

## Research Article

# Safety Analysis of Lining Structure Influenced by Blasting of Tunnel with Extralarge Section and Small Space

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In order to ensure the safety of the Daling tunnel with extralarge section and small space, the three-dimensional model of blasting dynamic simulation had been established and verified. Then, the model was used to analyze the influence of the surrounding rock characteristics and blasting design parameters on the blasting vibration of the first hole, and the analysis of the sensitivity of each factor was carried out. The results showed that blasting of the second hole had a serious impact on the safety of the first hole lining structure. Based on the safety threshold and analysis of sensitivity, the explosive velocity, charge density, and digging length were selected as the key parameters affecting the safety of the tunnel structure. Meanwhile, the corresponding engineering measure was taken based on the results of sensitivity and the actual situation on site, and, after that, the maximum PPV of the right wall of the first hole had been reduced to 9.3 cm/s, which effectively guaranteed the safe construction of the tunnel.

## 1. Introduction

Since the new century, due to the continuous improvement of comprehensive national strength and the continuous application of high and new technology, the Chinese highway tunnel has achieved unprecedented development [1–4]. With the increasing traffic volume of highway tunnels and the need to build tunnels under complex geological conditions, tunnels with large sections and small space have been gradually promoted during the construction of highway tunnels, thus further promoting the development of highway tunnel [5].

However, due to the special construction method of the tunnel with large section and small space, the stress changes caused by the construction and the disturbance to the lining structure are more intense than the traditional methods, and the damage is more likely to take place during the construction process, so scholars have made a deep study on the construction characteristics of the tunnel with large section and small space. Yang et al. [6] used theoretical analysis to study the stress variation characteristics of the overlying rock after the construction of the tunnel with large section and

small space, which provided the corresponding theoretical basis for the construction of the tunnel. Shi et al. [7] used finite-element numerical analysis to analyze the construction mechanics of the tunnel with large section and small space, calculated the dynamic response of the tunnel under the action of seismic force, and analyzed its dynamic stability. Wang and Su [8] used numerical simulation software to analyze the subsidence deformation of the tunnel vault during the excavation of the tunnel with large section and small space under the condition of the poor surrounding rock, and the feasibility of the bench method was analyzed. Wang et al. [9] used Python programming function of ABAQUS to determine the optimal flattening rate and space of the proposed tunnel by taking the safety aspect of tunnel construction as the goal. Hou et al. [10] and Gong et al. [11] compared the applicability of different excavation methods in the tunnel with large section and small space using numerical analysis and field measurement methods and determined the optimal construction method. Liu [12] established the finite-element model of the tunnel with large section and small space by FLAC<sup>3D</sup> software. They studied the surface settlement, surrounding rock, and lining

structure stress changed during construction and put forward the corresponding monitoring and reinforcement countermeasures. He et al. [13] analyzed the law of deformation failure and fracture evolution process of the surrounding rock in the shallow buried tunnel with large section and small space by means of discontinuous deformation analysis (DDARF) and optimized the tunnel support scheme accordingly.

It could be seen from the above research that in recent years, the feasibility of the tunnel with large section and small space construction and the corresponding support scheme had been studied deeply, but the research was based on the analysis of the stress and deformation characteristics of the tunnel structure after the completion of the tunnel structure, without considering the influence of blasting vibration of the second hole during actual construction. However, at this stage, the explosive blasting had caused a violent impact on the surrounding rock and lining structure, which leads to failure and instability of tunnel structure from time to time [14, 15]. Especially in tunnels with large sections and small space, the blasting operation would have a more severe impact on the safety of lining structure, and the possibility of blasting leading to instability of lining structure would be further increased.

At present, with the rapid development of computer technology and corresponding blasting theory, the precision and economy of numerical simulation have been continuously improved, which has been widely used in the research of tunnel blasting [16–21]. It has become an important means to study the characteristics of tunnel blasting. Therefore, in order to better analyze the vibration characteristics of the Daling tunnel with large section and small space, the corresponding numerical simulation model was established according to the actual situation of Daling tunnel, the blasting vibration on the initial lining structure constructed by CD method was analyzed, and the corresponding control measure was put forward to effectively guarantee the safe construction of Daling tunnel.

## 2. Geological Background and Vibration Speed Measurement of Tunnel Engineering

*2.1. Geological Background.* Daling tunnel is located in Jinan City, Shandong Province. It is a key and difficult tunnel in the Jinan City Expressway Project. The geographic location and layout of the tunnel are shown in Figures 1(a) and 1(b), the information of the research cross section is shown in Figure 1(c). The width and height of the tunnel are 19.4 m and 13.1 m, respectively, the excavation area is 219.8 m<sup>2</sup>, and the section area of the tunnel is extralarge. The distance between two holes in some tunnel sections is less than the specified value, so it belongs to the tunnel with extralarge section and small space. The Daling tunnel is constructed with information design and drilling and blasting method, during the blasting construction of the second hole, the first hole had been constructed with first lining, but no secondary lining. In view of its extralarge excavation section and small space, the blasting operation of the second hole would easily cause an adverse effect on the primary lining structure of the

first hole, affecting the safety of the lining structure of the first hole and even inducing accidents. According to the site construction situation and relevant construction experience, it was analyzed that the possibility of damage to the first lining of the first hole during the blasting construction near the ZK6 + 650 section of the Daling tunnel was extremely high. Therefore, in order to analyze the impact of the blasting vibration of the tunnel on the safety of the lining structure of the first hole during the construction, the tunnel at this section (ZK6 + 650) was selected as the research object. The distance between the two holes at the study section was 15 m, and the section position is shown in Figure 1(b). Besides, the burial depth is 40 m, the surrounding rock is mainly medium-weathered limestone, belonging to the surrounding rock grade IV. The conditions of the surrounding rock are poor, and the physical and mechanical parameters of the surrounding rock are shown in Table 1. C20 shotcrete was used as the primary supporting material of the first hole; its physical and mechanical parameters are shown in Table 2. Then, the CD method was used for the construction of the second hole, the design parameters of the cutting blasting holes were designed using the on-site blasting parameters; the layout of the blasting holes in the left blasting hole of the second hole is shown in Figure 1(d); and the time of delayed blasting of the explosives of the 3<sup>rd</sup>, 5<sup>th</sup>, 13<sup>th</sup>, 15<sup>th</sup>, and 19<sup>th</sup> sections are, respectively, 50 ms, 110 ms, 650 ms, 880 ms, 1700 ms. The explosives used in on-site tunnel blasting were mainly emulsified explosives and No. 2 ammonium nitrate explosives.

*2.2. Vibration Speed Measurement under the Influence of Blasting.* The peak particle velocity (PPV), which was the most commonly used and reliable index in the tunnel, was used as the basis for judging the degree of disturbance of the first hole lining structure [22]. Therefore, vibration velocity monitoring instruments were installed at the sidewall, arch waist, and vault of the first hole, which could be used to better analyze the characteristics of blasting vibration and provide the corresponding reference for numerical simulation, as shown in Figure 2.

Field monitoring results showed that the PPV at the right wall of the first hole was the largest with the blasting operation of the left cutting hole of the second hole. The change of the PPV of the right wall at the section of the first hole when blasting is shown in Figure 3, and through the sequence of blasting (first was cutting hole, then auxiliary hole, and finally the peripheral hole), the maximum disturbance caused by the blasting of several holes to the lining structure was known.

It could be seen from the actual measurement of PPV that the blasting of the cutting hole, the auxiliary hole, and the peripheral hole would cause a strong vibration of the right wall, and the maximum PPV was, respectively, 11.715 cm/s, 7.170 cm/s, and 2.643 cm/s. Among them, the vibration effect caused by the blasting of the cutting hole was the most severe, the vibration effect generated during the blasting of the cutting hole was 1.6 and 4.5 times bigger than the auxiliary hole and the peripheral hole, respectively.

