Research Article

Numerical Simulation of Surface Vibration Propagation in Tunnel Blasting

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In order to better study the propagation law of tunnel blasting in mountain landforms, taking the excavation blasting project of the Yangliu tunnel along the Yinsong expressway in Guizhou as the research object, the propagation law of vibration waves to tunnel blasting under the mountain tunnel was analyzed based on the ABAQUS finite element software and compared with the field monitoring data. The results show the peak vibration velocity of numerical simulation. Generally, the simulation value is slightly larger than the field monitoring value, but the average error of closing speed is less than 25% and the maximum error is less than 45%. The component velocity of surface peak vibration under blasting to load is the largest in the vertical direction. The “cavity effect” formed by the side-passing tunnel wall has the most significant amplification effect on the peak vibration velocity in the X direction of the rock and soil above it, which is about 1.62∼1.85 times and the resultant velocity is enlarged by 1.27∼1.45 times. Blasting vibration waves spread to the surface in the form of spherical waves inside the mountain, causing the vibration center of the surface to move to the area with lower elevation. The “cavity effect” caused by the side-through tunnel and the shift of the surface diffusion center to the lower part together led to the peak velocity of the lower measuring point of the Yangliu tunnel being much higher than that of the higher measuring point. The research results of this paper have certain reference significance in controlling the influence of underground blasting vibration on residential buildings in mountain areas.

1. Introduction

With the continuous advancement of infrastructure construction in China, tunnel engineering has developed rapidly and a large number of highway tunnels have emerged as mountainous areas, such as Guizhou. A drilling and blasting method is still the most commonly used tunnel excavation method of present because of its advantages, such as a wide application range, but the vibration wave generated by simultaneous blasting not only affects the safety of the tunnel structure but also harms the stability of residential buildings around the explosion source. Therefore, in the process of tunneling, it is necessary to monitor the vibration of surrounding residential buildings and study the propagation law of the blasting vibration wave by numerical simulation, so as to guide the design of blasting parameters and excavation construction [1, 2].

Many scholars have studied this, and some of them have produced some results. Combined with field monitoring and dynamic finite element numerical simulation, the vibration propagation law of the surface during blasting excavation of the lower step of ultra-shallow buried channel is studied. The cavity formed into the excavation area of the shallow tunnel changes the complete structure of the shallow rock mass above the tunnel, resulting in the “cavity effect” when vibration waves propagate to the surface. This effect was subsequently confirmed by more studies. In addition, research shows that the “cavity effect” caused by blasting construction within 28 m of the tunnel cavity area is particularly obvious and the “slope effect” and the “elevation amplification effect” are also amplifying the peak vibration velocity of complex terrain [3–5]. The amplification effect of blasting operation on the peak vibration velocity in the vertical direction of the ground surface is extremely
prominent, which not only has an adverse vibration effect on the building’s structures of the ground surface but also affects the stability and design of infrastructure in mountainous areas with complex terrain. The LY-DYNA software is used to simulate the propagation law of blasting vibration velocity in tunnel excavation, and it is found that controlling the charge and extending warranty time can effectively slow down the influence of blasting vibration \[6–10\]. Many scholars have conducted a lot of research on the propagation of tunnel blasting vibration waves in different landforms. However, the complex geological environment of mountain tunnels leads to a lot of randomness and unpredictability in the study of blasting vibration laws. In view of this, this paper relies on the blasting project of the Yangliu tunnel along the Yinsong expressway in Guizhou \[3,11–14\]. By using the method of field monitoring and numerical simulation, the propagation law of blasting vibration waves on the mountain surface is studied, the amplification effect of vibration wave in the tunnel is analyzed and the simulated value of vibration peak velocity is compared with the measured value \[15–18\]. The research results of this paper have certain reference significance for the prediction and safety control of blasting vibration in the tunnel.

