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Research Article

Influence of Blasting at Tunnel Face on an Existing Adjacent Tunnel with Oblique Cross Angle and Small Clear Spacing

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Abstract

The influence of blasting at a new tunnel face can directly influence the existing adjacent tunnel, especially for cross tunnels with a small clear spacing. To analyze the blasting vibration on the cross tunnels, this study took the cross tunnels in Lanzhou City, Gansu Province as the research background. These cross tunnels have an oblique cross angle and a small clear spacing of 1.365 m. First, blasting vibration on the existing tunnel was recorded in field tests. Second, the blast pattern and the resulting vibrations were simulated by software FLAC3d, and the simulation was verified by the recorded data in field tests. Finally, based on the peak particle velocity (PPV) on the lining area, the existing tunnel was divided into three sections, namely, the serious influence zone, slight influence zone, and no influence zone. Results demonstrate that the PPV induced by upper bench blasting is greater than that induced by the lower. The serious influence zone and slight influence zone of the existing tunnel are 9 m, 9–16 m from the intersection point, respectively. Meanwhile, the no influence zone is beyond 16 m from the intersection. When the blasting at the new tunnel face is 12 m in front of the cross-section and 10 m behind it, the PPV is relatively large, thus indicating that the blasting should be strictly controlled in that place. This study can effectively ensure the safety of existing structures and provide a reference for similar cross tunnels.

Keywords: Cross tunnel, Blasting vibration, Peak particle velocity, Blasting influence zone

1. Introduction

With the advantage of working, living, and education, a growing number of people are moving to big cities [1-4]. In turn, the rapid population growth in cities is increasing the need for infrastructure and transportation. Underground space is continuously being developed, and the utilization of underground space in the urban areas has improved. Inevitably, a large number of adjacent underground projects have been spearheaded. Therefore, researchers must examine the complex interaction between existing tunnels and new tunnels.

The drilling and blasting method [5] may be the most common and efficient tunneling approach in hard rock areas. During drilling and blasting, the vibration produced by blasting at the new tunnel face and the damage zone caused by excavation not only affects the safety of the new tunnel but also influences the safety of the existing adjacent structure. Hence, disruptions in the structural safety will endanger the transportation of existing tunnels [6]. Through field tests and numerical simulation, many scholars have studied the blasting-induced vibration on adjacents tunnel and assessed the safety of the tunnel lining.

Although several scholars [2, 4, 6-10] focus on the blasting-induced vibration on existing nearby tunnels, the most tunnels are perpendicular to new tunnels. The clear spacing distance between tunnels is always greater than 5 m, and the rock mass classification is always as good as grade III. Moreover, research on the vibration of cross tunnels is lacking, especially on cross tunnels with an oblique cross angle and a small clear spacing.

Therefore, this study takes practical cross tunnels in Gansu Province, China as the research background. The cross tunnels are located in Anning District, Lanzhou City, Gansu Province. The upper new tunnel is the Beihuan tunnel which is a part of the Zhong Cuan inter-city railway, and the lower existing tunnel is the Red Peak tunnel, which is on the right line of Lanzhou transfer hub. The new tunnel crosses with the existing tunnel at an oblique angle of 43.287°. As the minimum soil thickness is only 1.365 m, which is far less than half of the excavation diameter, the drilling blast at the new tunnel has large affection on the existing tunnel. Therefore, this research must monitor the vibration in the existing tunnel, investigate the influence of the blast on structure safety, and finally limit the damage to the existing tunnel lining. Using field tests and numerical simulation, the PPV induced by blasting at the new tunnel face is recorded and simulated. The PPV is used to analyze the influence of blasting on the vibration of the crossing tunnels. With the PPV on the lining area, the existing tunnel can be divided into three sections, namely, a serious influence zone, a slight influence zone, and a no influence zone. The research results can effectively ensure the safety of existing structures and provide a reference for similar cross tunnel projects.