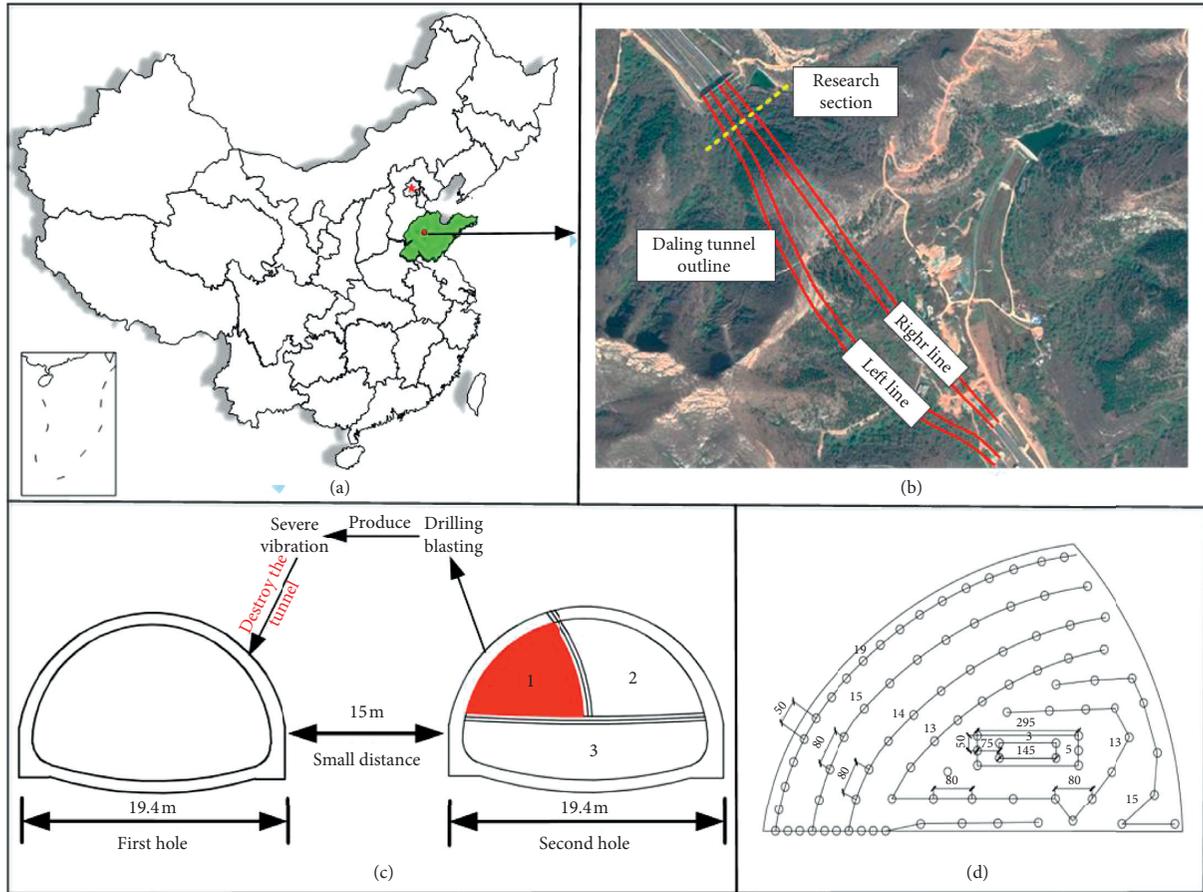


FIGURE 1: Construction information map of the Daling tunnel. (a) Geographic location of the tunnel. (b) Layout of the tunnel. (c) Information on the research cross section. (d) Layout of the blasting holes in the left blasting hole.

TABLE 1: Physical and mechanical parameters of surrounding rock.

Surrounding rock	Bulk density (kN/m <sup>3</sup> )	Dynamic elastic modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Friction angle (°)	Longitudinal velocity (m/s)
Grade IV	2100	30	0.31	0.2	29	4450

TABLE 2: Physical and mechanical parameters of lining structures.

Supporting structure	Material	Bulk density (kN/m <sup>3</sup> )	Elastic modulus (GPa)	Poisson's ratio
Primary support	C20	2500	22.5	0.25

Therefore, the blasting of the cutting hole, which was wedge-shaped (the angle is 30°, the length is 2.3 m, and the charge mass is 12.86 kg) and took the form of an uncoupled charge, was the main factor that affected the safety of the first hole. The results of field measurements were consistent with the results of the relevant literature research [23, 24]. Moreover, according to relevant regulations [25], the maximum allowable PPV of the lining structure during blasting was 10–20 cm/s and combined with the characteristics of the Daling tunnel being vulnerable to disturbance, the 10 cm/s was selected as the safety threshold for PPV of the lining structure. But it can be seen that the vibration caused by tunnel blasting was relatively large, the maximum PPV

(11.715 cm/s) of the lining structure had exceeded the safety threshold, which would affect the safety of the tunnel, and measures must be taken to control it.

### 3. Numerical Model Establishment

**3.1. Calculation Model and Parameter Selection.** FLAC<sup>3D</sup> is a mechanical analysis software for underground and geotechnical engineering launched by Itasca company based on the Lagrange finite difference principle. Ever since the advent of FLAC<sup>3D</sup> in 1994, the software has been widely used in geotechnical engineering and has been rapidly used in the simulation of tunnel blasting as a powerful tool for studying

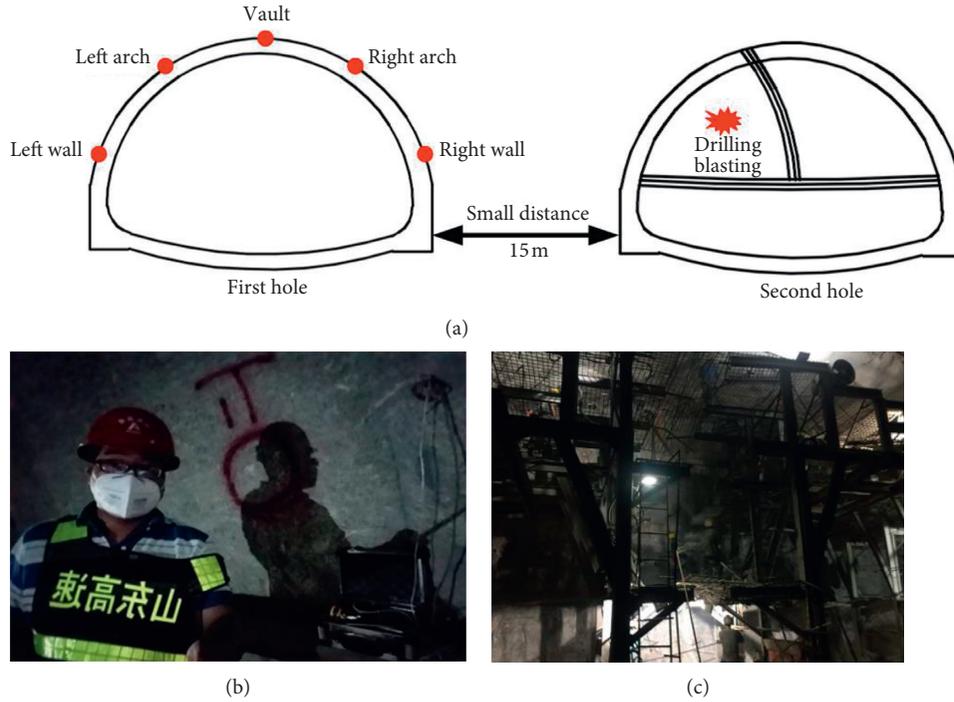


FIGURE 2: Daling tunnel vibration speed measurement points and on-site operation. (a) Location of the vibration measurement point. (b) Sensor installation. (c) Drilling and blasting operation.

