

# Study on the Dynamic Responses of Tunnel Linings with Small Net Distance Under Bias Pressures Caused by Blasting

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## Research Article

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# Abstract

The mutual influence of the parallel excavation of the tunnel can not be ignored. The control of the distance between the faces of the two tunnels is also a difficult point in the construction process. Taking the Nanshan Tunnel of Tieben Expressway in Liaoning Province as the background, the blasting simulation research was carried out under the conditions of different distances between the tunnel faces. Firstly, based on the field test data, the blasting conditions under different tunnel faces were simulated by numerical simulation. The research shows that: (1) The velocity effect of the preceding hole on the subsequent hole is embodied as: the smaller the distance between the face of the tunnel, the more obvious the velocity effect of the subsequent hole; the velocity effect of the subsequent hole on the preceding hole is mainly reflected in the change of the velocity propagation process; (2) The influence of the leading hole on the displacement of the trailing hole is mainly reflected in the following: the greater the distance between the tunnel faces, the later the peak appears, and the smaller the displacement peak; the influence of the trailing hole on the displacement of the leading hole is mainly reflected in the following: the greater the distance between the tunnel faces, the smaller the peak displacement.

## 1 Introduction

In recent years, the mileage of highways in our country has increased by leaps and bounds, providing people with a lot of convenience. However, during the construction of expressways, mountain tunnels are often encountered. Among them, small-distance tunnels are the difficulties in engineering practice. How to control construction conditions to ensure engineering safety is a key link in the actual construction process. In the process of parallel excavation of small clear distance tunnels, damage to the lining will often occur, which will adversely affect the construction and safety of the tunnel. In this paper, relying on the Nanshan Tunnel in the Tieben Expressway in Liaoning Province, it used finite element software to simulate its blasting and excavation process. The field measurement test data was compared with the simulated data to verify the rationality of the model. Furthermore, based on this model, the influence of the clear distance of the tunnel on the dynamic response of the lining during the tunnel blasting process was studied, and a conclusion was drawn to guide the safe construction of the site.

For the dynamic response of tunnel lining under the action of blasting, domestic scholars and foreign scholars have conducted certain researches. A.K.Verma et al. (2017) have investigated the response of a underground metro tunnel subjected dynamic loads including explosive capacity (30 kg TNT), ground characteristics, liner thickness and blast pressure characteristics. A three-dimensional explicit finite element method was used to analyze dynamic response and damage in twin tunnels of underground metro. M. Colombo et al. (2016) conducted a dynamic analysis on the background of the Brescia subway line in Italy, and evaluated the impact of the explosion source location on the dynamic response of the tunnel. To investigate the dynamic response of the primary lining structure under blasting loads, Hu et al. (2019) conducted a field test combined with numerical simulation on the new passenger line railway that traverses from Beijing to the Shenyang TJ-1 (Liaoning) Sanlengshan tunnel. Results show that the maximum stress of the tunnel primary-lining structure at the skew and vault in the X direction is greater

than at the haunch and spandrel. Tao et al. (2014) studied the influence of different confining pressure and surrounding rock types on the dynamic response of the tunnel under the blasting vibration load based on the finite element model of the tunnel. The results show that when the confining pressure increases, the maximum horizontal and vertical vibration speed, stress and displacement increase, and the horizontal vibration amplitude is smaller than the vertical vibration amplitude. Liu et al. (2020) used the basic finite element method and LS-DYNA software to establish a numerical model of the existing tunnel based on the Wuhan Huanglongshan Highway Tunnel in the background. The reliability and parameter selection of the model were verified according to the field monitoring data. The influence of the blasting of a new tunnel on the deformation, vibration velocity and stress of the existing tunnel was discussed. Duan et al. (2019) used Chongqing Gaojiu Lujiahua Cross Tunnel Project as a research background to evaluate the impact of blasting vibration of upper and lower span tunnels. Using the finite element method to simulate the construction and excavation process, the influence of the blasting of the No. 1 Gaojiu Road Tunnel on the left line of the Jiahua Tunnel below was analyzed. The actual measurement results show that in the small, clear-distance blasting excavation across the tunnel, the peak vibration velocity and peak acceleration at the vault of the second lining of the existing tunnel below are the largest. Shi et al. (2015) used blasting vibration testing instrument TC-4850, the vibration caused by blasting excavation in different region of Chongqing terminal connecting line tunnel was monitored and analyzed, and the vibration characteristics and attenuation law of different region in tunnel face were gained. Wang et al. (2011) studied the law of tunnel vibration speed based on the tunnel blasting vibration test of the Guiding Line Project of the Gaoqiao Bay Cross-sea Harbour Tunnel. The entrance section of a small spacing tunnel was chose as an example, Mo et al. (2013) adopted an explicit dynamic finite element model and Euler method to accurately simulate the blasting vibration process, and obtained the peak vibration velocity response of the tunnel. Based on the characteristics of the ultra-short-distance tunnel of the Nanjing Metro, Zhu et al. (2011) studied the peak distribution of the vibration velocity of the existing tunnel under different surrounding rock grades, and followed the law of ultra-small dynamic response. According to the blasting monitoring of the main tunnel at hidden digging section of Tuandao Second Road exiting ramp in Kiaochow Bay Cross-harbor Tunnel, Ding et al.(2011) showed the influence of vibration on the close-spaced main tunnel. For the Xinling highway tunnel project, Xue et al. (2019) comprehensively studied the influence of tunnel blasting excavation on the lining structure of adjacent tunnels. Bi et al. (2004) discussed the dynamic finite element method, blasting stress wave simulation, dynamic boundary conditions, etc. and analyzed the characteristics and influence of blasting vibration under different situations (such as different types of surrounding rock, different tunnel spacing, and different tunnel buried depths).