2. Materials and Methods

2.1. Project Overview. The left line of the Yangliu tunnel starts and ends at a pile number ZK2 + 445~ZK2 + 829, with a length of 384 m; right start-stop change YK2 + 430~YK2 + 845, 415 m long. The entrance to the cave is located on the steep slope on one side of the mountain, with steep terrain. The terrain of the Gonghe tunnel site area fluctuates greatly, which belongs to the middle-low hilly landform type. The ground elevation of the tunnel center is 691.21~802.57 m and the relative height difference is 111.36 mm. The stratum in the tunnel area is partially covered with Quaternary gravel soil, Lower Ordovician middle-upper series (O2-3) mudstone, and sandstone interbedded with limestone. Rock strata in the tunnel area are thin-to-medium-thick layers, with bedding development and multiple integrated contacts. Joints and fissures in bedrock are developed. Weathered fissures are mostly distributed over the shallow surface layer of weathered soft rock, showing a grid shape, and not extending far. Influenced by regional fold structures and fault structures, joints are widely distributed and most of them cut through the rock mass. The rock mass is cut into irregular shapes, with cracks ranging from 0.4 to 10 cm to 10 cm in width and most of them are unfilled, with large cracks, which are easy to form dangerous rocks.

2.2. On-Site Monitoring Scheme. As shown in Figure 1, the explosion source of the Yangliu tunnel are located at the right milege pile number YK2 + 780 of the tunnel and the monitoring data onto three times of blasting vibration are recorded. Two of them are selected for the follow-up study on the influence degree of blasting vibration on surrounding houses. Four monitoring points are set up in four representative houses near the Yangliu tunnel and the houses at measuring points A and C are brick structures. The houses in measuring points B and D are pure wood structure and brick-wood structure, respectively.

TC-4850N blasting vibration meter is used for data monitoring and the sensor is fixed on the ground with mixed hemihydrate gypsum to form a rigid connection with the ground, with the explosion source as the center, the X axis direction of the sensor is horizontally radial, the Y axis is horizontally tangential, and the Z axis is vertically upward. The parameters of each blasting of the two tunnels are shown in Table 1, where \(d\) is the distance from the blast hole to the load acting surface. \(Q\) is the charge of a single shot hole.

2.3. Blasting Vibration Monitoring Results. The peak vibration speeds of each monitoring point during the blasting excavation of the Yangliu tunnel are shown in Table 2, where \(V_x, V_y, V_z,\) and \(V\) are the X-direction sub-speed, Y-direction sub-speed, Z-direction sub-speed, and closing speed of the peak speed, \(Q\) is the charge of a single shot hole, \(H\) is the height difference between the measuring point and the blasting source, \(D\) is the horizontal distance between the measuring point and the blasting source, \(R\) is the blasting source distance and \(R^2 = H^2 + D^2\).

It can be seen from Table 1 that the larger the explosion source distance (measuring points A and B), the smaller the peak velocity and its component velocity; the smaller the height difference (measuring points C and D), the larger the peak velocity of measuring points and its subvelocities. In the same measuring point, the peak velocity in Z direction is the largest, followed by Y direction and the smallest in X direction.

2.4. Establishment of the Numerical Model. During blasting construction, the vibration wave will uniformly act on the surrounding rock along the radial direction of the tunnel and the surrounding rock will be compacted first and then it
will decay sharply after reaching the peak value. Therefore, the blasting compression wave in the geotechnical medium is generally simplified into a triangular load form. The burst pressure in the form of a triangular load is generally shown in Figure 2. The explosion pressure curve is mainly described by three characteristic values: peak pressure $P_{\text{max}}$, loading time $t_R$, and total action time $t_S$.

The peak value of blasting load stress $P_{\text{max}}$ is estimated according to the following empirical formula (1)

$$P_{\text{max}} = \frac{139.97}{Z} + \frac{844.81}{Z^2} + \frac{2154}{Z^3} - 0.8034.$$  \hspace{1cm} (1)

Among them, $Z = d/\sqrt{Q}$ is the proportional distance. According to the calculation, the peak stress values of the first and second blasting loads are 14.31 MPa and 10.59 MPa, respectively.