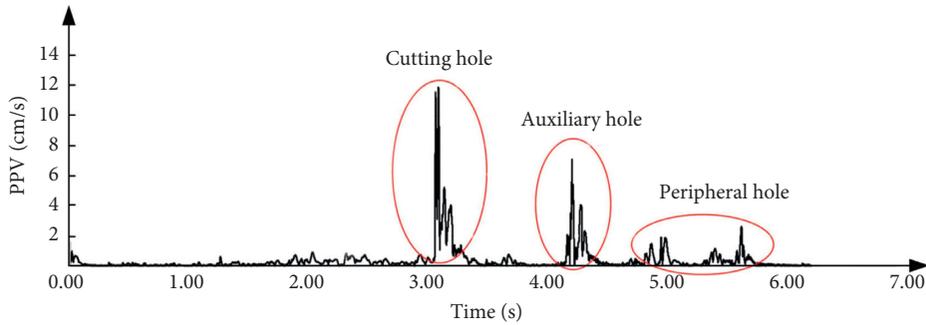


FIGURE 3: Time chart of vibration speed monitoring by the right wall of the first hole.

the vibration of tunnel blasting [26, 27]. Therefore, based on the geological condition of the Daling tunnel and the construction steps of the CD method, fully considering the conditions required for the accuracy of the calculation, a FLAC<sup>3D</sup> numerical model for Daling tunnel safety analysis under the influence of blasting disturbance was established, as shown in Figure 4.

The size of the model was 190 m × 128 m × 60 m, with a total of 19,735 nodes and 209,700 elements, and the acceleration of gravity was 9.81 m/s<sup>2</sup>. During the initial geostress balance and static calculation during the excavation and support phase, the left, right, and lower boundaries of the model were fixedly constrained, and the free field boundary was mainly used in the dynamic calculation. The impact of blasting on tunnel structure was simulated by

exponential loading method [26] compared with other two current mainstream stress loading methods (triangular loading method and simple harmonic function loading method), the exponential loading method could more truly reflect the generation and attenuation process of blasting load, and its principle was to load the dynamic load generated by blasting on the grid node of the simulated blast hole in the way of equivalent stress. The relationship between dynamic load ( $P(t)$ ) and time could be expressed as

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

In the above formula (1),  $P_b$  is the pulse peak,  $f(t)$  is the exponential time lag function, and the value of  $P_b$  and  $f(t)$  can be calculated by formulas (2) and (3), respectively:

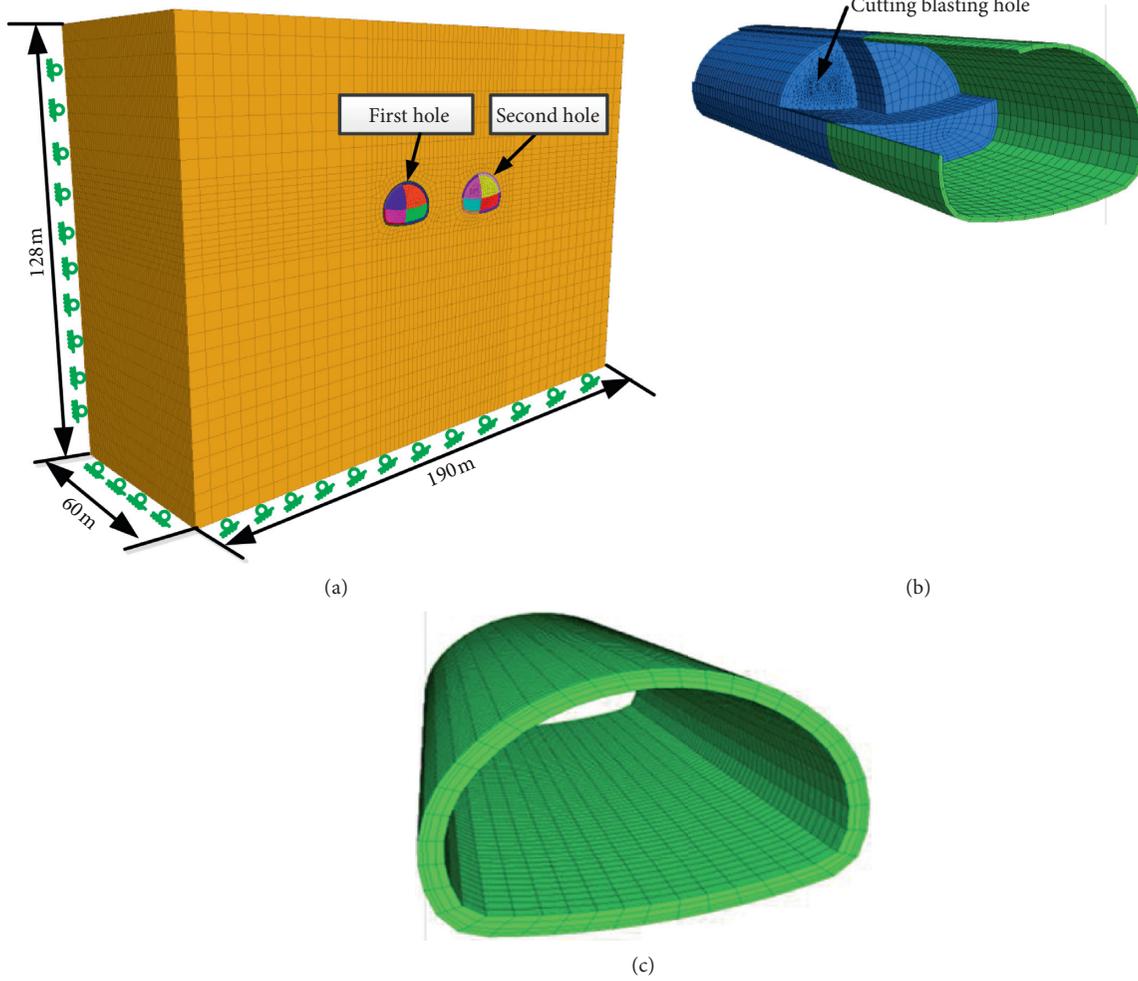


FIGURE 4: Simulation model of impact analysis of blasting vibration. (a) Numerical simulation meshing. (b) Mesh of cutting hole of the second hole. (c) Mesh of first hole lining structure.

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

$$f(t) = P_0 (e^{-wn} - e^{-wm}). \quad (3)$$

In the above two formulas,  $\rho_0$  is the charge density;  $D$  is the explosive velocity;  $R_C$  is the radius of the explosive charge;  $R_B$  is the radius of the blast hole;  $\eta$  is the pressure increase factor;  $n$  and  $m$  are the parameters that determine the rising and falling pressure time of the explosive pulse;  $w$  is the value related to the longitudinal wave velocity and hole diameter of the medium (in the initial simulation, the values of  $m$  and  $n$  were taken as 0.41 and 0.53, respectively, and the simulation of the time change of rising can be realized by changing the values of  $m$  and  $n$  in the subsequent simulation).

Considering the power of the computer, it was necessary to simplify the model, and the physical and mechanical parameters of surrounding rock of the whole model were selected parameters of the surrounding rock of section ZK6 + 650. In the calculation, the solid element was used to simulate the surrounding rock and lining. The surrounding

rock adopted the Mohr–Coulomb material model, and the lining adopted the linear elastic material model. In the simulation process, the first hole was first through and the initial lining support was applied; then, the second hole was partially excavated and the initial lining support was applied immediately after the partial excavation was completed. After excavating the palm face to the position of the cross section in the middle of the model, the blasting simulation of the cutting hole was carried out. At the same time, the field test results showed that the blasting of the left cutting hole of the second hole was the main factor causing the destruction of the first hole lining structure. Therefore, the numerical simulation mainly studied the impact of the blasting of the left blasting hole of the second hole on the tunnel structure. According to the actual construction of the Daling tunnel, the relevant numerical simulation parameters are determined as shown in Table 3.

**3.2. Correctness Verification.** In order to verify the correctness and reliability of the model, the first simulation experiment was carried out based on the actual construction conditions and blasting parameters, then the maximum PPV

TABLE 3: Loading parameter of the test.

Borehole radius (m)	Cartridge radius (m)	Explosive velocity (m/s)	Rising pressure time (ms)	Decompression time (ms)	Charge density ( $\text{kg/m}^3$ )	Charge weight (kg)	Digging length (m)	Number of holes
0.021	0.016	3600	10	90	1000	12.86	2	10

was extracted at different distances from the right wall and the right arch waist to the longitudinal face compared with the measured value, and the results are shown in Figures 5 and 6. It could be seen from the 2 diagrams that the trend of the two curves was basically the same, the difference between the two was relatively small, and the maximum error between the two was 12.2%. Therefore, the results of the numerical simulation were credible.

