Study on the response mechanism of tunnel blasting dynamics and the spatial variation characteristics of the surrounding rock

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Abstract: The construction of the new Orfa drill explosion is the main method of tunneling in mountainous areas at present, and the vibration waves produced by blasting have a great influence on the deformation and stability of the surrounding rock. Based on the tunnel project at the Dalong Expressway in Guizhou, China, the vibration and deformation parameters of the surrounding rock in the blasting construction process are monitored, and the dynamic response mechanisms are studied. Simulations are carried out using the FLAC3D software, and actual measurements of the deformation of the surrounding rock are compared with the results from the numerical simulations. The results show that the blasting parameter is the key influencing factor that determines the blasting power effect. The maximum displacement of the surrounding rock under blasting action occurs in the vault. The displacement area can be divided into five affected regions that show obviously different displacement degrees, where more deformation occurs for surrounding rock that is located closer to the explosion source. Of the three investigated waveforms, all show decreased displacement with distance. However, the exponential load waveform can more effectively represent the spatial variability characteristics of the surrounding rock than the other two load waveforms, where the simulated deformations obtained with this waveform are similar to those of the actual working conditions.

1 Introduction

With the rapid development of China’s economy and transportation, the importance of tunnel construction has become increasingly prominent. At present, the main method of tunnel excavation in China is NATM drilling and blasting. The vibration load produced by blasting has an important influence on the safety and efficiency of tunnel construction. The main effects caused by blasting are the subsequent vibrations, which deform and damage the tunnel’s surrounding rock. According to research and engineering practices, it is known that the damage caused to the surrounding rock is related to blasting construction and other factors. If the impact load produced by blasting reaches a certain limit, it will affect the stability of the surrounding rock.

Xie (2017)\textsuperscript{1} used non-linear regression to process and analyze data collected at different frequencies, including energy spectra of the vault, and waist and side wall. The author concluded that different distances have a great impact on the superimposed vibration waveforms. By combining theoretical analyses, numerical calculations and engineering verifications, Zhang et al. 2018\textsuperscript{2} concluded that the damage range of the surrounding rock under the coupling action of the blasting load and transient unloading is the largest, where the former is the main reason for the formation of tensile damage zones. Liu and Chen\textsuperscript{3} studied the blasting construction of a cut hole in the Dapingshan Tunnel, and isolated...
the influence of different surrounding rock grades on the surface vibration waveforms caused when cutting the hole of the tunnel. Zhang Ping et al. (2018)\cite{4} studied the vibration characteristics of the surrounding rock caused by tunnel blasting under different conditions using ANSYS numerical simulations. It was concluded that the top part is most affected by blasting vibrations, and the vibration velocity therein was the highest, followed by the velocities in the shoulder art and the waist. Mosinets et al. (1979)\cite{5} considered that explosive stress is the main cause of surrounding rock damage during the blasting excavation of rock masses, while secondary damage is caused by high-pressure gas produced by the explosives. Yang et al. (2018)\cite{6} established a two-dimensional theoretical model of circular excavation, and studied the stress evolution and rock damage caused by millisecond blasting.

At present, there is considerable research regarding the damage and destruction of the surrounding rock of tunnels. However, few studies exist on the displacement and deformation of the surrounding rock. Therefore, in this work we explore the displacement and deformation of the surrounding rock under blasting vibration loads. By taking NATM drilling and blasting excavation as an example, the influence of the vibration load generated by continuous blasting excavation on the surrounding rock support of tunnels is analyzed with the FLAC3D numerical simulation software. Our aim is to determine the deformation and dynamic response characteristics of the surrounding rock under drilling and blasting construction. This work has great engineering significance and scientific research value for blasting construction of such tunnels.

2. Test Area
The tunnel, which is located on the Dalong Expressway in Guizhou, China, is a long separated road tunnel with a net width of 10.25 m and a net height of 5 m. The building boundary of the emergency parking zone is 13.25 m, and has a net height of 5 m. The vehicle crossing tunnel is 4.5 m in net width and 5 m in net height. The pedestrian crossing tunnel is 2 m in net width and 2.5 m in net height. The total length is 2195 m. Bamboo-cutting portals and end-wall portals are used at both the left and right entrances of the tunnel. The maximum depth of the tunnel is about 139.8 m, the elevation of the tunnel entrance is about 689.6 m, and the elevation of the tunnel exit is about 673.7 m. The tunnel is divided into three classes, V, IV and III, which respectively consist of 9.8% (215 m), 58.3% (1280 m) and 31.9% (700 m) the total length of the tunnel. Based on the principle of NATM, composite lining is the main construction method for tunnel lining, and excavation occurs at both ends of the tunnel. Figure 1 is a schematic diagram of the internal structure of the tunnel.

