Influence of Hollow Effect on PPV of Wall Rock under Blasting Load

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Abstract. The purpose of writing this thesis is to solve the problem that the hollow effect of blasting construction affects the PPV of tunnel wall rock. Based on the law of energy attenuation and seismic wave propagation, the calculation equation of PPV of wall rock in excavation area and no-excavation area under blasting load is derived, and the variation law of PPV of wall rock under different loads is calculated by FLAC3D software. The results show that: (1) The accuracy of the calculation equation is verified by the calculation results of the software; the error between those is less than 6%; (2) In the range of twice the distance from the Heading Face, the hollow effect of wall rock is directly proportional to the load value; (3) The blasting load of 0.8MPa makes the maximum void effect concentrated in the wall rock 8m away from the face. The difference of PPV between the excavated area and the uncut area caused by void effect is 2.23 cm/s, and the quotient is 1.21 times.

Keywords. Tunnel engineering, PPV, energy method, numerical simulation.

1. Introduction
Tunnel blasting is one of the common ways of tunnel excavation, In the process of blasting construction, the peak particle vibration velocity (shorter form PPV) of wall rock and the cumulative damage of wall rock are caused by the propagation of seismic wave, therefore, the tunnel blasting construction process often causes part of the tunnel collapse. Due to the hollow effect of the tunnel, the collapse area often appears in the excavated area near the tunnel face [1]. How to determine the influence size and range of hollow effect on wall rock in the process of tunnel blasting is an urgent problem to be solved.

Relevant researchers have carried out the research on the hollow effect in the process of tunnel blasting construction. Yu [2] determined and proposed the tunnel blasting hollow effect though studying the blasting vibration mechanism of tunnel surface and using the blasting vibration instrument to monitor the surface vibration. Yang [3] further demonstrated the existence of hollow effect in the process of tunnel blasting construction by studying the surface vibration variation law of shallow tunnel blasting construction, and explained that the hollow effect is related to the tunnel section size, tunnel buried depth, blasting center distance and other related factors. Cai [4] determined the difference value and the quotient value of tunnel surface PPV between the excavated area and the non-excavated area under the effect of hollow effect through numerical simulation test. Some researchers have carried out the research on the attenuation law of the PPV of wall rock during the blasting process of tunnel. Such as, Fu [5] found that the PPV of tunnel wall rock decreases exponentially with the proportional distance of blasting; Shan [6] put forward the attenuation equation of PPV from the angle of energy; According to the reflection characteristics of seismic wave generated...
by blasting on the surface, He [7] proposed a equation for calculating the PPV attenuation of wall rock based on energy method. However, there is little research on the influence of hollow effect on the PPV of wall rock in the process of tunnel blasting construction.

In order to study the influence of hollow effect on the PPV of wall rock and its influence range, based on the study of the attenuation law of the wall rock PPV studied by He [7], and combined with the law of reflection of seismic wave generated in the process of blasting in wall rock media, the authors of the paper propose the attenuation equation of PPV of tunnel wall rock under hollow effect. The rationality of the PPV attenuation equation of tunnel wall rock is further demonstrated by numerical simulation method in this paper. Finally, different load values are loaded in the area where the tunnel blasting is located to determine the influence size and range of hollow effect during blasting construction.

2. Theoretical Analysis

2.1. Calculation Equation of Wall rock PPV

The seismic wave generated in the process of blasting is reflected and transmitted, which makes its energy dissipate, and the damping effect of tunnel wall rock makes the PPV of wall rock particle decrease continuously [8-9]. There are two main types of attenuation, one is Sadovsky attenuation equation, which is mainly applied to the calculation of surface PPV during tunnel blasting construction and shown in equation (1).

\[ V = k \left( \frac{Q^{1/3}}{R} \right)^{\alpha} \]  

(1)

The other is the energy attenuation equation, in the process of seismic wave propagation, the relative reduction of seismic wave energy is proportional to the distance of seismic wave propagation [8]. Therefore, the empirical equation of \( dx \) and \( dE \) can be determined as shown in equation (2).

\[ \frac{dE}{E} = -2\beta dx \]  

(2)

The relationship between the energy of tunnel blasting at the blasting source and the blasting energy at the tunnel wall rock \( r \) point is shown in equations (3) and (4). The energy attenuation equation of tunnel blasting can be obtained by solving the differential equation (2).

\[ E_0 = 4\pi r^2 \rho c_p \int_0^T v^2 dt \]  

(3)

\[ E_r = \eta E_0 e^{-2\beta r} \]  