#### 4. Tunnel Safety and Sensitivity Analysis under the Influence of Blasting Vibration

**4.1. Analysis of Tunnel Stress Characteristics under the Influence of Blasting Vibration.** In order to analyze the failure characteristics of the first hole lining structure in the blasting process, the research simulated the tunnel stress changed under the influence of blasting vibration based on the actual conditions and blasting parameters. And the maximum and minimum principal stress of the first hole lining structure before blasting and at the peak of blasting were extracted, as shown in Figures 7 and 8. Then, the adverse effects of the blasting on the tunnel structure of the first hole were analyzed. According to the extracted stress, before blasting, the maximum value of maximum principal stress of the lining structure was 0.0363 MPa, located near the vault, and the maximum value of the minimum principal stress was  $-3.0792$  MPa, located between the arch foot and the sidewall. However, when at the peak of the blasting vibration, the maximum value of maximum principal stress of the first hole lining structure was 0.5626 MPa, which was located on the sidewall about 4.1 meters in front of the blasting cross section of the second hole and the maximum value of minimum principal stress of the first hole lining structure was  $-4.6227$  MPa, which was located on the corner of the sidewall about 6.7 m in front of the blasting cross section of the second hole.

From the above research, we could see that the location and the maximum value of the maximum and minimum principal stress of the first hole lining structure were changed. The position of the maximum value of the maximum and minimum principal stress was about 5 m in front of the cross section of the second hole, the maximum value of maximum principal stress was 15.5 times the initial value, and the maximum value of minimum principal stress was 1.5 times the initial value. Therefore, the blasting would lead to sudden changes in the stress of the first hole lining structure, which would greatly threaten the safety of the first hole.

**4.2. Analysis of Influencing Factors of Tunnel Safety Influenced by Blasting Vibration.** From the above analysis, it could be seen that the blasting of the Daling tunnel was very likely to

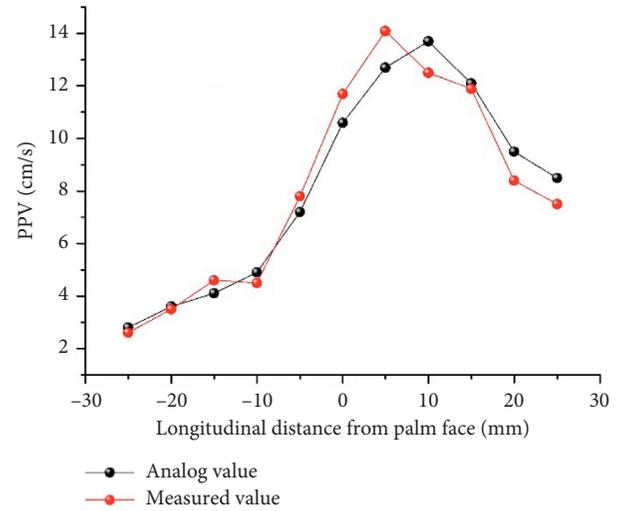


FIGURE 5: PPV from the right wall.

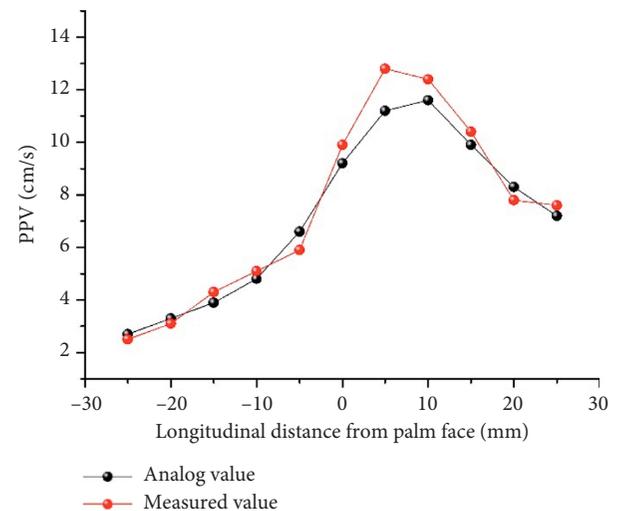


FIGURE 6: PPV from the right arch waist.

have a bad influence on the safety of the initial lining structure. Therefore, the  $\text{FLAC}^{3D}$  software was used to analyze the influence of blasting factors on the safety of the lining structure.

According to the experience of field construction, it could be known that the influencing factors of tunnel blasting safety could be divided into two categories: surrounding rock characteristics and blasting parameters. Among the surrounding rock characteristics, bulk density, dynamic elastic modulus, Poisson's ratio, and cohesion were the main influencing factors. Among the blasting

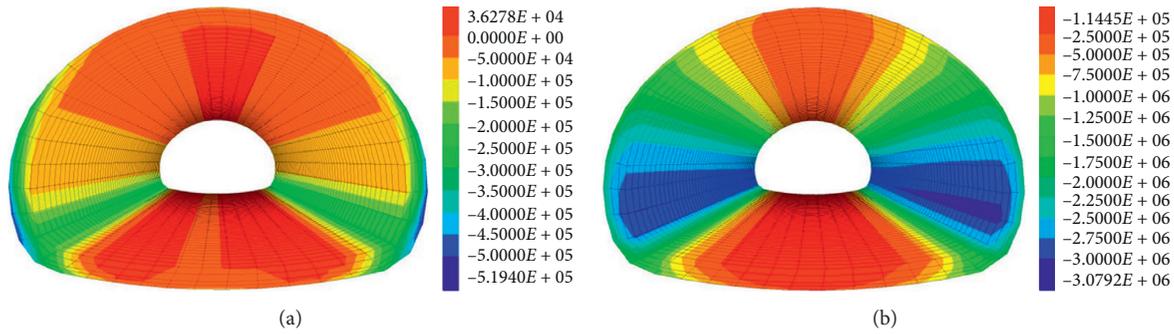


FIGURE 7: Lining structure stress of the first hole before blasting. (a) Maximum principal stress. (b) Minimum principal stress.

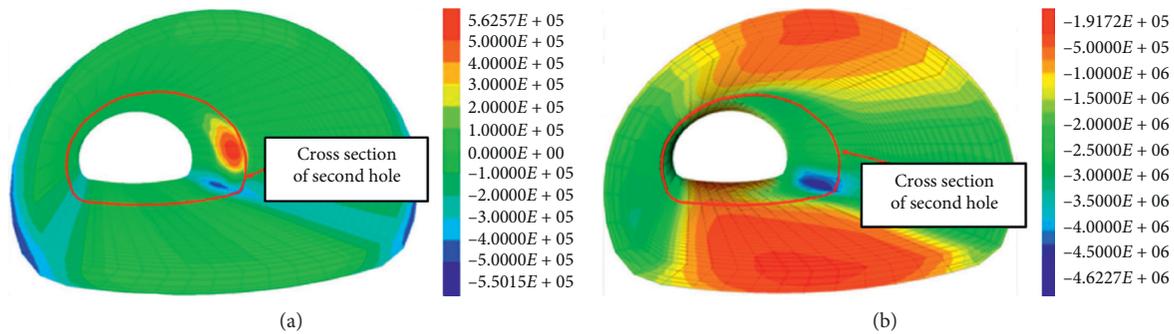


FIGURE 8: Stress change of the lining of the leading tunnel during peak blasting. (a) Maximum principal stress. (b) Minimum principal stress.

parameters, explosive velocity, rising and falling pressure time of stress, charge density, and digging length were the main influencing factors. Therefore, the above eight factors were analyzed in this paper, and the PPV was used as the basis for judging the degree of disturbance of the first hole lining structure. Moreover, according to relevant regulations and the vulnerable characteristics of the Daling tunnel, the PPV of 10 cm/s was taken as a judgment to judge whether the tunnel safety was seriously disturbed.