2. State of the art

The existing tunnel is hugely affected by nearby construction activities, especially the explosion at the new tunnel face. The vibration caused by blasting may damage the lining of adjacent tunnels. Hence, the blasting-induced vibration on the existing tunnel must be examined to manage such damage. Li et al. [11] discussed the influence of the blasting at the subway

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tunnel on the nearby civil air defense engineering using field tests and numerical simulation. Meanwhile, Reza [12] took the construction process of the Gotvand Dam in Iran as background. In addition, Reza found that rock types, blasting plans, and blasting parameters affect the vibration of nearby buildings and structures. In different directions, the impact of blasting vibration is different. Therefore, based on the PPV in a merged transition section, Feng [7] found that the PPV in front of the blasting face is greater than that behind the blasting face. The PPV on the existing tunnel should be less than 10 cm/s. In another study, Li et al. [13] used an actual tunnel project to analyze the impact of blasting vibration on the dynamic damage of the rear shotcrete and calculated the minimum safety distance between shotcrete and blasting positions.

Although many scholars use the PPV to analyze the dynamic response of cross tunnels, the PPV on the existing tunnel in field tests is difficult to obtain, especially for the existing tunnels with heavy traffic. Therefore, Xian [14] analyzed the cross tunnels in Longquan County, Zhejiang Province through numerical simulation. The new tunnel intersects the existing tunnel at a small angle, and the blasting at the new tunnel affects the vibration of the existing tunnel. Therefore, Qin [15] took the blasting excavation of a large-section tunnel in Chongqing as background, used ANSYS/LS-DYNA to simulate the blasting process, and obtained the PPV of adjacent tunnels. The critical PPV was defined as 10 cm/s, which was used to determine the maximum explosive charge. Taking the Croix-Rousse tunnel project in Lyon, France as background, Dang et al. [16] predicted the existing structural damage caused by blasting vibration. Meanwhile, Li et al. [11] studied the effect of blasting direction on the PPV in adjacent existing tunnels through physical model tests. They found that the blasting at the new tunnel can damage the rock between the blasting hole and the existing tunnel. Then, the process speeds up the cracks penetrating and damaging the existing tunnel lining. In another research, a high-precision seismic monitoring system was used to compare the difference between stress-releasing blasting and conventional blasting [18]. The conventional blasting damage area was found to be located at 3.6 m in front of the tunnel face.

Furthermore, the impact of the blasting vibration must be reduced, and the impact area of the blasting vibration must be divided. Hakan et al. [5] established the relationship between blasting and PPV in discontinuous structural surfaces based on field tests of a quarry in Turkey (Eskisehir). In addition, the parameters of the PPV prediction model proposed by Nicholls et al. [19] were modified so that the influence of the discontinuous structure surface can be considered. Another related study is that of Sharafat et al. [17], who investigated the drilling and blasting construction of parallel small-pitch tunnels in the Neelum Jhelum hydropower development project. The research found that PPV field tests can effectively control the amount of blasting charge and reduce blasting damage to the surrounding rock. Besides the safety of the nearby existing tunnels, Yao [20] discussed the blasting vibration effect on the buried pipeline. To get the vibration of the existing structure in time, Gómez [21] carried out the structural health monitoring with distributed optical fiber sensors of tunnel lining.

Above all, field experiments and numerical simulations are the main methods to analyze the impact of blasting at the tunnel face on the rock and nearby existing structures. However, the influence of blasting on cross tunnels with an oblique cross angle and an ultra-small clear spacing is still unclear due to the difficulty in conducting field testing in the existing tunnels. This study takes two actual cross tunnel projects in Anning District, Lanzhou City, Gansu Province as the background. With both the PPV in the field experiments and the blasting simulations, this study analyzes the impact of blasting vibration on the cross tunnels.

The rest of this study is organized as follows. In the third section, the PPV on the existing tunnel lining was monitored in field tests, and the dynamic response of both cross tunnels induced by blasting at the new tunnel was simulated. In the fourth section, combined with the field tests and blasting numerical simulation, the PPV distribution in the existing tunnel lining and the influence zone of existing tunnels have been found. The last section summarizes the full text and provides relevant conclusions.

3. Methodology

This study takes the actual cross tunnels in Lanzhou City, Gansu Province as the research background and combines blasting field tests and simulation to analyze the blasting vibration in cross tunnels. The cross tunnels are located in Anning District, Lanzhou City, Gansu Province. The upper new tunnel is the Beihuan tunnel, which is a part of the Zhong Cuan inter-city railway, and the lower existing tunnel is the Red Peak tunnel, which is on the right line of the Lanzhou transfer hub. The new tunnel crosses with the existing tunnel at an oblique angle of 43.287°. In addition, the mileage at the cross point is HKO+875 in the new tunnel and HDYK61+888 in the existing tunnel. The rock is mudstone intercalated by sandstone. As the minimum soil thickness is only 1.365 m, which is far less than half the excavation diameter, the drilling blast at the new tunnel face may have a large affection on the existing tunnel. Therefore, the blasting vibration in the existing tunnel and the safety of the existing tunnel lining must be analyzed.