The duration of the blasting shock wave generally ranges from $10^{-6}$ to 0.1 s. Referring to similar research, loading time $t_R = 0.01$ s and total action time $t_S = 0.08$ s.

The surrounding rock at the right exit section of the Yangliu tunnel is Grade IV. According to the engineering rock mass classification standard and similar projects, the Rayleigh damping coefficients of the surrounding rock $\alpha = 0.075$, $\beta = 0.01$ and other parameters of the surrounding rock and lining are shown in Table 3.

Through the simulation of the ABAQUS finite element software, the cut-off surface with viscoelastic boundary conditions is more consistent with the actual situation. In this paper, referring to the similar project, the bottom is constrained by a fixed end and the four cut-off surfaces except the bottom are all subjected to viscoelastic boundary conditions with the corresponding spring stiffness coefficient of 0.01 and a damper coefficient of 0.12. The built model and the spatial position of each measuring point are shown in Figure 3.

### 3. Results and Discussion

#### 3.1. Comparison of Simulated and Measured Data

The maximum explosive charge of the 1st and 2nd blasting is 18 kg and 13 kg, respectively. Table 4 shows the numerical simulation and measured peak velocity and its subvelocity of each measuring point.

It can be seen from Table 4 that the simulated value is generally larger than the measured value, but the average error of closing speed is less than 25% and the maximum error is less than 45%. The simulated values of peak velocities and subvelocities of all measuring points are greater than the measured values; the larger the measuring point elevation (A and B measuring points), the larger the error; at the same measuring point position, the peak velocity error in Z direction is the smallest, the closing velocity is the second, and the errors in X and Y directions are the largest. The larger the maximum section charge, the larger the values of peak velocity and subvelocity, but the smaller the error between the simulated value and the measured value is sluggish. Therefore, the finite element numerical model in this paper has strong credibility for the prediction of blasting peak vibration velocity.

There is little difference between the maximum charge of the two blasts and the evolution trend of the vibration velocity field is roughly the same. Here, it is enough to analyze the propagation law of the blasting vibration wave when $Q = 18$ kg. The propagation law of the first blasting ($Q = 18$ kg) at the speed of the site table is shown in Figure 4.
(speed unit: m/s), in which the white elevation line is the relative contour line and the lowest point of the ground surface in Figure 3 is 0 point. The propagation law of the combined velocity field of first blasting inside the mountain is shown in Figure 5. The internal section is parallel to the z-x plane and the cutting point is the explosion source point.

As can be seen from Figures 4 and 5, the maximum velocity point of the vibration wave is located in front of the tunnel excavation face and the vibration wave diffuses outward in the form of an approximate spherical wave inside the mountain. After it reaches the surface, because the terrain of the surface is high on the left and low on the right, the point that the spherical wave first touches is located right above the explosion source (towards the surface with lower elevation). Then on the ground, along the tunnel axis, it is scattered to the terrain with different heights on the left and right in an approximately symmetrical way (Figure 4). However, as the surface diffusion points are close to C and D points, the vibration peak velocity at the lower C and D points is higher than that at the higher A and B points.

### 3.2. Cavity Effect

In order to analyze the influence of the right-hand tunnel in Figure 5 (the left exit in Figure 1) on blasting vibration waves, three monitoring points (right monitoring points 1, 2, and 3) are selected directly above the right-hand tunnel, which are 5.2 m, 10.4 m, and 15.6 m away from the tunnel vault, respectively, with the explosion source as the symmetric center and three measuring points with the same height as the right-hand monitoring points are arranged on the left side of the explosion source (left monitoring points 1, 2, and 3), left monitoring point 1. The layout of measuring points is shown in Figure 6.