The numerical simulation used a single-variable method: change a single variable under the condition of actual surrounding rock characteristics and blasting parameters, so as to analyze the influence of this variable on the safety of the tunnel. Moreover, according to the previous stress-changed numerical simulation, it could be seen that the vibration of the first hole lining structure around 5 m in front of the face of blasting cross section of the second hole was the most affected, so the PPV of the measuring points at the location was extracted and compared with the PPV safety threshold. The value of each variable is based on the following.

**4.2.1. Bulk Density.** The surrounding rock of the Daling tunnel of study section mainly belongs to grade IV and grade V, which is relatively fragile. Therefore, this paper took 5 working conditions with surrounding rock bulk density of  $17 \text{ kN/m}^3$ ,  $19 \text{ kN/m}^3$ ,  $21 \text{ kN/m}^3$ ,  $22 \text{ kN/m}^3$ ,  $23 \text{ kN/m}^3$  for numerical simulation.

**4.2.2. Dynamic Elastic Modulus.** Under the blasting action, the surrounding rock is subjected to dynamic load, and its elastic modulus (dynamic elastic modulus) will increase, compared with the static load. Therefore, according to the main surrounding rock characteristics of the research section and its vicinity, this paper took 6 working conditions with dynamic elastic moduli of 5 GPa, 10 GPa, 20 GPa, 30 GPa, 40 GPa, and 50 GPa, respectively.

**4.2.3. Poisson's Ratio.** According to the properties of the surrounding rocks at and around the study section, this paper took a total of 5 working conditions with Poisson's ratios of 0.31, 0.35, 0.38, 0.42, and 0.45 for numerical simulation.

**4.2.4. Cohesion.** According to the properties of the surrounding rock at and around the study section, this paper took a total of 5 working conditions with a cohesive force of 0.05 MPa, 0.1 MPa, 0.2 MPa, 0.35 MPa, 0.7 MPa for numerical simulation.

**4.2.5. Explosive Velocity.** Explosive velocity is the velocity of explosive wave propagation during an explosive reaction. The explosives used in on-site tunnel blasting were mainly emulsified explosives and No. 2 ammonium nitrate explosives, and their blasting velocities were concentrated at 3000~4500 m/s. So, there were 5 working conditions with

explosive velocities of 3000 m/s, 3300 m/s, 3600 m/s, 4000 m/s, and 4500 m/s for numerical simulation.

**4.2.6. Rising and Falling Time of Stress.** The times of explosive pressure rising and falling are the stress rising time and stress falling time of the explosive wave in the chemical reaction of the explosion. Different explosives and different forms of cartridges have different times of pressure rising and falling. Usually, the rising time is 8 to 12 ms and the decompression time is 80 to 100 ms. Therefore, this paper took 5 working conditions of rising time as 8 ms, 9 ms, 10 ms, 11 ms, and 12 ms, respectively, and carried out numerical simulation corresponding to the falling time as 80 ms, 85 ms, 90 ms, 95 ms, and 100 ms, respectively.

**4.2.7. Charge Density.** Charge density refers to the ratio of the weight of the explosive to its volume. On the basis of engineering experience, the charge density of the cutting hole ranges 800~1200 kg/m<sup>3</sup>. So, this paper took 5 working conditions with charge densities of 800 kg/m<sup>3</sup>, 900 kg/m<sup>3</sup>, 1000 kg/m<sup>3</sup>, 1100 kg/m<sup>3</sup>, and 1200 kg/m<sup>3</sup> for numerical simulation.

**4.2.8. Digging Length.** The digging length is the depth of one blasting excavation. According to engineering experience, the digging length is generally 1 to 3 m. This article did not change the charging coefficient and charge density of the cutting hole and took 3 working conditions with digging lengths of 1.0 m, 2.0 m, and 3.0 m (the corresponding charge masses are 6.43 kg, 12.86 kg, and 19.29 kg).

The maximum values of PPV of different measuring points under various working conditions are shown in Figures 9–16. In particular, the maximum values of PPV of the right wall which was most susceptible to blasting vibration were extracted, as shown in Figures 17–24.

It could be seen from the analysis of the PPV extracted under the above working conditions that the PPV on the right wall of the first hole were greater than other parts, which further confirmed that the right wall of the first hole was most vulnerable to disturbance and damage. Therefore, the monitoring and protection of this area should be strengthened when blasting. More seriously, it can be seen from the simulation data that the change of the bulk density, Poisson's ratio, time of rising and falling pressure, elastic modulus, cohesion, explosive velocity, charge density, and digging length would cause the maximum PPV of the right wall to exceed the safety threshold of 10 cm/s; when the bulk density was 17 kg/m<sup>3</sup>, the dynamic elastic modulus was 5 GPa, Poisson's ratio was 0.31, the cohesive force was 0.05 MPa, explosive speed was 4500 m/s, rising time was 9 ms, the charge density was 1200 kg/m<sup>3</sup>, and the digging length was 3 m, respectively, the maximum vibration velocity of the right wall was 14.6 cm/s, 24.5 cm/s, 12.8 cm/s, 17.6 cm/s, 27.8 cm/s, 13.2 cm/s, 17.5 cm/s, and 16.1 cm/s, respectively, which was 1.5, 2.5, 1.3, 1.8, 2.8, 1.3, 1.8, and 1.6 times the safety threshold of the PPV, respectively. From the above studies, it could be concluded

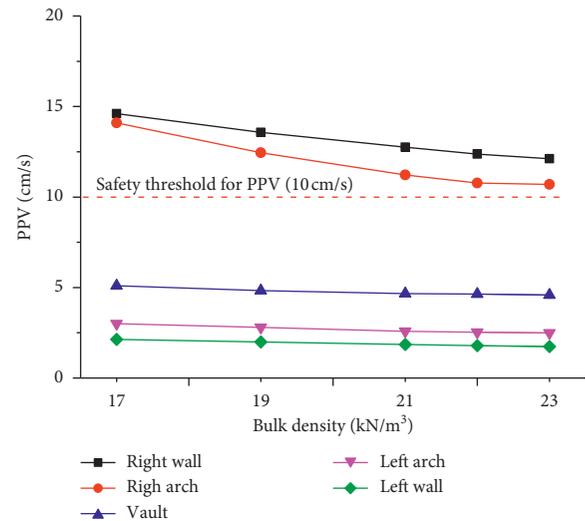


FIGURE 9: Changes of maximum PPV with bulk density.

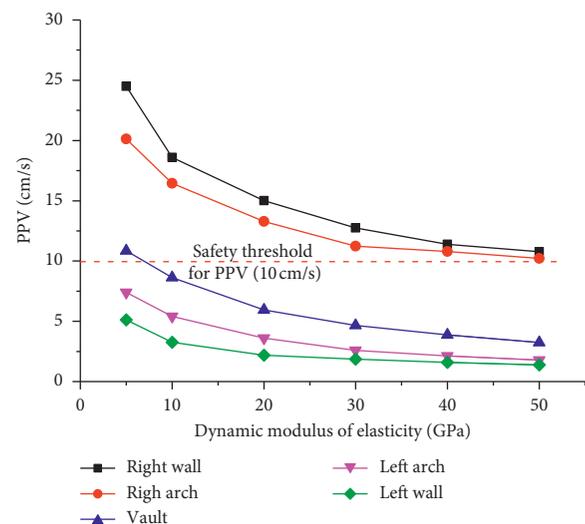


FIGURE 10: Changes of maximum PPV with a dynamic modulus of elasticity.

that the change of surrounding rock and blasting parameters may lead to a dangerous state of the Daling tunnel, and the condition of the Daling tunnel was very dangerous.

**4.3. Sensitivity Analysis of Factors Affecting PPV and Control Measures under the Influence of Blasting Vibration.** From the above research, it could be seen that the bulk density, Poisson's ratio, time of rising and falling pressure, elastic modulus, cohesion, explosive velocity, charge density, and digging length would affect the safety of the lining structure of the first hole during the blasting process of the Daling tunnel. However, the sensitivity of the above factors affecting the safety of the lining structure was different, so the Morris screening method was used to analyze the sensitivity of the above blasting factors.