3.1 Vibration experiment in the field

3.1.1 Monitor equipment

As shown in Fig. 1a, the particle vibration velocity was monitored by the TC-4850 blasting vibration instrument in the field tests. The TC-4850 was produced by Zhongke (Chengdu) Instruments. The measuring range of TC-4850 is within 10 V. The minimum triggering velocity is 0.05 cm/s, and the triggering style is a continued trigger. The recording time can last 2 seconds.

The TCS-B3 velocity sensor was in charge of capturing the blast signal. The TCS-B3 can monitor the velocity in X, Y, and Z directions instantaneously. Its response range is 1–500 Hz, and its sensitivity is within 28 V/m/s. Furthermore, gypsum was used as the bonding and coupling medium in the sensor site. As shown in Fig. 1b, within a coordinate, the Z direction was regulated as the radical direction, the X direction was the longitudinal direction, and the Y direction was the tangent direction.

3.1.2 Monitor plan

Different countries have different PPV standards. For instance, the critical PPV is 5–10 cm/s in Europe, 30 cm/s in Russia, and 50 cm/s in the United States. These critical PPVs are determined by the building protection level and the tolerance of residents to vibration. Jan Fehler et al. [6] posited that the critical PPV for old and vulnerable buildings should be limited to 3 mm/s.

(a) (b)

Fig. 1. The equipment for monitoring vibration. (a) TC-4850 for receiving electrical signals from sensors. (b) Installation of the TCS-B3 sensor

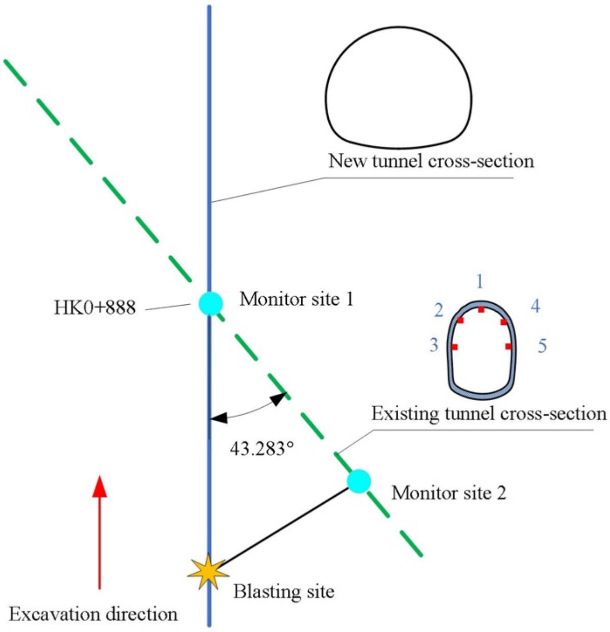


Fig. 2. Experimental results on the GN extended benchmark networks

Cross tunnels have a small distance between each other. The blasting point of the new tunnel is relatively close to the lining of the existing tunnel. Hence, the critical PPV must be further limited. At the same time, the existing tunnel is a new railway tunnel that has just been put into operation for less than one year. Above all, the critical PPV standard can be appropriately increased. Kim et al. [7] asserted that blasting construction brings about great noise and vibration problems. However, reducing the vibration may require reducing the amount of charge and short blasting footage, which will increase the construction period, the blasting cost, and the damage to the existing tunnel lining.

Based on the situation condition, the critical PPV is considered as 7 cm/s. Two monitory sections were placed on the existing tunnel lining. The detailed layout of the monitoring point and section is shown in Fig. 2.