## 2 Project Overview And Test Situation

The Nanshan Tunnel is located at the junction of Tieling City and Fushun City, and is one of the key and difficult projects of the Tieben Project. The left line of the tunnel is 1075m long and the right line is 1210m long. All of them are grade Ⅱ and Ⅲ surrounding rocks. The overlying soil is relatively thin. The thickness of the overlying soil on the first tunnel (right tunnel) is 21m, and the thickness of the overlying

soil on the backward tunnel (left tunnel) is 9.9m, the tunnel spacing is about 18m. It is a shallow buried and biased small clear distance tunnel. The groundwater is extremely rich. The construction organization is difficult and the safety production risk is great. The small clear curve ultra-shallow buried biased section excavation technology and the new Austrian method of construction were adopted. The tunnel was excavated at the same time on the left and right lines and the length of the two tunnels differed by 30m. During the field test, the left tunnel had a footage of 220m and the right tunnel had a footage of 250m. The measurement content of the field test is the velocity generated on the lining of the tunnel and adjacent tunnels during blasting and excavation.

## 2.1 On-site vibration test program

In the field test, the INV software of Beijing Oriental Institute of Vibration and Noise was used to detect the speed and displacement of the lining during blasting and present it in the form of a curve through the software. Mainly collect data on the vault and waist. Test underwent hole located 190m and 190m from the working face of the position.

The field test situation is shown as in Fig. 1.

## 2.2 Field test results

The typical data waveform of the field test is shown in Fig. 2.

## 3 Numerical Simulation

### 3.1 Theoretical basis of numerical simulation

About underground chambers blasting impact load is determined, there is no a well-established theories and methods. According to literature (Wang et al. 2004), blasting load is a process of loading first and then unloading. Triangular load is used for blasting. The typical blasting vibration boost time is about 8-12 ms, and the unloading time is about 50-120 ms. In order to simplify the analysis process and reasonably reduce the calculation workload, this paper makes the following assumptions without loss of generality (Bao et al. 2008):

- Assuming that the blasting load is uniformly distributed on the periphery of the construction tunnel in the form of dynamic pressure, and the acting direction is the normal direction of the periphery.
- Assuming that the blasting load curve is a triangular wave, as shown in Figure 3,  $P_{\max}$  is the peak pressure on the wall of the blast hole, which is related to factors such as the type of explosive, the structure of the charge, and the nature of the surrounding rock. At present, there is no theoretical method to calculate its accurate value.  $P_{\max}$  is usually determined by the initial peak pressure of the shock wave and the initial peak pressure can be calculated by the following formula:

$$P_r = \frac{2\rho_r C_{er}}{\rho_r C_{er} + \rho_0 D} \cdot P_e \quad (1)$$

In the formula:  $P_r$  is the rock density,  $C_{er}$  is the longitudinal wave velocity of the rock weight,  $P_e$  is the explosive density,  $D$  is the explosive detonation velocity, and  $P_e$  is the detonation pressure of the explosive.

Blasting load theory and its determination: The loading time used in this paper is 10ms, and the unloading time is 50ms. The peak pressure of the blasting load is 100 MPa.

## 3.2 Finite element modeling

In this paper, ABAQUS software is used for numerical simulation, including three parts: surrounding rock of the mountain and the lining of the two tunnels on the left and right. Considering the accuracy and calculation time of the simulation results, the model chooses 100m×70m×500m (respectively the overall width, height, and length of the surrounding rock), and the top surface is curved to simulate the bias effect. In the initial model, the clear distance between the two tunnels is 18m, the tunnel lining thickness is 0.4m, the first tunnel (on the right) has a footage of 250m, and the latter tunnel (on the left) has a footage of 220m. The model is shown in the figure below:

### 3.2.1 Mechanical parameters of surrounding rock

It is generally believed that under impact load of concrete materials, when the load time is reduced from 100s to 0.03s, the strength and elastic modulus will increase by 30%~56% and 20%~5% respectively, and the strength of rock will also increase by 5~10 times (Bi et al. 2004). Taking this factor into account, this article assumes that the elastic modulus of the surrounding rock under impact load is increased to 5 times the original strength of the lining and the elastic modulus is increased by 50% and 25%, respectively.