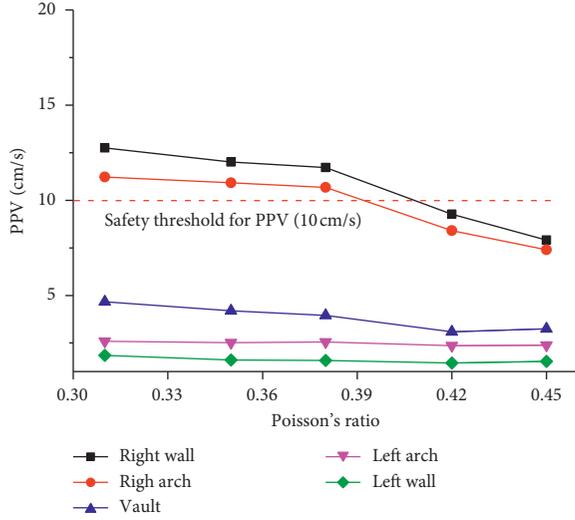


FIGURE 11: Changes of maximum PPV with Poisson's ratio.

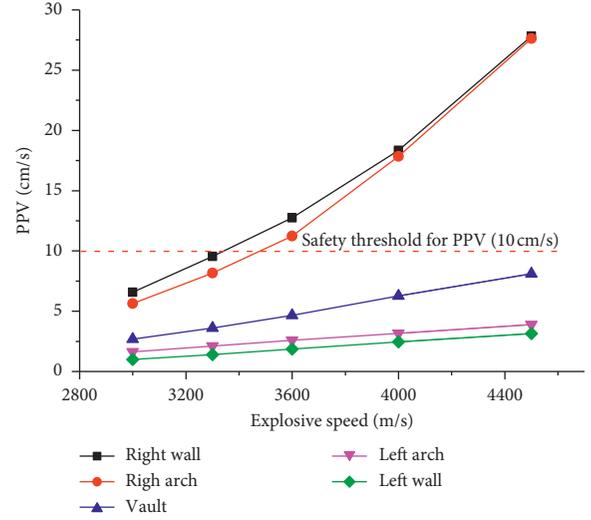


FIGURE 13: Changes of maximum PPV with explosive speed.

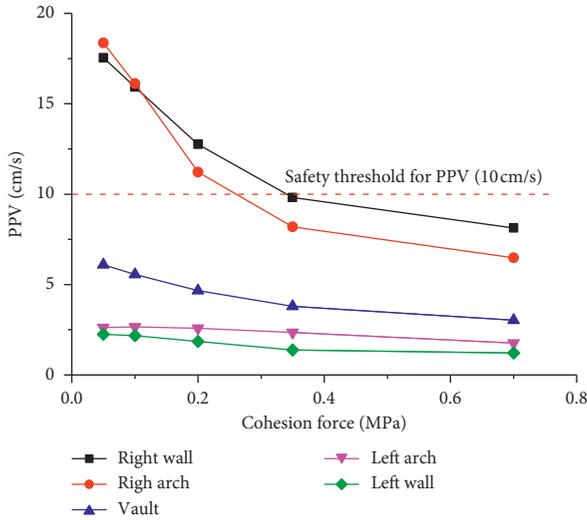


FIGURE 12: Changes of maximum PPV with cohesion.

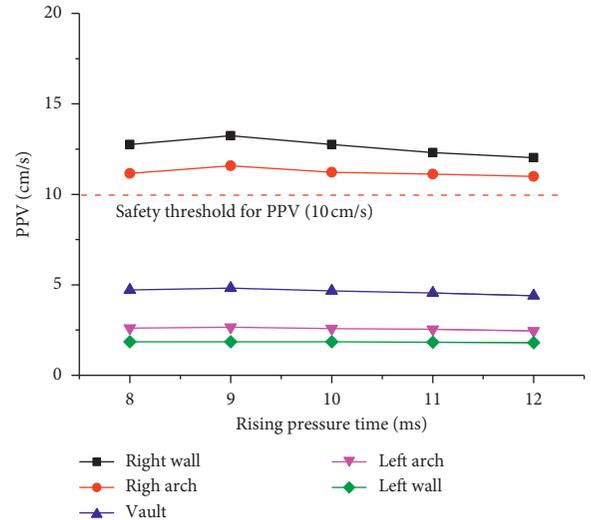


FIGURE 14: Changes of maximum PPV with rising pressure time.

The Morris screening method is used to select a variable  $x_i$  in the model. Randomly change the value of  $x_i$  within the threshold range with the remaining parameter values fixed, and run the model to obtain the value of objective function  $y$  ( $x$ ) =  $y(x_1, x_2, \dots, x_n)$ . The influence value  $e_i$  is used to judge the influence degree of the parameter changed on the output value, as shown in

$$e_i = \frac{y^* - y}{\Delta_i} \quad (4)$$

In the previous formula,  $y^*$  is the output value after the parameter changed;  $y$  is the output value before the parameter changed; and  $\Delta_i$  is the variation ranged of parameter  $i$ .

The modified Morris screening method uses independent variables to change with fixed step size, and the sensitivity discriminant factor  $S$  takes multiple averages of Morris, as shown in

$$S = \frac{\left[ \sum_{i=0}^{n-1} ((Y_{i+1} - Y_i)/Y_0) / ((P_{i+1} - P_i)/100) \right]}{n - 1} \quad (5)$$

In the previous formula,  $Y_i$  is the output value of the  $i$ -th ran of the model;  $Y_0$  is the initial value of the calculation result;  $P_i$  is the percentage change of the parameter value of the  $i$ -th model calculation relative to the initial parameter value; and  $n$  is the number of times the model runs.

According to the above formula, the sensitivity results of blasting influence factors at the right wall and right arch waist of the Daling tunnel are shown in Figures 25 and 26.

From Figures 25 and 26, it could be seen that the sensitivity of bulk density, dynamic modulus of elasticity, Poisson's ratio, cohesive, explosive velocity, rising time, charge density, and digging length to the safety of the first hole lining structure was not consistent during the blasting of Daling tunnel. The sensitivity of explosive velocity was the largest, and the sensitivity of explosive velocity of the right

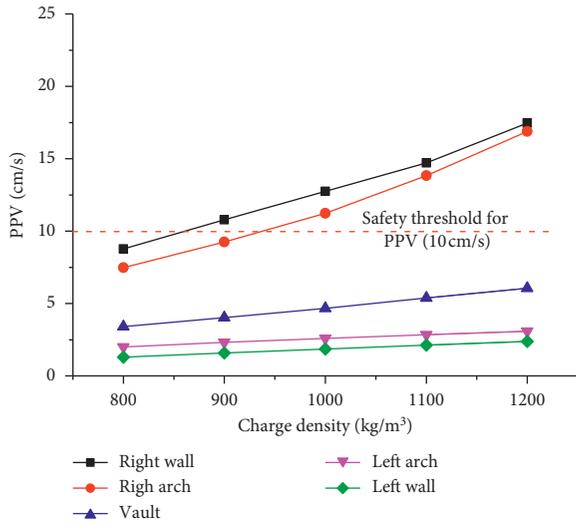


FIGURE 15: Changes of maximum PPV with charge density.

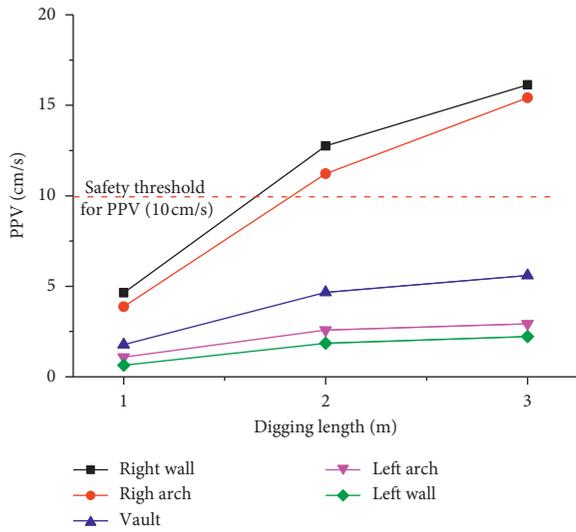


FIGURE 16: Changes of maximum PPV with digging length.