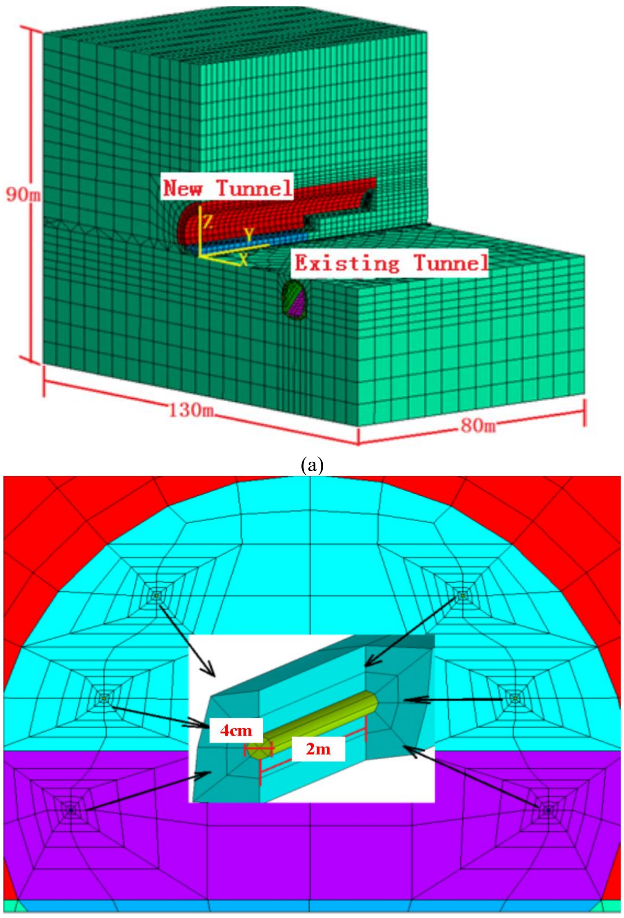
The first monitoring section was placed at cross point 1 (HDYK61+888 in the Red Peak tunnel and HDYK61+888 in the existing tunnel), which was also the key monitoring section. The second monitoring section was a dynamic section, which was changed with the blasting point at the new tunnel.

As shown in Fig. 2, the line between the blasting point and the second section was always perpendicular to the existing tunnel axial.

3.2 Blasting Simulation

3.2.1 Blasting Model

On the basis of the situation geological data and space relationship between two tunnels in Fig. 2, the 3D model was constructed, as presented in Fig. 3a. The horizontal direction is the x-direction, the vertical direction is the z-direction, the longitudinal direction is the y-direction, and the coordinate corresponds with the counterpart of the sensor. The detailed size is shown in Fig. 3a. The drill hole in the model is displayed in Fig. 3b, The model has six drill holes, including four on the up bench and two on the down bench. The diameter of the hole is 4 cm, and the depth is 2 m.



(a)

(b)

Fig. 3. The finite element model for blasting simulation in software ANSYS. (a) 3D numerical model of cross tunnels. (b) Zoom of the 3D simulation model and the arrangement of blasting holes

The surrounding rock is mudstone, whose bearing capacity is 400 kPa. The parameters are selected on the basis of the design specification of the railway tunnel, which is displayed in Table 1.

Table 1. Physical-mechanical parameters of material in model

Material	Shear module G /(GPa)	Bulk module K /(GPa)	Natural unit weight γ /($kN\cdot m^3$)	Cohesion c /(MPa)	Friction angle φ /(cm/s)
Rock	1.54	3.33	21.3	0.45	33
C25 concrete	9.35	14.20	23	-	-
C20 concrete	11.38	17.28	23	-	-
C40 reinforced concrete	14.23	21.60	25	-	-
Reinforcement	1.54	3.33	22	1.45	-

3.2.2 Blasting load
A general international plus model was selected as the blast load. The function is shown as Equations 1 and Equation 2 [19], where ρ_0 is the explosive density ($\rho_0 = M / V$, M is the explosive quantity per drilling hole, V is the volume per blast hole). Moreover, D is the detonation velocity, R_c and R_b are the radii of the explosive tube and the blast hole, respectively, and η is the amplification constant as blast product impact on hole wall, η=8–10.

$$P(t) = P_b f(t) \quad (1)$$

P_b is the initial peak value. P_b can be calculated by the following formula:

$$P_b = \frac{1}{8}\rho_0 D^2 \left(\frac{R_c}{R_b}\right)^6 \eta \quad (2)$$

$f(t)$ is an exponential function considered a plus load, and the expression is as follows:

$$f(t) = P_0(e^{-nwt\sqrt{2}} - e^{-mwt\sqrt{2}}) \quad (3)$$

where n and m are dimensionless and are damp parameters depending on the distance. Their function controls the location and shape of the blasting load. In addition, P_0 is a constant, which makes $f(t_R) = 1$. $t = t_R$ is the start time of blast load, w is a function of wave velocity c_p , and a is the diameter of the blasting hole. t_R is the function of n, m, and w.

$$w = \frac{2\sqrt{2c_p}}{3a} \quad (4)$$

$$t_R = \frac{\sqrt{2}\ln(n/m)}{(n-m)w} \quad (5)$$

The expression of P_0 is

$$P_0 = 1/(e^{-nwt_R\sqrt{2}} - e^{-mwt_R\sqrt{2}}) \quad (6)$$

The n and m are first assumed. Then, the adjusted wave is calculated with the measure data closely by calibrating n and m. The load time is 10 ms, the unload time is 90 ms, and the total affection time is 100 ms. Then, the n and m for the blasting at the Beihuan tunnel are shown in Table 2.