**Table 1** Mechanical parameters of rocks and linings

Material name	Elastic modulus/ GPa	Poisson's ratio	Density/kg·m <sup>-3</sup>
Surrounding rock	5.0	0.30	2300
Lining	30.0	0.17	2400

Boundary condition processing: In order to eliminate the influence of the boundary on the simulation results, this paper adopts the viscoelastic boundary to deal with the boundary.

### 3.2.2 Research methods and content

First, according to the actual engineering situation, simulate the field test according to the distance between the left and right tunnel face during the field test (the initial simulation distance between the face faces is 30m), extract the test data corresponding to the field test, and compare the two, verify the correctness of the model, and then use this model as the basis to simulate the dynamic response of the lining under different distances between the tunnel faces of the first and subsequent tunnels. Along the excavation direction, the distance between the tunnel faces is 0m, 10m, 20m, 40m.

### 3.3 Comparative analysis

Comparing the test speed data with the simulated speed data, it is found that most of the simulated values are higher than the field measured data. After consideration and analysis, the error is mainly caused by factors such as gaps in the actual surrounding rock of the mountain being not considered in the simulation process. However, the higher value is basically within 10%, and the error is small and within the normal range. Therefore, it is believed that the model is basically in line with the actual situation. This model can be used as a basis for further research.

## 4 Research On The Case Of Different Distances Between The Tunnel Faces

### 4.1 Research object

Based on the model described in Chapter 2, we then study the dynamic response of the lining when the distance between the tunnel faces of the preceding and following tunnels is 0m, 10m, 20m, 30m, and 40m, including the vibration speed of the lining and the lining Displacement caused by the tunnel.

### 4.2 Speed influence research

After the blasting load is generated, the maximum speed of the lining at different times. First study the impact of the blasting of the back hole (right hole) on the blasting of this hole and adjacent tunnels.

**Table 2** Effect of the blasting of the trailing hole (right hole) on the speed of the preceding hole (left hole)

time(s)	The speed of the advance hole at different locations (cm/s)				
	0m	10m	20m	30m	40m
0.018	1.25	2.35	1.86	2.74	1.64
0.022	2.02	3.16	2.72	3.57	3.67
0.028	2.78	2.67	2.98	2.55	2.99
0.035	4.97	5.29	5.48	5.70	5.71
0.043	3.42	3.85	4.30	4.45	4.69
0.053	3.50	3.65	4.23	4.53	5.61
0.063	2.21	2.42	2.57	3.03	3.19
0.073	1.52	2.44	2.64	2.84	3.25
0.083	3.51	3.66	3.95	4.16	4.29
0.093	2.13	2.52	2.78	2.44	2.90
0.103	2.03	2.48	2.82	2.33	2.76
0.113	1.37	1.42	1.55	2.01	2.11
0.123	1.20	1.27	1.43	1.33	1.80
0.133	1.20	1.39	1.43	1.53	1.61
0.143	0.96	0.98	0.97	0.98	1.23

**Table 3** Effect of blasting on the speed of the hole in the back hole (right hole)

time/s	0.0028	0.0056	0.0071	0.0089	0.012	0.0176	0.022	0.276	0.345
speed cm/s	1.406	8.079	14.30	17.22	17.40	11.43	15.72	7.137	4.553
time/s	0.531	0.731	0.831	0.931	0.531	0.631	0.731	0.831	0.931
speed cm/s	6.112	2.884	2.504	2.195	2.802	3.160	2.443	1.390	1.810

From the above data, it can be seen that the impact of blasting on the cave is much higher than that of adjacent caves. The vibration velocity at multiple points in time has been greater than 10cm/s, which is higher than the specified critical velocity, and the cloud diagram shows that after the blasting load was applied, The maximum velocity of this hole is always near the blasting position, which conforms to the

objective law of the maximum vibration dynamic response near the blasting position. In view of this, the study of the vibration velocity in this paper mainly focuses on the influence of blasting on adjacent tunnels.

It can be seen from the velocity curve that after the blasting load is applied, the velocity curve first rose in a wave form, the tunnels with different tunnel face spacings all reach the peak velocity at 0.0345s, and then continue to gradually decrease in the form of waves. After 0.0831s, the speed change range of different tunnel face spacings gradually tends to be the same. The peak speed tends to increase with the increase of the distance between the tunnel faces. When the distance between the tunnel faces is 40, the peak speed is the largest, which is 5.709cm/s. When the distance between the tunnel faces is 0, the peak speed is the smallest. The value is 4.973cm/s, which is less than the critical speed, indicating a safe state.

After the blasting load of the trailing tunnel is applied, the maximum velocity cloud diagram of the advance tunnel lining is shown in Fig. 7 under the conditions of different distances between the tunnel faces.

It can be seen from Fig. 7 that the position at the time of maximum speed appears in the arch waist part of the tunnel on the explosion-incoming side, and this part needs to be reinforced during the construction process.