The peak vibration speed of each measuring point in Figure 6 is shown in Table 5.

| Category       | Heavy kN/m³ | Elastic modulus (GPa) | Poisson’s ratio | Cohesion (kPa) | Friction angle (°) |
|----------------|-------------|-----------------------|-----------------|----------------|--------------------|
| Surrounding rock | 23          | 2.5                   | 0.35            | 700            | 39                 |
| Liner          | 24          | 32.5                  | 0.167           | —              | —                  |

### 3.3. Amplification Effect of the Low Surface

From Table 2, it can be seen that the horizontal distances of the four measuring points A, B, C, and D relative to the blasting source are not much different. The heights of measuring points C
Table 4: Comparison of numerical simulation results and actual measurement results of the Yangliu tunnel.

| Blasting times | Survey station | X direction/(cm/s) | Error/ % | Y direction/(cm/s) | Error/ % | Z direction/(cm/s) | Error/ % | Combined speed/(cm/s) | Error/ % |
|----------------|----------------|--------------------|----------|--------------------|----------|--------------------|----------|------------------------|----------|
|                | A              | 0.22               | 0.15     | 46.67              | 0.33     | 22.73              | 0.90     | 0.72                   | 25.00    |
|                | B              | 0.17               | 0.12     | 41.67              | 0.27     | 20.93              | 0.61     | 0.49                   | 24.71    |
|                | C              | 0.63               | 0.52     | 30.00              | 0.22     | 12.82              | 3.01     | 2.67                   | 13.87    |
|                | D              | 1.20               | 1.02     | 17.65              | 1.19     | 17.65              | 1.19     | 1.01                   | 13.87    |

| Blasting times | Survey station | X direction/(cm/s) | Error/ % | Y direction/(cm/s) | Error/ % | Z direction/(cm/s) | Error/ % | Combined speed/(cm/s) | Error/ % |
|----------------|----------------|--------------------|----------|--------------------|----------|--------------------|----------|------------------------|----------|
|                | A              | 0.20               | 0.11     | 81.82              | 0.31     | 47.62              | 0.53     | 0.30                   | 38.88    |
|                | B              | 0.12               | 0.07     | 71.43              | 0.16     | 47.62              | 0.53     | 0.30                   | 38.88    |
|                | C              | 0.70               | 0.56     | 25.00              | 0.92     | 22.67              | 1.03     | 0.88                   | 20.82    |
|                | D              | 0.36               | 0.29     | 24.14              | 1.04     | 22.67              | 1.03     | 0.88                   | 20.82    |
and D are small but the peak vibration velocity is large, and the heights of measuring points A and B are large but the peak vibration velocity is small. In other words, there is no elevation amplification effect in the blasting construction area of the Yangliu tunnel, mainly due to the following two reasons: First, because the blasting vibration wave almost diffuses outward in the form of a spherical wave inside the mountain (as shown in Figure 5) and the uneven surface in the mountain area causes the surface vibration center to shift to the lower elevation, which in turn causes the C and D measuring points to be closer to the surface diffusion center and finally makes the peak vibration ratio of the C and D measuring points at the lower level larger than that of the A and B measuring points at the higher level; Second, because

\[
V, \text{ Magnitude} \\
+2.692e-02 \\
+2.580e-02 \\
+2.468e-02 \\
+2.356e-02 \\
+2.243e-02 \\
+2.131e-02 \\
+2.019e-02 \\
+1.907e-02 \\
+1.795e-02 \\
+1.683e-02 \\
+1.570e-02 \\
+1.458e-02 \\
+1.346e-02 \\
+1.234e-02 \\
+1.122e-02 \\
+1.010e-02 \\
+8.973e-03 \\
+7.852e-03 \\
+6.730e-03 \\
+5.608e-03 \\
+4.487e-03 \\
+3.365e-03 \\
+2.243e-03 \\
+1.122e-03 \\
+3.168e-11
\]