Table 2. Physical-mechanical parameters of material in model

Blast item	Detonation velocity / (km/s)	Explosive tube radius /(m)	Blast hole radius /(m)	*m*	*n*	Explosive density (kg/cm³)
Upper blast	2	0.016	0.02	0.031	0.052	0.433
Lower blast	2	0.016	0.02	0.031	0.052	0.257

The longitude wave velocity of surrounding rock is calculated as [11]:

$$c_p = \sqrt{\frac{K + 4/3G}{\rho}} \quad (7)$$

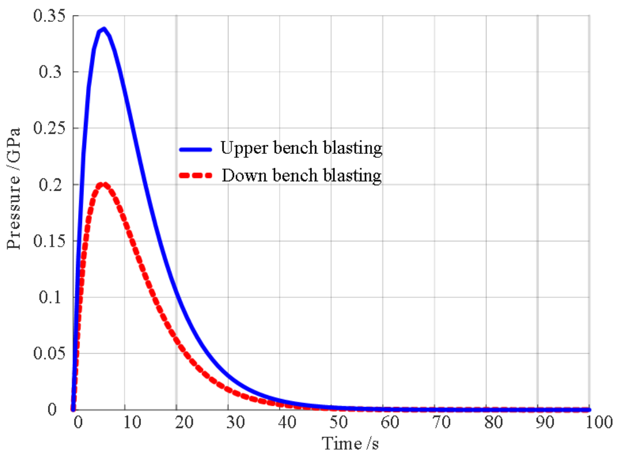


Fig. 4 Time-history curves of explosive load for upper and lower benching blast

where K is the bulk module, G is the shear module and ρ is the surrounding rock density, calculated through Formulas 3–8. The final blast load-time curve of the up bench blast and the down bench blast is displayed in Fig. 4, respectively. As shown in Fig. 4, the load time is 10 ms, and the unload time is 90 ms, thus satisfying the need feature of blast load. The blast load of the upper bench blast is larger than the counterpart of the lower bench blast.

4. Result Analysis and Discussion

4.1 Field experiments
Both field experiments and references find that the maximum PPV on the existing tunnel lining is at the upper bench blast and the lower bench blast. With consideration for safety and simplification, the PPV is synthetic velocity. The velocity of the existing tunnel when blasting at cross point HKO+875 is listed in Table 1. As indicated in Table 3, the maximum PPV within the existing tunnel is 6.55cm/s, which is less than 7 cm/s, thus entailing that the existing tunnel is safe.

Table 3. The measured PPV (cm/s) for the existing tunnel

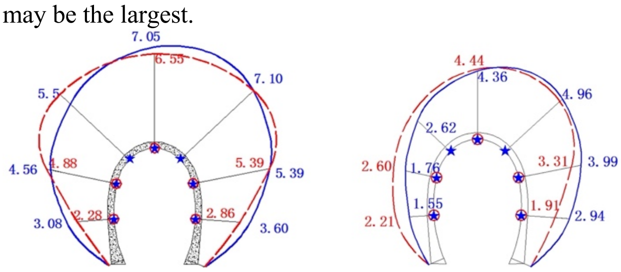
Location	Upper bench blast	Lower bench blast
Left middle wall	2.28	2.21
Left wall crown	4.88	2.60
Apex of arch	6.55	4.44
Right wall crown	5.39	3.31
Right middle wall	2.86	1.91

The maximum PPV was induced by blasting at the upper bench, and all the PPV induced by blasting at the upper bench is bigger than that induced by blasting at the lower bench.

4.2 Blasting Simulation

4.2.1 PPV induced by blasting at the intersection mileage in the new tunnel
The closer the distance is from the blasting location in the new tunnel, the stronger the PPV is produced in the existing tunnel. When the blasting location is at HKO+875 in the new tunnel,

the produced PPVs at HDYK61+888 in the existing tunnel may be the largest.