It can be seen from the velocity graph that when the blasting load is applied to the advance hole, the peak velocity of the lining of the advance hole (left hole) gradually decreases with the increase of the distance between the tunnel faces, with the increase of the distance between the tunnel faces, the speed change amplitude gradually Decrease, and finally tend to be the same, as the distance between the tunnel faces increases, the time when the blasting affects the back hole (left hole) gradually lags: when the lining speed first appears 1.5cm/s, the time for the tunnel face is 0m is about 0.0175s, the time for the tunnel face is 10m is about 0.022s, the time for the tunnel face is 20m is 0.0276s, the time for the tunnel face is 30m is 0.0345s, and the time for the tunnel face is 40m is 0.0431s.

After the blasting load of the advance hole is applied, the maximum speed cloud diagram of the back hole lining under different distances between tunnel faces conditions is as follows:

It can be seen from the cloud diagram that the maximum velocity effect of the blasting of the leading hole (right hole) on the trailing hole (left hole) is mainly concentrated on the lining near the tunnel face, and this part needs to be reinforced during the construction process.

## 4.3 Research on the influence of displacement

We have studied the displacements in the three directions of X (radial), Y (circular), and Z (axial) and found that the displacement in the Z direction has a similar change trend with the combined displacement. The displacement trend in the X and Y directions is quite different from the combined displacement trend, and the change in the whole process is very small, so here we study the displacement part of the lining, we only study the displacement U3 in the Z direction.

The following is the displacement U3 of the tunnel lining in the Z direction.

The influence of the blasting of the trailing hole on the Z-direction displacement of the leading hole: As can be seen from the curve in the figure, in the whole process, under different working conditions, the displacement of the lining Z-direction shows a similar trend over time in the case of. Taking the peak time 0.0431s as the demarcation point, the maximum displacement in the first half is increased at a larger rate, and after reaching the peak, the second half is decreased again at a smaller rate. After 0.0732s, the displacement change gradually stabilized. During the blasting process, the maximum displacement showed a trend of gradually decreasing with the increase of the distance between the tunnel faces. Among them, when the distance between the tunnel faces was 0, the maximum displacement was 0.441mm, and when the distance between the tunnel faces was 40, the maximum displacement was 0.361mm. But overall, the scope of change is relatively small.

The cloud diagram of the maximum displacement of the lining of the advance tunnel under different distances between the tunnel faces after the blasting load is applied is as follows:

It can be seen from the above cloud diagram that the maximum displacement effect of the blasting of the trailing hole (left hole) on the leading hole (right hole) appears on the front hole's front blast side arch waist, and with the change of the distance between the tunnel faces, this location has always been near the same location as the rear tunnel. During the construction process, this location should be reinforced.

It can be seen from the curve in the figure that as the distance between the tunnel faces increases, the maximum displacement of the tunnel lining gradually decreases, and the time for the maximum displacement gradually goes back, and as the distance between the tunnel faces increases, before reaching the peak of displacement, the rate of change of the ascending section gradually decreases, and after reaching the peak, the rate of change of the descending section is closer. When the distance between the tunnel faces is different and the displacement is about 0.09s, the changes begin to tend to be the same.

After the blasting load of the advance tunnel is applied, the maximum displacement cloud diagram of the back tunnel lining is as follows:

From this series of cloud diagrams, it can be seen that the largest displacement impact of the front hole (right hole) blasting on the back hole (left hole) is concentrated in the vicinity of the tunnel face of the back hole, including the arch and vault on the side of the explosion. During the construction process, this part should be reinforced.

## 5 Conclusion

Through the research of this article, we draw the following conclusions: In terms of speed, after the blasting load is generated, the speed on the lining first increases with a higher growth rate, and after reaching the peak, it decreases with a slightly smaller speed, and then the speed stabilizes. Specifically embodied as:

(1) When the blasting load is located in the leading hole (right hole), as the distance between the tunnel faces increases, the impact of the blasting load on the peak velocity of the leading hole (left hole) lining continues to decrease. The position at the time of maximum speed mainly appears in the arch waist part of the tunnel on the explosion side.

(2) When the blasting load is located in the back hole (left hole), as the distance between the tunnel faces increases, the impact of the blasting load on the peak velocity of the back hole (right hole) lining gradually increases. The location at the time of maximum speed mainly appears in the tunnel arch waist part on the explosion-incoming side, and the reinforcement should be emphasized during the construction process.

In terms of displacement, the maximum displacement value curve is similar to the velocity curve. After the blasting load is generated, the maximum displacement value on the lining first increases at a higher growth rate, and after reaching the peak, it decreases at a slightly smaller rate, then the maximum displacement value tends to stabilize. Specifically embodied as:

(1) The impact of the blasting of the backward hole (left hole) on the displacement of the preceding hole (right hole) is mainly concentrated on the peak value. The maximum lining displacement caused by blasting increases as the distance between the tunnel face increases, and the displacement gradually decreases. The areas with the largest displacements all appear on the arch waist of the front hole on the explosion side, and with the change of the distance between the tunnel faces, this position is always near the same position as the trailing hole. During the construction process, the location should be reinforced.