(4)

where \( E_0 \) is the total energy produced during blasting; Where \( Er \) is the total energy of blasting seismic wave passing through the spherical surface at the monitoring point; Where \( r \) is the distance between explosion centers; Where \( \rho \) is the density of propagation medium; Where \( C_p \) is the acoustic velocity of medium; Where \( R \) is the distance between explosion centers; Where \( V \) is the PPV of particles allowed by safety; Where \( t \) is the duration of vibration at monitoring point. Where \( \eta \) is the constant related to the medium coefficient and attenuation coefficient, which is usually expressed by equation (5), and \( \beta \) is the medium absorption coefficient.

\[ \eta = \left( k \times 10^{2.3-\alpha} \right)^{3\alpha} \]  

(5)

Equation (3) is simplified as shown in equation (6):

\[ E_r = \eta E_0 e^{-2\beta r} \]  

(6)

Combined with equations (4) and (6), it can be deduced that:
Equation (8) can be derived from equation (7):

\[ v_r = v_0 \times \left( k \times 10^{-2 \cdot u} \right)^{(3/2 \alpha)} \times e^{-2\beta_r} \]  

where \( v_0 \) is the PPV of rock and soil at the explosion source. Where, \( v_r \) is the PPV of the tunnel wall rock at the distance \( r \) from the blasting source. When the seismic wave generated by blasting is not completely attenuated when transmitted to the surface, the residual seismic wave energy can be calculated by fitting equation \([7]\), in other words, the fitting energy attenuation equation is solved by integration. The calculation equation is shown in equation (9). The residual seismic wave energy continues to decay in the form of reflection wave:

\[ E' = cv_r^2 = c \left( \int_0^\infty f(r)dr \right)^2 \]  

where \( f(r) \) is the attenuation function of seismic wave PPV with distance; \( h \) is the distance from the surface to the explosion source; \( v_h \) is the sum of the residual PPV of seismic wave propagating to the surface, and the residual energy will be attenuated in the form of reflected wave \([7]\).

The PPV \( v \) of seismic wave near the ground surface is the superposition of the original attenuated PPV \( v_0 \) and the seismic wave PPV \( v_r \) reflected on the surface. In the process of downward propagation, the PPV of the surface reflection wave decreases continuously, and the energy retention ratio of seismic wave in the process of projection and reflection is 0.1~0.5 \([10]\), that is to say, the energy of seismic wave rapidly attenuates after reflected by the medium interface, which is only 0.1~0.5 of the original incident wave energy.

2.2. Calculation Equation of PPV Caused by Hollow Effect

In the process of tunnel blasting construction, due to the formation of a huge hollow in the excavated area of the tunnel, the seismic wave generated during the blasting construction is transmitted and reflected multiple times over the excavated area \([11-12]\), and which is superimposed with the seismic waves of other paths (which is shown in figure 1), so that the surface PPV of the excavated area is larger than that of the unearthed area.

![Figure 1. Schematic diagram of seismic wave propagation path under hollow effect.](image-url)
waves from other paths [13-15]. The number of propagation paths is odd and the number of reflection attenuation is even. Therefore, the equation of PPV is shown in equation (11):

\[ v_{r-non} = \left( k \times 10^{-\alpha} \right)^{3/2} \times e^{-\beta(1-\epsilon)} \times v_0 \]  

(10)

\[ v_{r-done} = \sum_{i=1}^{n} \left( k \times 10^{-\alpha} \right)^{3/2} \times e^{-\beta(1-\epsilon)} \times v_0 \times \xi^{2(n-1)} \]  

(11)

where \( L \) is the horizontal distance between the surface monitoring point and the blasting source, \( h \) is the vertical distance between the surface monitoring point and the blasting source, and \( \epsilon \) is the primary attenuation coefficient of reflection in the process of seismic wave propagation, and its value is related to the reflection angle.

To sum up, due to the excavation process of the tunnel, a large hollow area is formed behind the tunnel. Due to the influence of the hollow effect, the PPV of wall rock on the left and right sides of the tunnel face is inconsistent.

3. Field Test Analysis

3.1. General Situation of Engineering Geology

In order to analyze the variation law of wall rock PPV caused by hollow effect in the process of tunnel blasting construction, this paper takes a tunnel project in a highway as the basis. Tunnel starting-ending mileage is K72+440~K72+740. The buried depth of the tunnel is about 24 m, and the design height and width of the tunnel are 6.5 m and 6.1 m respectively. The geological conditions of the tunnel are shown in table 1.