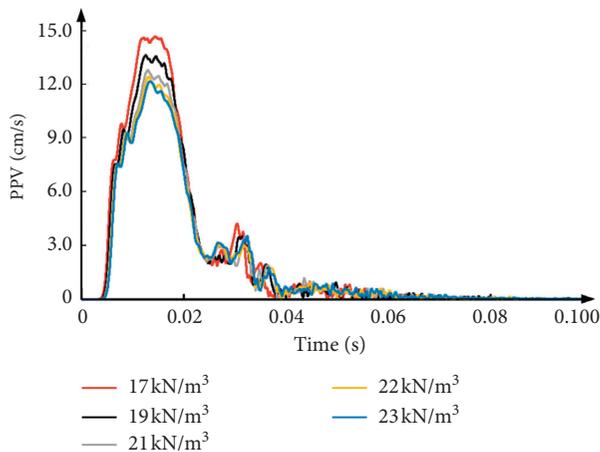


FIGURE 17: Changes of PPV of right wall with different bulk density versus time.

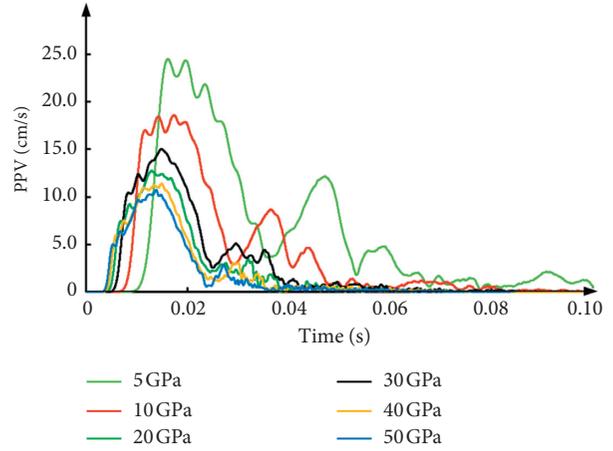


FIGURE 18: Changes of PPV of right wall with different dynamic modulus of elasticity versus time.

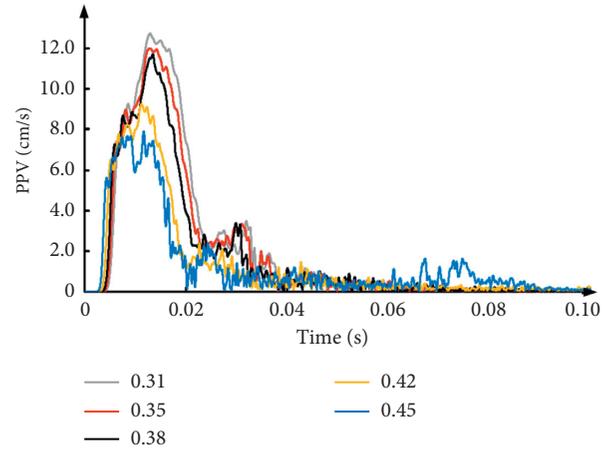


FIGURE 19: Changes of PPV of right wall with different Poisson's ratio versus time.

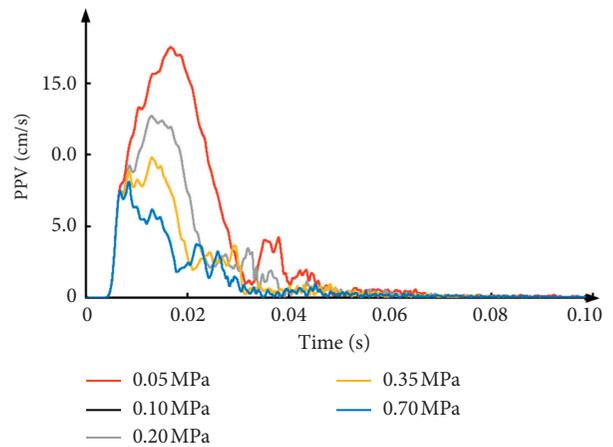


FIGURE 20: Changes of PPV of right wall with different cohesion versus time.

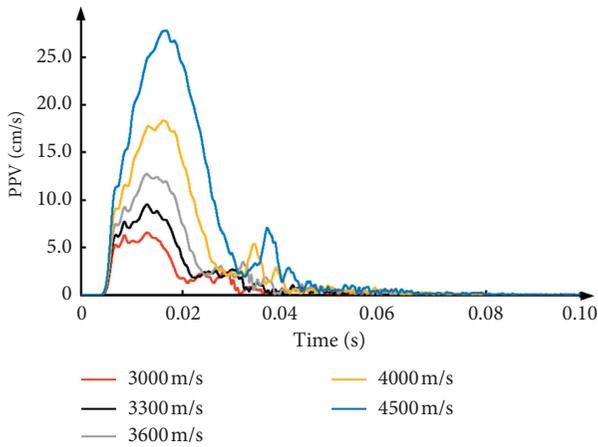


FIGURE 21: Changes of PPV of right wall with different explosive speed versus time.

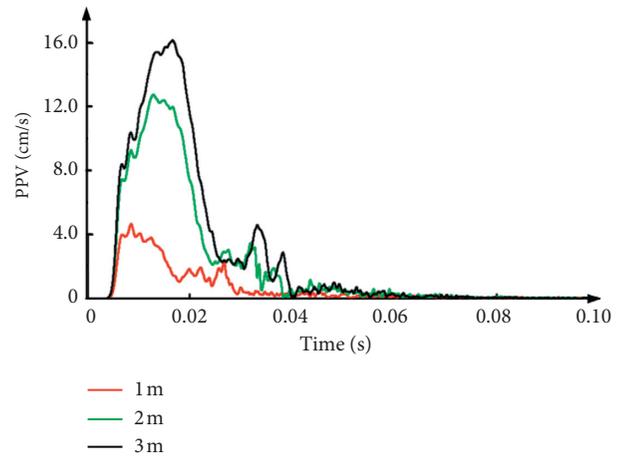


FIGURE 24: Changes of PPV of right wall with different digging length time versus time.

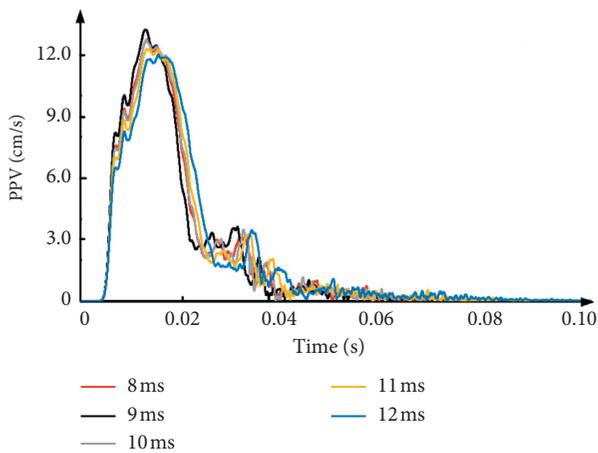


FIGURE 22: Changes of PPV of right wall with different rising pressure time versus time.

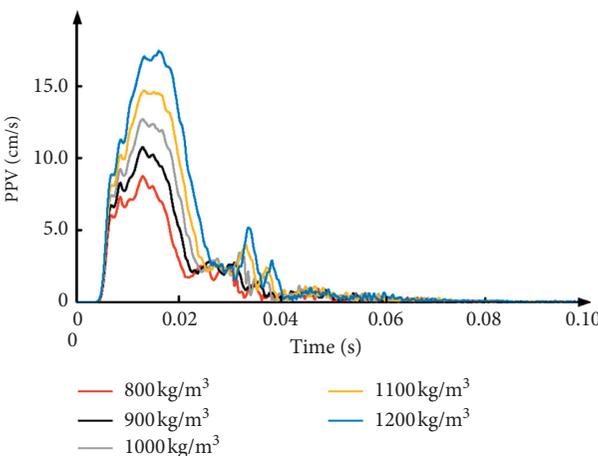


FIGURE 23: Changes of PPV of right wall with different charge density time versus time.