(2) The impact of the blasting of the leading hole (right hole) on the trailing hole (left hole) is embodied as follows: As the distance between the tunnel faces increases, the maximum displacement of the tunnel lining gradually decreases, and the time for the maximum displacement gradually goes back, and as the distance between the tunnel faces increases, the rate of change of the ascending section gradually decreases before reaching the peak of the displacement, and after reaching the peak, the rate of change of the descending section is closer.

# Declarations

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## Figures



Figure 1

Photo of field test

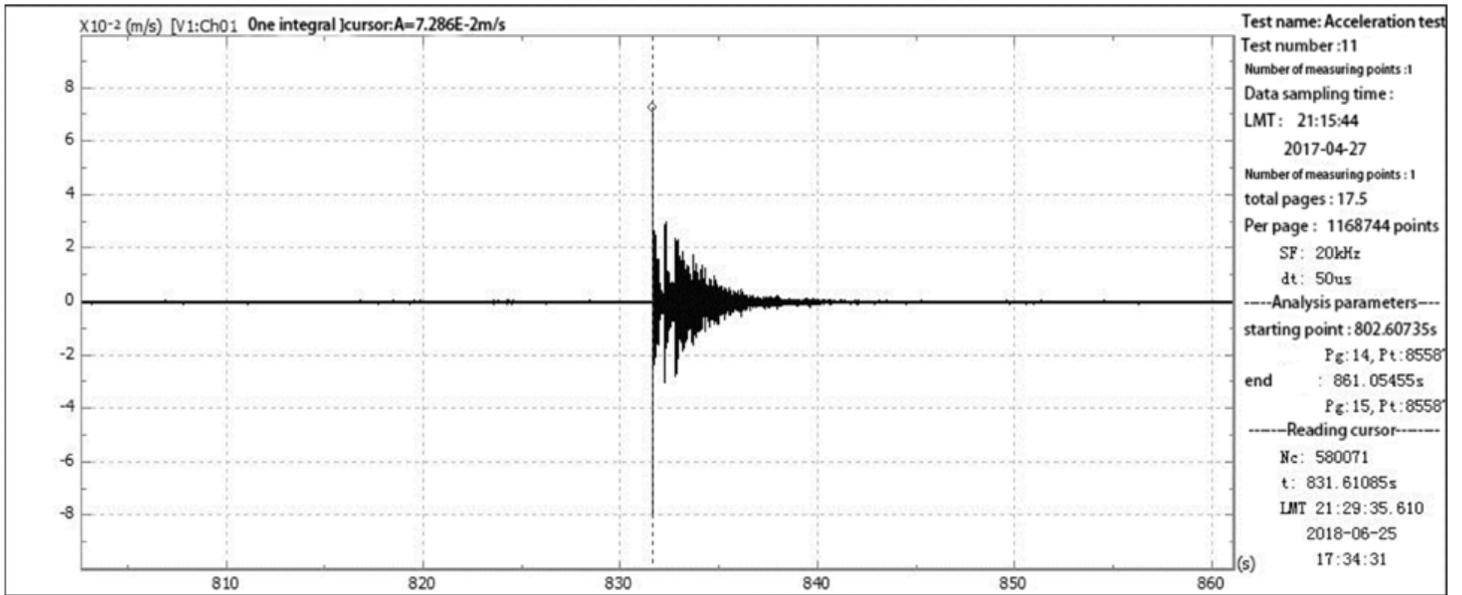


