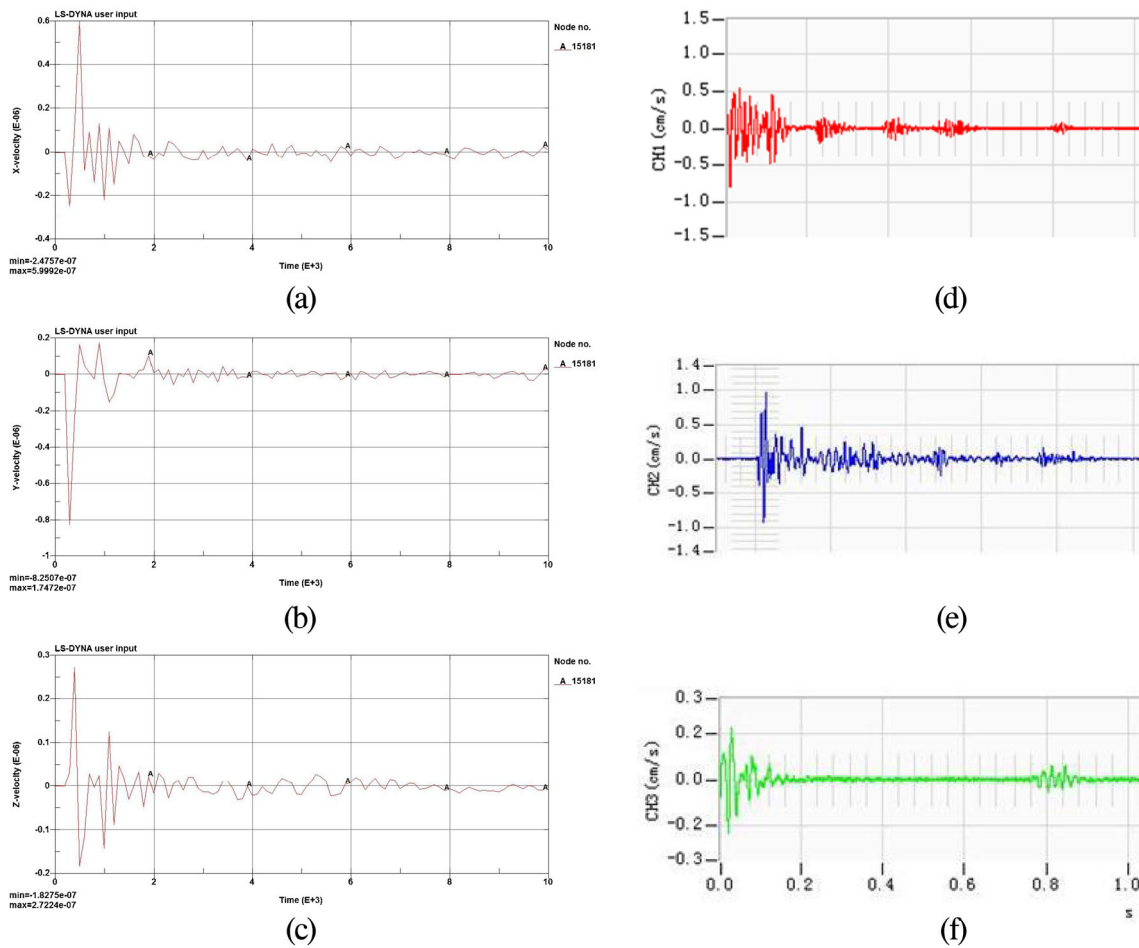


Fig. 17 Comparison between numerical simulation results and field monitoring results during lower bench excavation. **a** Numerical simulation of vibration velocity in the X direction of measuring point. **b** Numerical simulation of vibration velocity in the Y direction of measuring point. **c** Numerical simulation of vibration velocity in the Z

direction of measuring point. **d** Vibration velocity in the X direction of the field monitoring point. **e** Vibration velocity in the Y direction of the field monitoring point. **f** Vibration velocity in the Z direction of the field monitoring point

As can be seen from Fig. 21, with the excavation of upper bench, middle bench, lower bench, and inverted arch, the field measured results show a change law of greater than, approximate to, less than, and then greater than the numerical simulation results. When excavating the upper bench, the surrounding rock is a whole block, which is conducive to the transmission of blasting vibration speed; when excavating inverted arch, due to the close distance to the monitoring point, the surrounding rock has not played its energy dissipation role. Therefore, it is necessary to pay attention to the control of blasting vibration velocity when excavating the upper steps and inverted arches.