2.1 Exponential Load Waveform
The exponential carrier shape considers a spherically symmetric blast in an infinite medium. According to the principle of the blasting equivalent hole, the blasting source is regarded as a uniform pressure acting on the inner wall of a cavity, which varies with time. The relationship between the load and time is as follows:

\[ P(t) = P_b f(t) \]  \hspace{1cm} (1)

where \( P_b \) is the peak value of the pulse and \( f(t) \) is the exponential time lag function, given as:

\[ f(t) = P_0 \left( e^{-\frac{nt}{\sqrt{2}}} - e^{-\frac{mnt}{\sqrt{2}}} \right) \]  \hspace{1cm} (2)

where m and n are dimensionless damping coefficients related to the distance, which determine the starting position and waveform of the explosion pulse.

In practical engineering applications, m and n are assigned according to experience, and then the theoretical waveforms are compared and corrected by monitoring measurement results and theoretical calculations.

2.2 Smooth Curve Load Waveform
In numerical simulations, the load attenuated by the blasting stress wave through the crushing zone and the rupture zone acts directly on the elastic vibration zone at the edge of the rupture zone\cite{7}. The mathematical expression of the load waveform is as follows:
\[
\begin{cases}
P(t) = \sigma_r \left( \frac{1}{2} - \frac{1}{2} \cos \frac{\pi}{t_0} t \right) & (t < 0) \\
P(t) = 0 & (t > 0)
\end{cases}
\]

where \( \sigma_r \) is the radial load and \( t_0 \) is the blasting loading time.

### 2.3 Triangular Load Waveform

As shown in Figure 1, the triangular load waveform considers the explosive compression wave in a geotechnical medium\(^8\). After its peak value, the compression wave decays rapidly and propagates according to the unloading carrier. In triangular loads, the typical time order of pressure rise is 10 ms, while the time order of unloading is about 100 ms.

![Fig. 1. Blast pulse load.](image)

The triangular load generated by the explosion of a single borehole is as follows:

\[
P(t) = P_m f(t)
\]

where \( f(t) \) is a function reflecting the change of the blasting load with time, which can be calculated by the boosting time and positive pressure time, and \( P_m \) is the peak value of blasting load, which is mainly related to the properties of the explosives.

Under the condition of uncoupled continuous change, \( P_m \) can be calculated as:

\[
P_m = \frac{1}{5} \rho_c D^2 k_c^{-6} \eta
\]

where \( \rho_c \) is the charge density, \( D \) is the explosive detonation velocity, \( k_c \) is the uncoupling coefficient, and \( \eta \) is the expansion multiple of hole wall pressure affected by the detonation gas.

### 3. Numerical Simulations of the Dynamic Response

According to the design standard of expressways, and the topographic and geological conditions of the tunnel, a separated two-way four-lane design was constructed.

The three different load waveforms were simulated to get the deformation size of each area in the surrounding rock. According to the deformation characteristics, the following results were obtained.

#### 3.1 Exponential Simulation Results

Based on the three-dimensional explicit difference method, the lumped mass in the distributed grid nodes was calculated using the real density of the surrounding area, and the motion equation was solved nonlinearly.

By incorporating historical records into the model, we determined the displacement of the surrounding rock in different directions under different blasting vibration loads. It was found that the larger the load, the larger the vertical displacement of surrounding rock. Shorter distances to the central axis also resulted in larger vertical displacements. Smaller horizontal displacements occurred at the waist of the tunnel.
Figure 2 shows that the maximum vertical displacement occurs at the vault, which is 2.083 mm. The displacement from the vault to the surface of the stratum decreases gradually, and the ground at the bottom of the tunnel also decreases gradually to the surrounding area. In the horizontal direction, the deformation of the vault is less than that of the side wall and less than that of the arch waist. It can be concluded that the arch waist is more vulnerable to horizontal deformations and failures than other positions in the tunnel.