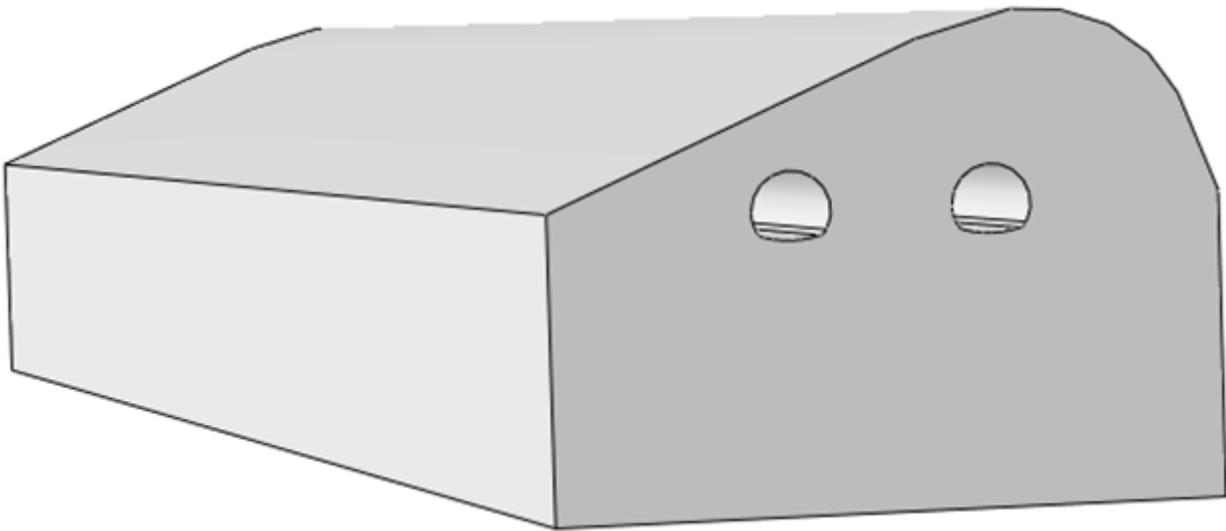
Figure 2

Field test speed icon



Figure 3

blasting load loading-unloading curve



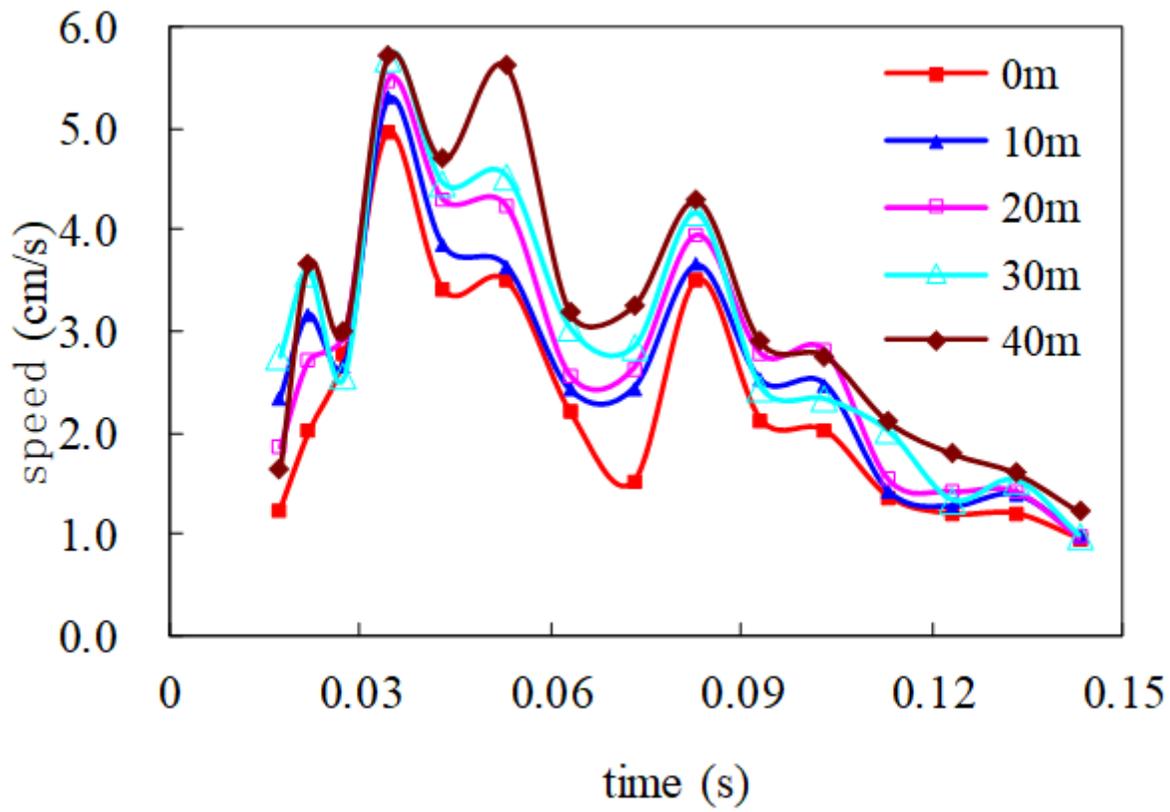
**Figure 4**

Mountain model



**Figure 5**

Tunnel lining model



**Figure 6**

Effect of the blasting of the trailing hole (left hole) on the speed of the preceding hole (right hole)



(a) When the distance between the tunnel faces is 0m



(b) When the distance between the tunnel faces is 10m



(c) When the distance between the tunnel faces is 20m



(d) When the distance between the tunnel faces is 30m



(e) When the distance between the tunnel faces is 40m

**Figure 7**

Maximum speed of the lining under different face spacing (Explosion side)