Based on the above analysis results, it can be seen that the seismic velocity on the sidewall of the blasting

face of the existing Metro Line 5, when excavating the upper stage, mainly happens in the Y direction and is relatively small in X and Z directions; on the middle stage, the seismic velocity is mainly in the X direction and is relatively small in Y and Z directions; while at the lower stage, the seismic velocity is mainly in Y, and smaller in X and Z; when excavating the inverted arch, the seismic velocity is mainly in X and is relatively small in Y and Z. The horizontal velocity, therefore, is an appropriate control factor. Simulation results and field monitoring results show that the existing Metro Line 5 tunnel below is free from the blasting excavation of the Hongshi road tunnel. Moreover, the safety space in between can appropriately increase the charge and speed up the construction.

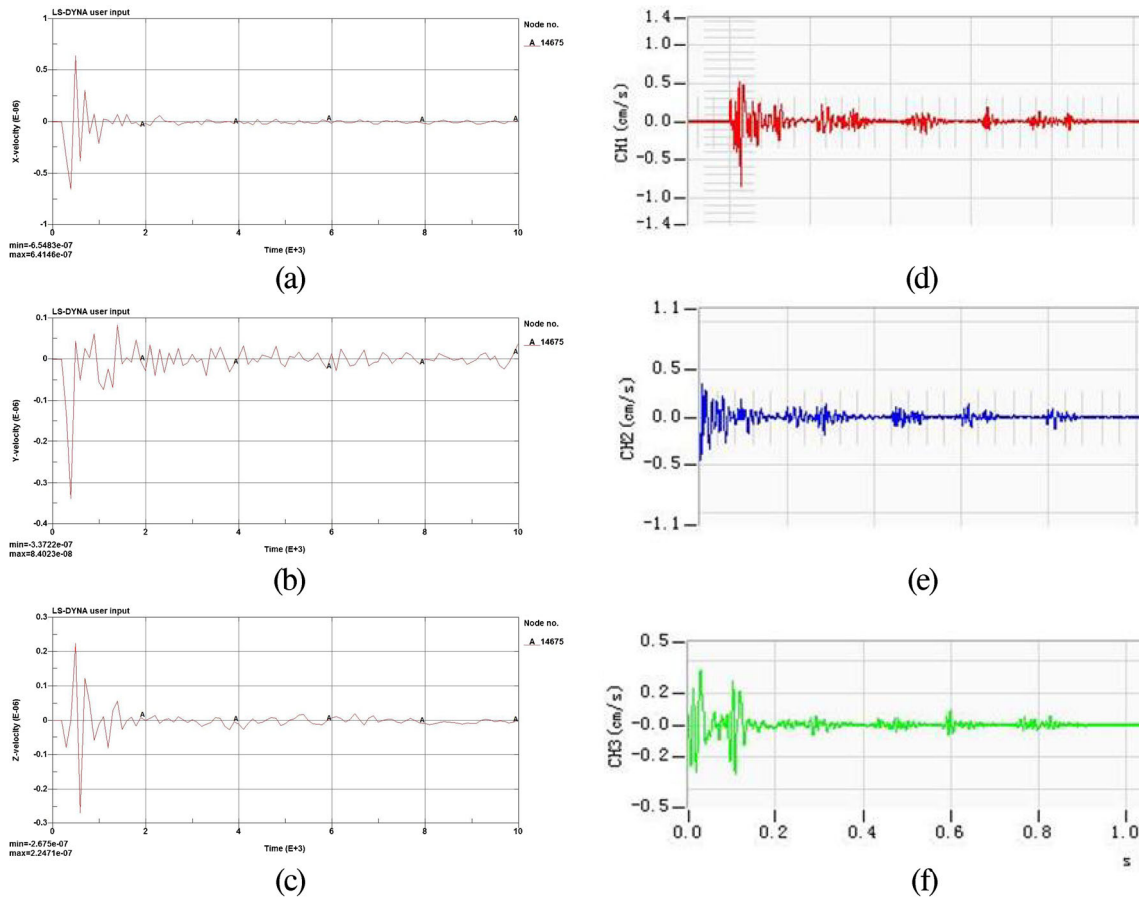


Fig. 18 Comparison between numerical simulation results and field monitoring results during inverted arch excavation. **a** Numerical simulation of vibration velocity in the X direction of measuring point. **b** Numerical simulation of vibration velocity in the Y direction of measuring point. **c** Numerical simulation of vibration velocity in the Z direction of measuring point.

d Vibration velocity in the X direction of the field monitoring point. **e** Vibration velocity in the Y direction of the field monitoring point. **f** Vibration velocity in the Z direction of the field monitoring point