The total displacement of the tunnel-surrounding rock is shown in Fig. 4. The maximum displacement occurs at the vault, which is 6.822 mm. The vault displacement area can be divided into five affected areas, each with different displacement degrees. The first and second areas are near the surrounding explosion source, and the displacement degree is the largest, ranging from 6.5 mm to 6.8 mm. The main impact energy is generated by the explosion. Once the explosion has been initiated, the rock near the explosion source is destroyed by the initial shock wave and high-pressure gas, and the rock’s mechanical parameters are weakened rapidly. Rock failure, compression, shear and crushing occur in the most serious deformation area and produce the largest displacement. However, it can be seen from Fig. 6 that the deformation area is small and the horizontal diffusion range is not large, which is similar to the tunnel width, and the vertical influence is concentrated. The third and fourth regions are located at intermediate distances to the explosion source, whose displacements range from 5.0 mm to 5.5 mm, which is mainly caused by extrusions imparted by the vibration load. The vibration load propagates in the form of stress waves in the surrounding rock, causing the rock particles to vibrate as well as imparting strain and displacements to the rock mass. The fifth area is the far-end radiation area, and the vibration load is continuously attenuated in the process of transmission to the far-end until there is no deformation, and the remaining energy is absorbed by the surrounding rock mass. The displacements of these five deformation regions correspond to the law of descending zone of time history curve of a blasting impulse vibration load, which fully illustrates the good correlation between the degree of deformation and the displacement generated by the blast and its vibration load. The displacement from the vault to the surface decreases gradually, and the displacement is more concentrated and directional, which is around the vertical direction of the central axis of the vault. The displacement of the arch waist and the side wall is small, and the total displacement follows the sequence: side wall deformation < arch waist deformation < vault deformation.

The Origin drawing software was used to display the displacement of vault and tunnel bottom and the distance of explosion source, as shown in Fig.5.
According to the curve shown in Fig. 5, it can be observed that the displacement of the surrounding rock is related to the distance of the explosion source, where the closer to the explosion source, the more the surrounding rock is displaced and deformed.

3.2 Curvilinear Simulation Results
The transverse load ‘parameter_r’ was substituted into the curve load formula to obtain the mechanical equation, which was imported into FLAC3D to determine the node displacement.

It can be observed from Fig. 6 that the curved load is similar to the exponential load and the displacement law is the same. The difference between them is that their peak values are different and the vertical range of the curvilinear load is larger.

3.3 Triangular Simulation Results
When calculating the impulse loads, the load can be approximated by a triangle. The load time history curve is shown in Fig. 7.

From Fig. 7, it can be seen that the blasting form can be divided into two stages: ascending and descending. The action time of the load is related to the blockage of the borehole and the expansion of the chamber. The duration is generally considered to be 10−6 to 0.1 s. The blasting boost time is 5 ms and the positive pressure action time is 30 ms.
Fig. 7. Triangle blast load time curve. Fig. 8. Total displacement under a triangular load.

It can be seen from Fig 8 that the total displacement under a triangular load is widely distributed and concentrated. Although the maximum displacement is located at the vault, which is 10 mm, the radiation range is small and the deformation area is small. The dome displacement area can be divided into two affected areas with different displacement degrees. The first area is near the surrounding explosion source, which has the largest displacement, ranging from 9 mm to 10 mm, with a small radiation range and concentrated deformation. The second affected area is in the middle of the explosion source, where the displacement range is 5–8 mm, and the radiation range is also small. In the arch waist area, there is one more far-end radiation area than the vault area, and the displacement is less than 1 mm.

The displacement of the vault and the tunnel’s bottom, and the distance of explosion source, are shown in Fig. 9.

Fig. 9. Distance between the displaced surrounding rock and the explosion source under the action of a triangular load.

4. Engineering Comparison
Measurement points were laid out and recorded immediately after the tunnel excavation, where the horizontal convergence and vault subsidence of the tunnel were obtained. The settlement of the vault was obtained from the measured data, as shown in Table 1, which are compared with the simulated results.