In the construction process of tunnel engineering, C20 and C25 concrete are used as the primary support and secondary lining materials respectively. The physical and mechanical parameters of concrete are shown in table 2. STW-Rock is the strongly weathered rock shorter form, and INW-Rock means Intermediary weathered rock, SLW-rock: Slightly weathered rock.

| Geotechnical type       | Severity kN/m³ | Poisson’s ratio | Elastic modulus MPa | Cohesion kPa | Friction angle | Thickness m |
|-------------------------|----------------|-----------------|---------------------|--------------|----------------|-------------|
| Miscellaneous soil      | 18.5           | 0.33            | 8                   | 8            | 10             | 2.5         |
| STW-Rock                | 20.8           | 0.30            | 440                 | 30           | 24             | 3.5         |
| INW-Rock                | 22.9           | 0.28            | 536                 | 70           | 28             | 14          |
| SLW-Rock                | 24.6           | 0.25            | 740                 | 120          | 35             | 40          |

| Material type           | Density g/cm³ | Poisson’s ratio | Elastic modulus GPa |
|-------------------------|---------------|-----------------|---------------------|
| C20 Concrete            | 24.0          | 0.22            | 26                  |
| C25 Concrete            | 24.6          | 0.18            | 30                  |

3.2. Field Test

In order to determine the K and \( \alpha \) value of Sadovsky's empirical equation, monitoring points were randomly arranged on the surface above the tunnel’s uncut area. During the blasting process, the maximum blasting charge of a single section is set as 3.6 kg, 4.5 kg, 7.2 kg and 9.6 kg. Record the blasting related parameters and draw the PPV attenuation diagram. The horizontal axis is the proportional distance, and the longitudinal axis is the PPV, as shown in figure 2.
In order to determine the absorption coefficient of the medium to the PPV in the process of seismic wave propagation, monitoring points are arranged every 2 m on both sides of the surface heading face above the direction of tunnel excavation in the field test. The blasting charge of single section is 3.6 kg, and the PPV of monitoring point is monitored respectively. The monitoring values are shown in figure 3.

![Figure 2. Diagram of the relation between the PPV and the proportional distance.](image)

![Figure 3. Diagram of the relation between the PPV and the distance from explosion Center.](image)

The fitting equation of monitoring data is $y = 7031.1x^{2.1943}$, the coefficient related to medium and blasting conditions is 7031.1, and the vibration attenuation coefficient is 2.1943. Due to the complex environment of blasting construction, the site monitoring points are too scattered, which makes the $K$ value too large.

The field test in figure 3 shows that the surface PPV above the excavated area is slightly higher than that above the unearthed area, which verifies the correctness of the theoretical analysis equation (11).

According to the neutralization equation (4) in figure 3, the absorption coefficient of rock medium in the tunnel project is 0.048 (half of the fitting equation index), and the absorption coefficient of the surface above the unearthed area is 0.063 (half of the fitting equation index).

The relationship between the PPV of the seismic wave generated by blasting in the propagation process and the PPV at the blasting source and the blasting center distance is shown in equation (12):

$$v_r = v_0 \times \left(7031.1 \times 10^{-2.1943}\right) \times e^{-0.062r}$$

(12)

It is simplified as follows:

$$v_r = 0.5789v_0 \times e^{-0.062r}$$

(13)

4. Numerical Simulation Analysis

4.1. Numerical Model
The numerical calculation model of tunnel engineering established by FLAC3D software is shown in figure 4. The numerical calculation model is 160 m in length, 50 m in width and 60 m in height. The tunnel depth is 25 m. The rock strata above the tunnel are respectively slightly weathered sandstone, moderately weathered sandstone, strongly weathered sandstone and miscellaneous filling soil layer. The displacements at both ends of x-axis and y-axis are calculated, and the bottom displacement constraint in z-axis is fixed, and the top of z-axis is free boundary.

4.2. Determination of Blasting Load
For the convenience of calculation, the blasting load is simplified as triangle load. The total time of
blasting load action is 0.06 s, in which the loading time is 0.01 s, the unloading time is 0.05 s, and the peak load is 103 MPa, as shown in figure 5.

![Numerical calculation model of tunnel](image)

**Figure 4.** Numerical calculation model of tunnel.  **Figure 5.** Time range map of blasting impact load.

### 4.3. Influence of Blasting Construction on PPV of Tunnel Wall rock

One part of the energy generated in the blasting construction is used to break the rock and cause rock vibration, and the other part causes damage to the rock mass and damage the engineering disaster. In order to analyze the influence of blasting construction on the PPV of tunnel wall rock, the numerical simulation and theoretical calculation are discussed respectively.