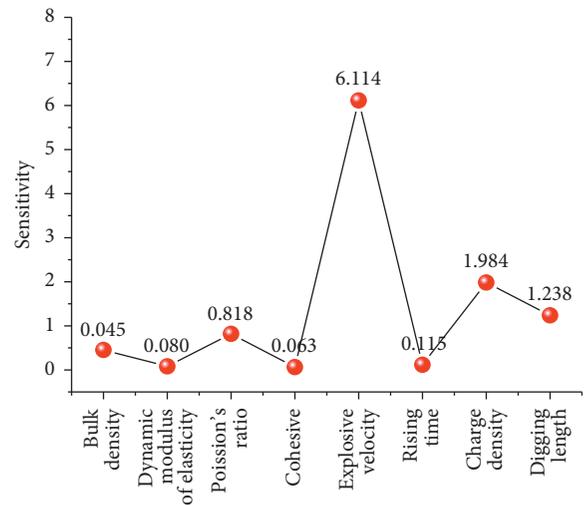


FIGURE 25: Sensitivity analysis of the right wall.

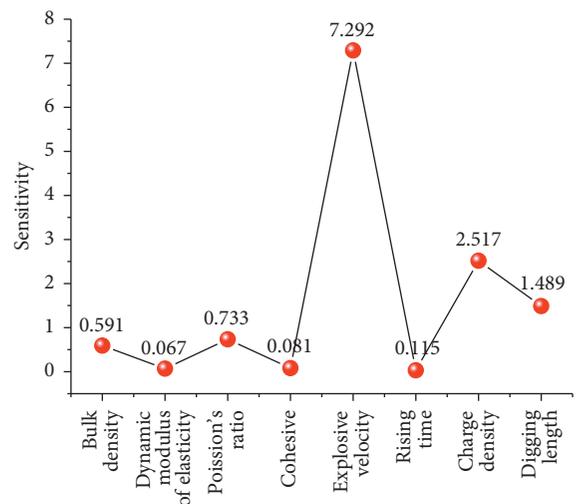


FIGURE 26: Sensitivity analysis of the right arch waist.

wall and right arch waist was 6.114 and 7.292, respectively, far more than other factors, followed by charge density, digging length, and the sensitivity of Poisson's ratio, bulk

density, dynamic modulus of elasticity, cohesive, and rising time were very small, indicating that changing the above factors had little effect on the detonation velocity.

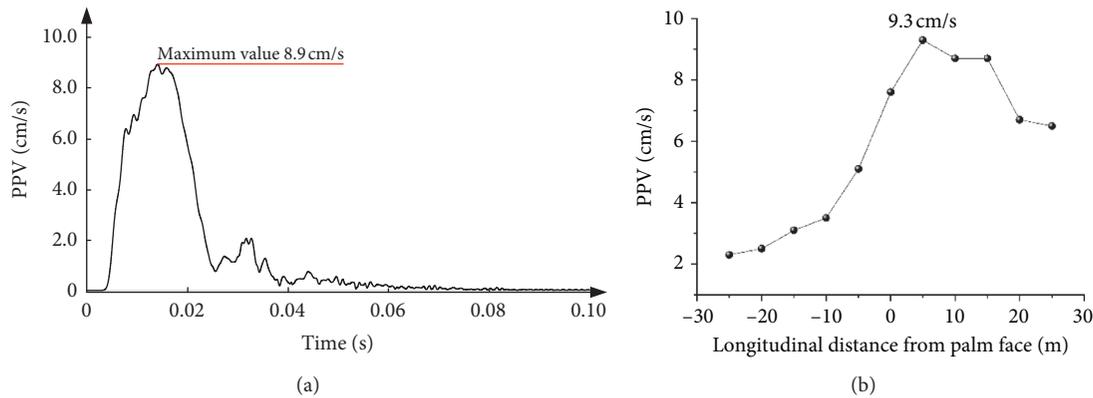


FIGURE 27: PPV of the right wall after adopting the new scheme. (a) Numerical simulation. (b) On-site measurement.

## 5. Vibration Control Measures under the Influence of Blasting

From the sensitivity analysis conducted above, it can be seen that when controlling the bad influence of the tunnel blasting of the Daling tunnel, the low-velocity explosives should be preferred, followed by adjusting the charge density and the digging length, so as to achieve the purpose of controlling blasting vibration and protecting the structure of the first hole. But the explosive velocity was determined by the type of explosives, repurchasing explosives took a long time, and the procedures were cumbersome, so the method of changing the explosive velocity was not feasible. Therefore, the method of changing the charge density and digging length to ensure safety during the blasting process of the Daling tunnel was adopted. However, changing the charge density alone would easily lead to poor blasting effects, and changing the charge digging length alone would greatly extend the construction period. Therefore, the method of combination of changing the charge density and digging length to achieve the safety of the blasting process was adopted, and the sensitivity of the charge density was about twice the sensitivity of a digging length, so changing the charge density was of greater significance, the charge density was changed to  $900 \text{ kg/m}^3$  (down 10%), and the digging length was changed to 1.9 m (down 5%).

In order to test the feasibility of the above scheme, the numerical simulation experiment was conducted again. The PPV of the right wall measured in the numerical simulation experiment is shown in Figure 27(a). The maximum PPV of the right wall was 8.9 cm/s, which meant that the blasting under this condition had met the safety requirements. Therefore, in the excavated tunnel, the digging length was adjusted to 1.9 m, the charge density was adjusted to  $900 \text{ kg/m}^3$ , and the blasting construction on-site was carried out again. Then, the PPV of the right wall at different positions of the first hole was extracted according to field experiment, as shown in Figure 27(b), the maximum value of the measured PPV of the right wall was 9.3 cm/s, which also showed that the optimized scheme was correct.

Therefore, the Daling tunnel continued to be constructed in accordance with this scheme, the PPV of the right wall

measured on site has never exceeded 10 cm/s while passing the small clear distance section, and the research content of the article effectively guaranteed the safe construction of Daling Tunnel and at the same time provided a corresponding reference for similar projects.

## 6. Conclusion

In this paper, the influence of the blasting on the lining structure of the first hole under different surrounding rock characteristics and blasting parameters was researched, and the sensitivity analysis and the control measure of the blasting vibration were further clarified. The main conclusions were as follows:

- (1) The blasting of the second hole would cause significant changes in the stress of the lining structure of the first hole, the maximum principal stress was 15.5 times the initial value, the minimum principal stress was 1.5 times the initial value, and the maximum PPV of the right wall had exceeded the safety threshold of 10 cm/s, which meant that the Daling tunnel was in a dangerous state.
- (2) The changing of all parameters would cause the maximum PPV of the right wall to exceed the safety threshold of 10 cm/s, but the sensitivity of various factors was different. The sensitivities of the explosive velocity of the right wall and the right arch waist were 6.114 and 7.292, respectively, far exceeding other factors, followed by the charge density and digging length. And the sensitivity of other parameters was relatively small, indicating that changing the explosive velocity had the greatest impacted on the vibration velocity, followed by the charge density and digging length.
- (3) The corresponding control measure was taken based on the results of sensitivity and actual situation on site, the charge density was changed to  $900 \text{ kg/m}^3$  (down 10%), and the digging length was changed to 1.9 m (down 5%), and after that, the maximum PPV of the right wall of the first hole had reduced 9.3 cm/s and did not exceed the safety limit. The research

content of the article effectively guaranteed the safe construction of the Daling tunnel and, at the same time, provided a corresponding reference for similar projects.

## Nomenclature

- $e_i$ : The value which is used to judge the influence degree of the parameter changed on the output value  
 $y^*$ : Output value after the parameter changed  
 $y$ : Output value before the parameter changed  
 $\Delta_i$ : Variation ranged of parameter  $i$   
 $S$ : Sensitivity discriminant factor  
 $Y_i$ : Output value of the  $i$ -th ran of the model  
 $Y_0$ : Initial value of the calculation result  
 $P_i$ : Percentage change of the parameter value of the  $i$ -th model calculation relative to the initial parameter value  
 $n$ : The number of times the model runs.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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