Conclusion

Taking the Hongshi road tunnel crossing the Metro Line 5 section tunnel as the research object, the paper adopts studies the influence of the maximum section charge during blasting excavation on the lower section of Metro Line 5 through numerical simulation calculation through ANSYS/LS-DYNA, a

finite element calculation software. The conclusions are as follows:

- (1) When the tunnel is excavated by the four-step method of “three steps + invert” with the charge of each excavation step at 56.8 kg, 40.2 kg, 37.1 kg, and 21.6 kg

Table 5 Comparison of numerical simulation results with field measurement results

Maximum section charge/ kg	Maximum vibration speed in the X direction/(cm/s)		Maximum vibration speed in the Y direction/(cm/s)		Maximum vibration speed in the Z direction/(cm/s)	
	Numerical simulation	Field measurement	Numerical simulation	Field measurement	Numerical simulation	Field measurement
4.8	0.419	0.3309	0.723	0.675	0.395	0.5658
3.6	0.488	0.361	0.406	0.3487	0.313	0.3081
3.0	0.600	0.7947	0.825	0.9676	0.272	0.2325
2.0	0.655	0.837	0.337	0.4367	0.267	0.3415

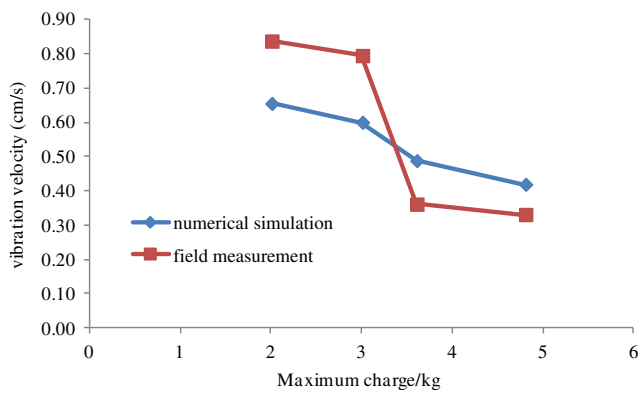


Fig. 19 Comparison of blasting vibration velocity in the X direction

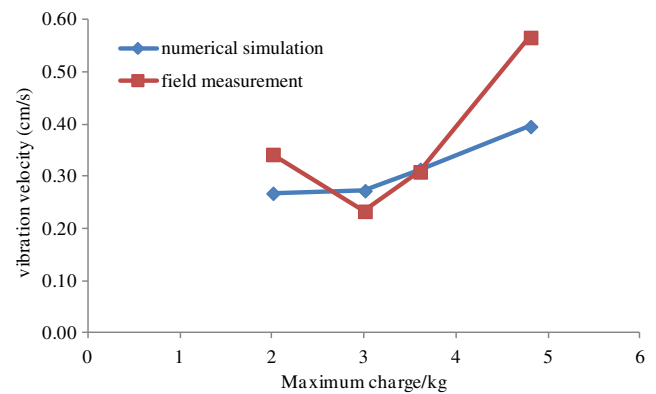


Fig. 21 Comparison of blasting vibration velocity in the Z direction

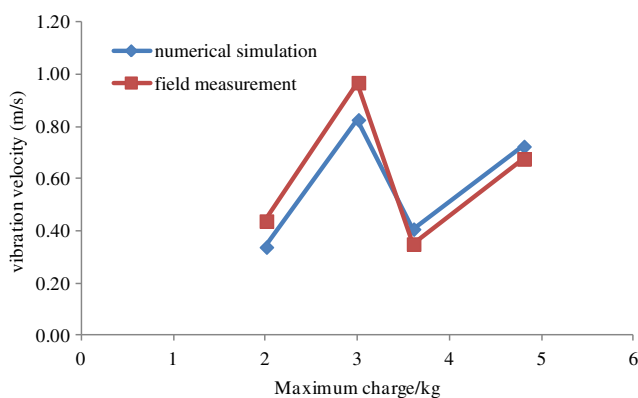


Fig. 20 Comparison of blasting vibration velocity in the Y direction

respectively, the vibration velocity of the control measuring point is less than 1.5 cm/s, meeting the design requirements.

- (2) The simulation results are basically consistent with the field measurement results. The vibration velocity in the tunnel of the existing Metro Line 5 below mainly occurs in the horizontal direction, while the vertical velocity is relatively smaller. In the blasting construction of the upper and middle stages, the blasting charge can be increased to speed up the construction progress.
- (3) When blasting the section of Hongshi road tunnel across the track line 5, the monitoring data should be fed back in time, and the blasting parameters should be dynamically corrected to ensure the vibration speed of the lining structure in Metro Line 5 section meet the design requirements so that the lining structure in the section of Metro Line 5 is safe and stable.

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