(a) (b)

Fig. 5 PPV distribution at the cross-section HDYK61+888 in the existing tunnel (a) PPV distribution was induced by the blasting at the upper bench in the new tunnel. (b) PPV distribution was induced by the blasting at the lower bench in the new tunnel.

The following are shown in Fig. 5:

(1) The PPV produced in the simulation is close to the PPV in the field tests. The variations between the field and simulation results are within an acceptable range. The average deviation is 21.73%, and the minimum is only 1.8%. The trench of both PPVs is similar, thus validating the reliability of the blasting simulation.

(2) The PPV at the foot is the smallest, and the PPV at the arch is the highest. This outcome shows that the closer the distance is to the blasting location in the new tunnel, the greater the PPV of the existing tunnel will be.

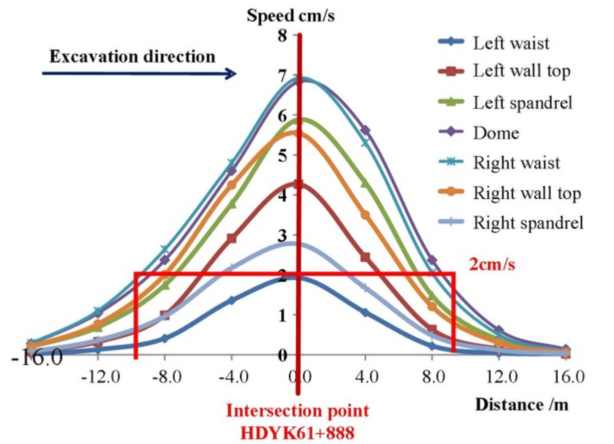
The PPV also changes along the existing tunnel. The changes of PPV within 16 m from the cross mileage HDYK61+888 are shown in Fig. 6. The horizontal direction is the distance from the cross point, and the advance directive is the positive direction

The following are shown in Fig. 6:

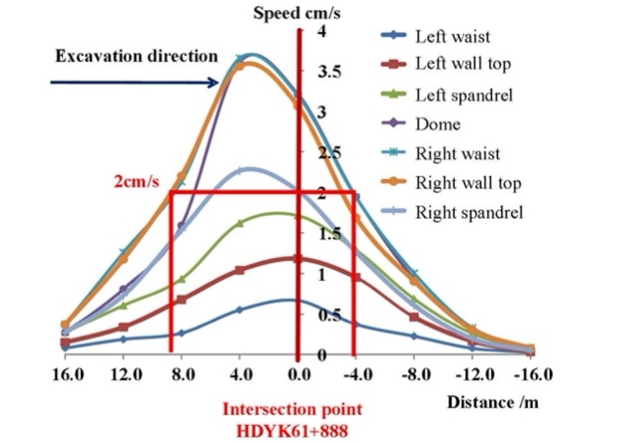
1) The PPV induced by blasting at the upper bench is larger than that induced by blasting at the lower bench. The closer the blast point is, the larger the induced PPV will be.

2) The serious influence zone is around 9 m from the cross-section HDYK61+888. The little influence zone is around 9–16 m, and the no influence zone is out of 16 m.

3) The PPV distribution induced by blasting at the lower bench is not uniform. The length of the influence zone after the blasting location is double the length before that.



(a)



(b)

Fig. 6 Longitudinal variation of PPV within the existing tunnel. (a) Longitudinal variations of PPV were induced by upper bench blasting at cross mileage. (b) Longitudinal variation of PPV were induced by lower bench blasting at cross mileage.

4.2.2 PPV induced by blasting at different mileages in the new tunnel

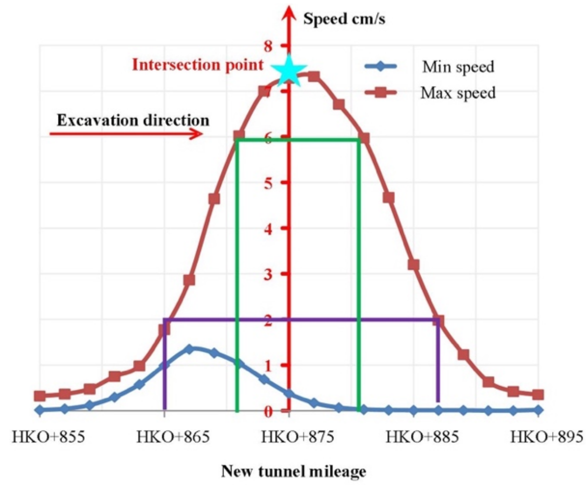
The blasting location is changed within 20 m from cross mileage HKO+875 in the new tunnel, and the PPVs produced at HDYK61+888 in the existing tunnel are simulated. Under different blasting mileages, the maximum and minimum PPVs induced by the upper and lower bench blasting are shown in Fig. 7. The following are shown in Fig. 7:

1) Under the same blasting mileage, the maximum PPV generated by the upper bench blasting is larger than that generated by the lower bench blasting. The closer blasting mileage is to the cross-section, the greater the maximum PPV is produced in the existing tunnel.

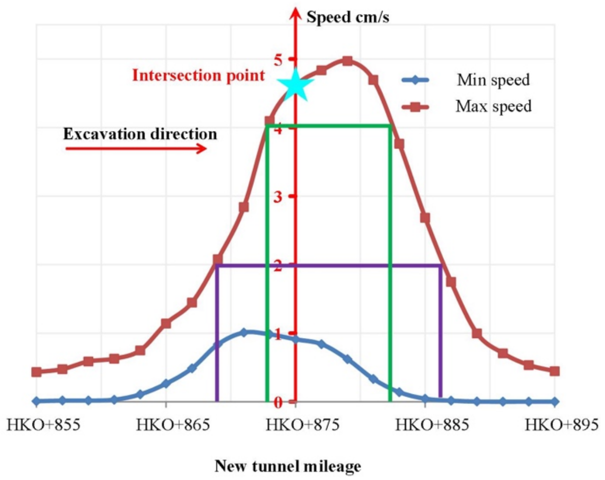
2) The strong blasting mileage is set as PPV bigger than 2 cm/s, and other areas have weak blasting. The strong blasting mileage is located 12 m in front of the HKO+875 and 10 m behind. Other areas are weak blasting mileage.

3) The range of the strong influence zone in front of the cross-section is longer than the rear, and the maximum PPV also occurs in front of HKO+875, especially during the lower bench blasting. The length of the strong influence zone behind the HKO+875 is only half of the front influence range.

4) Blasting 4 m before and 2 m behind the HKO+875 in the new tunnel, the PPV produced in the existing tunnel is the largest, and the PPV is evenly distributed. This outcome shows that within this range, the blasting should be strictly controlled to reduce the impact on the existing tunnel structure.



(a)



(b)

Fig. 7 PPV induced by blasting at different locations in the new tunnel. (a) PPV were induced by upper bench blasting. (b) PPV were induced by lower bench blasting.

5. Conclusions

To analyze the structural safety of cross tunnels with an ultra-small clear distance and an oblique crossing accurately, this study has taken the actual cross tunnels in Lanzhou City, Gansu Province as the research background and combined field measurement and simulation to analyze the dynamic response of the existing tunnel under different blasting sites in the new tunnel. The following conclusions can be drawn:

(1) The difference between the PPV simulated by the FLAC3D and the PPV in field tests is small, and the minimum deviation is 1.8%. This finding shows that the blasting simulations are reliable.

(2) The PPV induced by the lower bench blasting is weaker than that induced by the upper bench blasting. The impact range of blasting on the upper bench is larger than that of blasting on the lower bench. On the basis of the PPV, the existing tunnel has been divided into three sections, namely, a serious influence zone, a slight influence zone, and a no influence zone. The serious influence zone and the slight influence zone of the existing tunnel are 9 m and 9–16 m from the cross-section, respectively, and the no influence zone is bigger than 16 m from the cross-section.

(3) When the blasting is carried out 12 m in front of the HKO+875 in the new tunnel and 10 m behind it, the PPV on the existing tunnel is relatively large. This finding shows that when the blasting is located near this area, the blasting should be strictly controlled to reduce the impact of the blasting construction of the new tunnel on the existing tunnel.

The results of this study can effectively ensure the safety of cross tunnels that have an ultra-fine spacing and an oblique angle. Moreover, these findings can provide a scientific basis for the optimization of blasting in new tunnels. However, given the lack of field PPV in the existing tunnels, the research results need to be verified. In future research, the PPV of existing tunnels with small spacing will be further collected to find the strong influence zone accurately and protect the existing tunnel better.

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