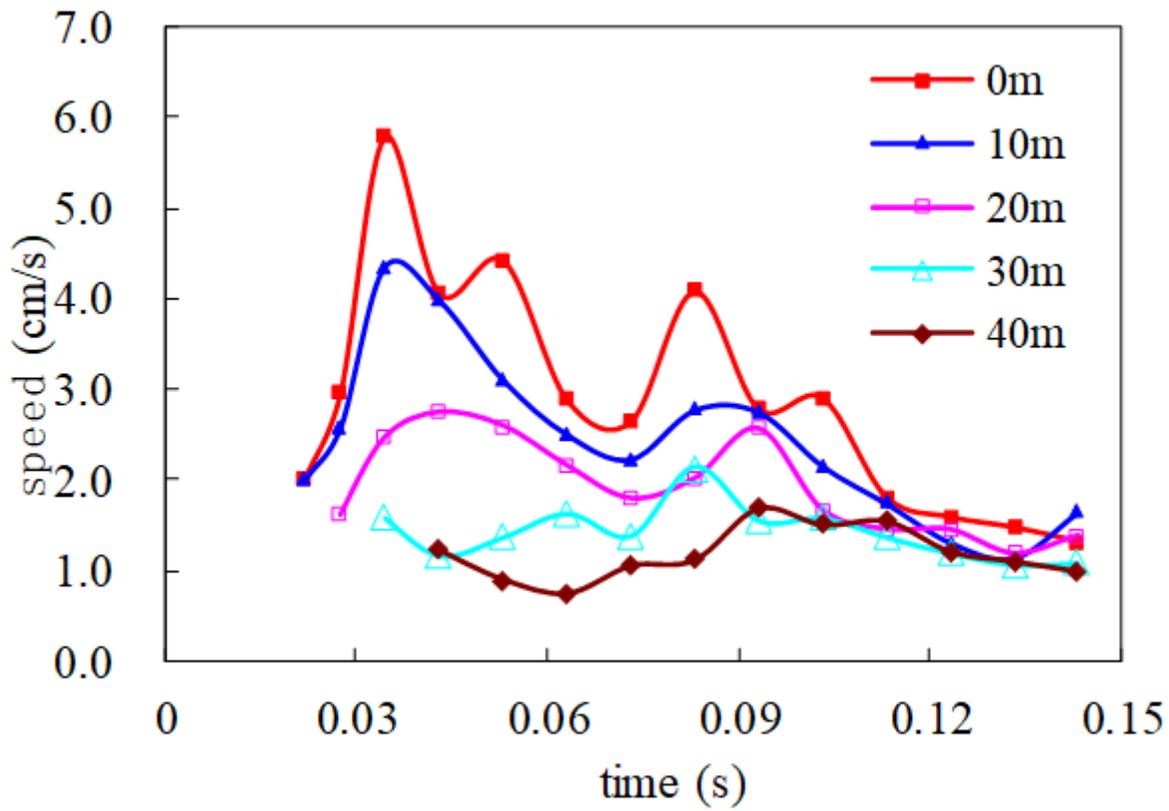


Figure 8

Speed effect of the first hole (right hole) on the back hole (left hole)