Table 1. Comparison of the vault settlement simulated with the three waveforms with actual measured values.

| Measuring point | D | δ₁ | δ₂ | δ₃ | δANNOTATION |
|-----------------|---|----|----|----|-------------|
| 1               | 0 | 6.822 | 7.207 | 4.972 | 6.697 |
| 2               | 0.114 | 6.699 | 7.152 | 2.624 | 6.504 |
| 3               | 0.77 | 6.616 | 6.997 | 1.413 | 6.457 |
| 4               | 1.065 | 6.572 | 6.921 | 1.065 | 6.443 |
| 5               | 1.413 | 6.532 | 6.898 | 0.770 | 6.342 |
| 6               | 2.624 | 6.47 | 6.795 | 0.114 | 6.162 |
| 7               | 4.972 | 6.105 | 6.554 | 0.000 | 5.87 |

In Table 1, D is the thickness of the tunnel top at the deformation measuring point, δ₁ is the displacement value of exponential load waveform, δ₂ is the displacement value of the smooth curve load waveform, δ₃ is the displacement value of triangular load waveform, and δ is the measured settlement value of the vault. In the table it can be seen that the vault settlement simulated by the exponential load waveform is closest to the measured value.
The deviations between the settlement of the exponential-simulated vault and the measured value are compared in Table 2.

| Measuring point | D /m | δ₁ /mm | δ /mm | Δδ /mm | K /% |
|-----------------|------|---------|-------|--------|------|
| 1               | 0    | 6.822   | 6.697 | 0.125  | 1.9  |
| 2               | 0.114 | 6.699   | 6.504 | 0.195  | 2.9  |
| 3               | 0.77  | 6.616   | 6.457 | 0.159  | 2.4  |
| 4               | 1.065 | 6.572   | 6.443 | 0.129  | 2.0  |
| 5               | 1.413 | 6.532   | 6.342 | 0.190  | 2.9  |
| 6               | 2.624 | 6.47    | 6.162 | 0.308  | 4.7  |
| 7               | 4.972 | 6.105   | 5.87  | 0.235  | 3.8  |

In Table 2, the parameters have the same meaning as in Table 1, while \( \Delta \delta \) is the absolute estimation deviation, and K is the relative estimation deviation, which are given as:

\[
\Delta \delta = \delta_1 - \delta \tag{6}
\]

\[
K = \left( \frac{\Delta \delta}{\delta} \right) \times 100\% \tag{7}
\]

A comparison of the different simulated load waveforms is given in Fig. 10. From the figure we can make the following points.

The exponential-load waveform and the curve-load waveform can approximately simulate the real displacement, however, the exponential-load waveform is the closest to the actual displacement curve. In all cases, the simulated results are slightly larger than the actual displacements. Considering that the simulation is in the ideal state, the actual conditions are often affected by many factors.

The waveform error of each curve load is large. Although the displacement of the simulated blasting area accords with the law, the peak value is large. The maximum acceleration amplitude of each curved load waveform occurs within 100 ms after the arrival of the seismic wave. Only when the interval between two periods is greater than 100 ms can the error caused by the peak superposition be avoided.

Due to the relationship between the frequency and action time, the maximum peak value of the triangular load waveform is smaller than the actual peak value, and there is a big error. The periodicity of the triangular load waveform is also quite different from that of actual vibration waveform. As the modelled input load, loading was considered as a simple process of loading and unloading, and it likely does not fully reflect the periodic vibration effect imparted by the vibration load.

5. Conclusions
Through simulations of tunnel blasting, the following conclusions can be drawn from our study of the vibration area zones and their comparison with actual tunnel blasting measurements.
(1) The influence of blasting vibrations on the surrounding rock of tunnel is mainly in the vertical direction, which diffuse vertically and longitudinally in waveform. In the simulated blasting conditions, the closer the blasting source is, the more serious the surrounding rock is deformed, and the larger its displacement is. The displacement decreases with distance.

(2) When the tunnel is blasted at different locations, the influence of the blasting vibrations is different. The displacement and deformation of the vault are the largest, while the arch waist is the second-most affected area, and the side wall is the least affected area. When the tunnel is blasted, the displacement of the surrounding rock is concentrated and directional.

(3) Combining the simulated results with the actual working conditions, it is suggested that the blasting arrangement can be adjusted according to the strength of the surrounding rock of the project site, and the vertical displacement of the vault can be controlled to avoid the potential safety hazards caused by the excessive deformation of the surrounding rock at the top.

(4) The exponential load waveform can more accurately show the influence of the blasting load on the deformation of the surrounding rock. However, for distant regions, the exponential load waveform and the curve load waveform are more in line with the actual working conditions than the triangular load waveform.

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