In terms of numerical simulation, the variation law of PPV of wall rock above the face under blasting impact load in figure 5 is simulated; in theoretical calculation, attenuation equation (11) derived from PPV and equation (9) for residual capacity are used to calculate the variation law of PPV of wall rock. The comparison values of the two are shown in figure 6.

![The comparison between the theoretical and simulated value of the surface PPV](image)

**Figure 6.** The comparison between the theoretical and simulated value of the surface PPV.

It can be seen from table 1 and figure 6 that the theoretical value and simulation value of the wall rock PPV in the blasting process are close to each other. Except for the PPV error near the interface of each rock stratum, the relative error of the PPV of the wall rock is controlled within 6%. The error between the calculated value and the simulation value of the PPV of the wall rock near the interface of each rock layer increases. The main reason is that the reflection of the rock interface to the seismic wave is not considered in the derivation process of the calculation equation, resulting in a large difference near the midpoint between the rock layers.

### 4.4. Influence of Hollow Effect on PPV of Tunnel Wall Rock

In order to calculate and analyze the influence of hollow effect on the PPV of tunnel wall rock in the process of tunnel blasting construction, the maximum influence area of tunnel effect is determined by numerical simulation method. In order to ensure the stability of wall rock in the process of simulated blasting construction, the blasting load is determined in a small numerical range, i.e. 0.4 MPa – 0.8
MPa, and the variation law of surface PPV in the area affected by tunnel blasting excavation is recorded, as shown in figure 7.

In order to further analyze the effect of hollow effect on the surface PPV above the tunnel excavation area, the difference calculation of the surface PPV above the excavated area and the unearthed area of the tunnel is carried out. The calculation results are shown in figure 8.

![Figure 7. The variation law of the PPV under different loads.](image)

![Figure 8. The Void effect of surface the PPV under different loads.](image)

It can be seen from figure 7 and figure 8 that when the load value is within a certain range, the greater the load is, the greater the difference between the surface PPV of the excavated area and that of the unearthed area. In addition, with the increase of load value, the distance between the maximum value of void effect and the face of the tunnel is further. Through the surface PPV (figure 7), equation (11) and equation (13), we can deduce and analyze the influence of hollow effect on the PPV of wall rock particles under different loads. Taking the load of 0.8 MPa as an example, the variation law of PPV of wall rock in the excavation area and the excavated area 8m away from the tunnel face is calculated and drawn, as shown in figure 9.

![Figure 9. Comparison of wall rock PPV under 0.8 MPa load.](image)

It can be seen from figure 8 and figure 9 that under the action of blasting load of 0.8 MPa, the PPV of wall rock in the excavated area is slightly higher than that in the non-excavated area, and the most obvious void effect area is located at the vault of the excavated area 8m~12m away from the tunnel face. The difference of the PPV of the tunnel vault in the excavated area and the unearthed area is 2.23 cm/s, and the quotient value of the two is 1.21 times. Therefore, in the process of blasting excavation, the blasting charge should be controlled. When a large amount of blasting charge is needed, the
support of the tunnel vault in the excavated area should be strengthened, and the tunnel vault area in the excavation area is needed to pre-supported to prevent large-scale collapse.

5. Conclusion
(1) Based on the energy method, the relationship between the rock PPV and the PPV at the blasting source is derived; According to the propagation law of seismic wave reflection and transmission, the calculation equation of PPV of wall rock in tunnel excavation area and non-excitation area is derived. The results show that the PPV of the wall rock in the excavated area is slightly higher than that in the non-excavation area;
(2) Based on the tunnel blasting field test and numerical simulation test, the accuracy of the derivation equation of wall rock PPV is verified. The relative error of wall rock PPV calculated by numerical simulation test and calculation equation is controlled within 6%;
(3) In a certain load range, the larger the load, the more obvious the hollow effect on the wall rock PPV, and the farther the peak value of the PPV difference between the excavated area and the non-excavated area is from the tunnel face;
(4) The next research work is based on the calculation equation of the effect of hollow effect on the PPV of tunnel wall rock.

Acknowledgments
This study was financially supported by the Fund projects: 2020 Guangxi University Young Teachers' basic scientific research ability improvement project (2020KY18023); 2017 School level scientific research projects of Natural Science in Hezhou University (2017ZZZK12)

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