(a) When the distance between the tunnel faces is 0m



(b) When the distance between the tunnel faces is 10m



(c) When the distance between the tunnel faces is 20m



(d) When the distance between the tunnel faces is 30m



(e) When the distance between the tunnel faces is 40m

**Figure 9**

Maximum speed of the lining under different face spacings

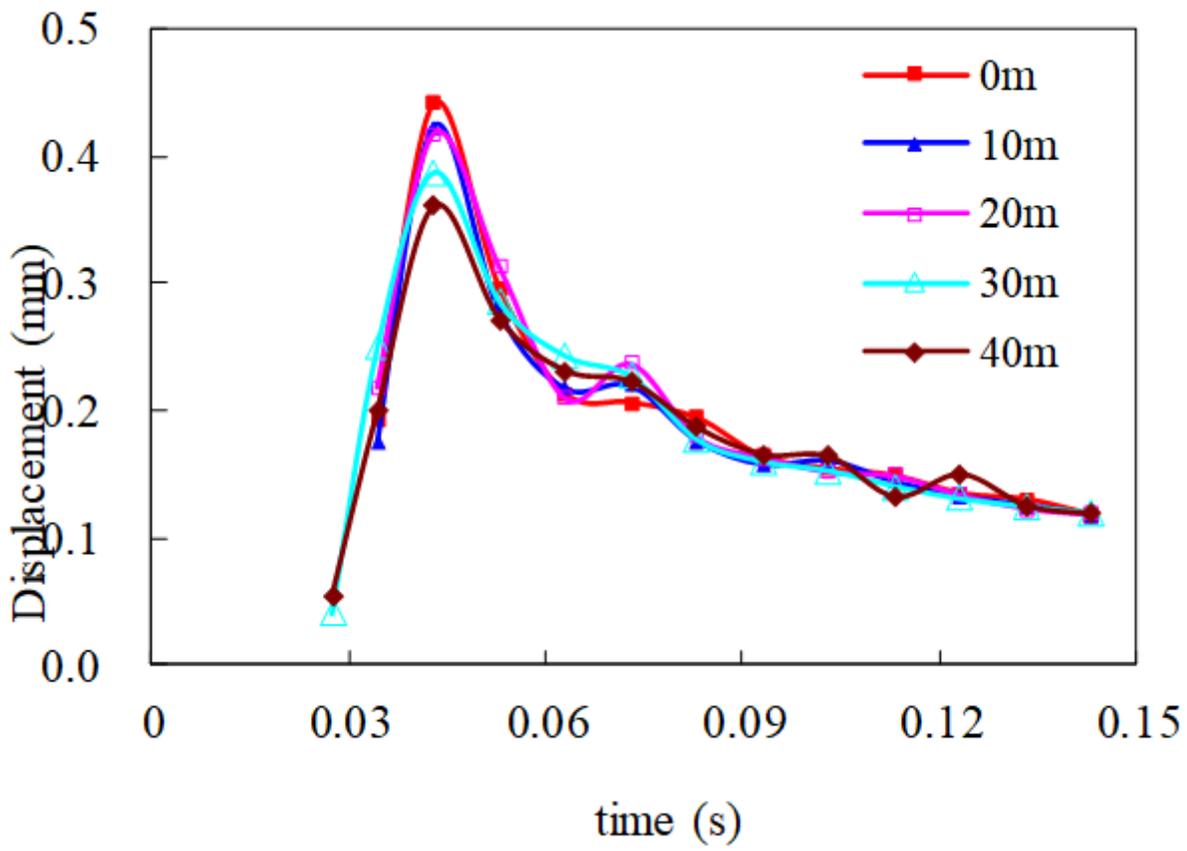


Figure 10

Effect of the blasting of the trailing hole (left hole) on the preceding hole (right hole)



(a) When the distance between the tunnel faces is 0m



(b) When the distance between the tunnel faces is 10m



(c) When the distance between the tunnel faces is 20m



(d) When the distance between the tunnel faces is 30m



(e) When the distance between the tunnel faces is 40m

Figure 11

Maximum displacement of the lining under different face spacings (cloud side)

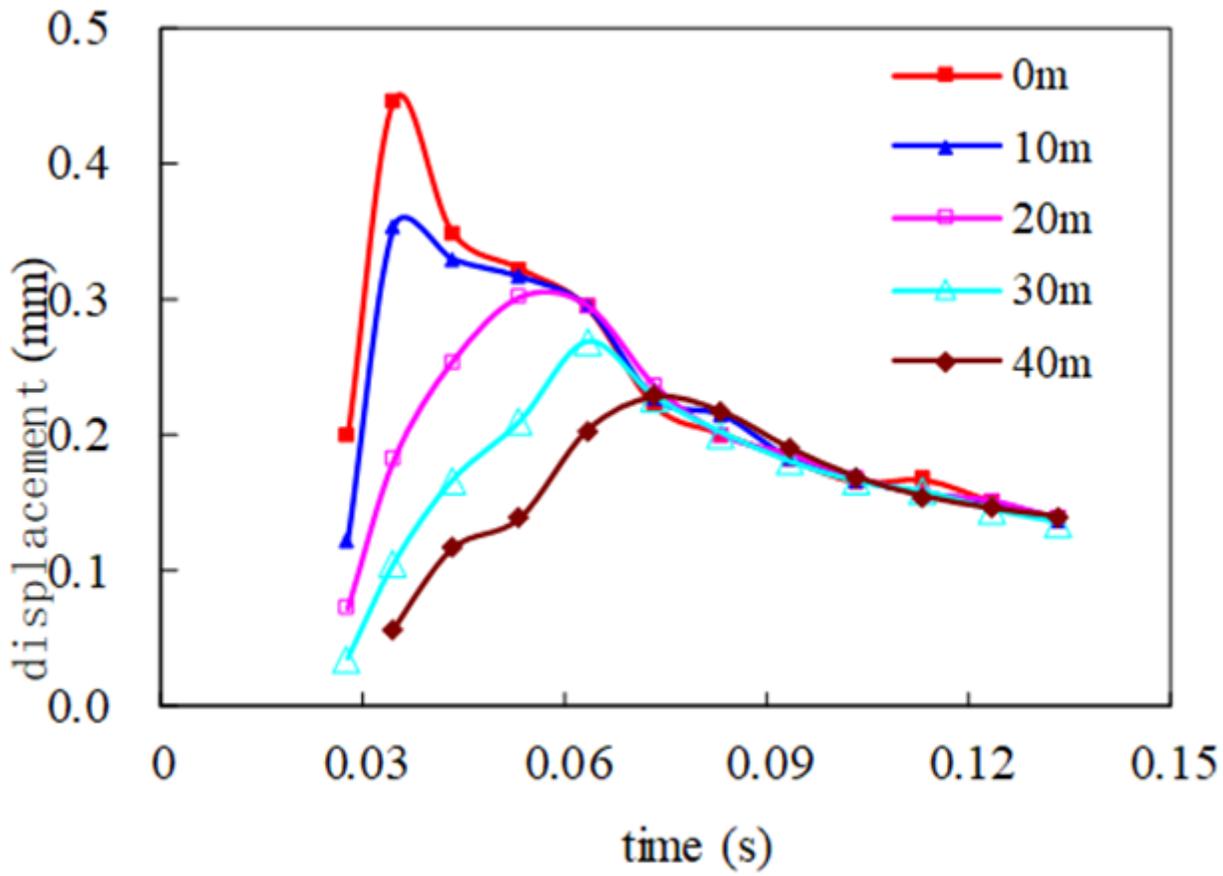


Figure 12

Effect of the first hole (right hole) blasting on the back hole (left hole)



(a) When the distance between the tunnel faces is 0m



(b) When the distance between the tunnel faces is 10m



(c) When the distance between the tunnel faces is 20m



(d) When the distance between the tunnel faces is 30m



(e) When the distance between the tunnel faces is 40m

**Figure 13**

Effect of the first hole (right hole) blasting on the back hole (left hole)