\[
V, \text{ Magnitude} \\
+1.103e-01 \\
+1.057e-01 \\
+1.011e-01 \\
+9.649e-02 \\
+9.190e-02 \\
+8.731e-02 \\
+8.272e-02 \\
+7.813e-02 \\
+7.354e-02 \\
+6.895e-02 \\
+6.437e-02 \\
+5.978e-02 \\
+5.519e-02 \\
+5.060e-02 \\
+4.601e-02 \\
+4.142e-02 \\
+3.683e-02 \\
+3.224e-02 \\
+2.765e-02 \\
+2.306e-02 \\
+1.847e-02 \\
+1.389e-02 \\
+9.297e-03 \\
+4.708e-03 \\
+1.187e-04
\]

\[
V, \text{ Magnitude} \\
+1.511e-01 \\
+1.449e-01 \\
+1.386e-01 \\
+1.323e-01 \\
+1.261e-01 \\
+1.198e-01 \\
+1.135e-01 \\
+1.072e-01 \\
+1.010e-01 \\
+9.470e-02 \\
+8.843e-02 \\
+8.216e-02 \\
+7.589e-02 \\
+6.962e-02 \\
+6.335e-02 \\
+5.708e-02 \\
+5.081e-02 \\
+4.454e-02 \\
+3.827e-02 \\
+3.199e-02 \\
+2.572e-02 \\
+1.945e-02 \\
+1.318e-02 \\
+6.912e-03 \\
+6.412e-04
\]

Figure 4: Surface velocity field after the first blasting of the Yangliu tunnel \( (Q = 18 \text{ kg}) \). (a) \( t = 0.01 \text{ s} \). (b) \( t = 0.04 \text{ s} \). (c) \( t = 0.08 \text{ s} \).
Figure 5: Continued.
Figure 6: Velocity monitoring point inside the mountain ($Q = 18$ kg).

Table 5: Parameters of surrounding rock and lining.

| Measuring point position | Measuring point number | $x$ direction | $y$ direction | $z$ direction | Resultant velocity |
|--------------------------|------------------------|---------------|---------------|---------------|--------------------|
| Left                     | 1                      | 0.62          | 0.87          | 4.59          | 4.68               |
|                          | 2                      | 1.68          | 2.27          | 4.46          | 5.52               |
|                          | 3                      | 0.59          | 1.03          | 4.17          | 4.33               |
| Right side               | 1                      | 1.15          | 1.27          | 5.86          | 6.10               |
|                          | 2                      | 2.96          | 3.35          | 5.80          | 7.32               |
|                          | 3                      | 0.96          | 1.51          | 6.06          | 6.32               |
there is a through tunnel under measuring points C and D, the “cavity effect” of the through tunnel has an amplification effect on the peak vibration velocity of the rock and soil above it (as shown in Figure 7). The vibration wave bounced by the through tunnel wall is superimposed with the non-bounced vibration wave, and the superimposed vibration wave continues to propagate to measuring points C and D, further amplifying the peak vibration velocity of the lower measuring points.

4. Conclusion

The peak vibration velocity of numerical simulation is slightly larger than the measured value and the larger the velocity value, the smaller the error. The error between the peak vertical vibration velocity and the combined velocity is smaller than the other two subvelocities, but the average error of the combined velocity is less than 25% and the maximum error is less than 45%. It is suggested to strengthen the geological exploration of the tunnel sites area and increase the prediction accuracy of numerical simulation. The blasting vibration wave uniformly propagates outward in the form of spherical waves of the mountain and the spread center of the surface is closer to the area with low elevation, which leads to the higher peak vibration velocity of the surface measuring point in low elevation.

The existence of the side tunnel will rebound the vibration wave, which will cause the “cavity effect” to the rock and soil above it and amplify the peak vibration velocity of measuring points near the tunnel. Therefore, in practical engineering, shock absorption measures can be applied to the inner wall of the tunnel lining to reduce the impact of the rebound wave. The “cavity effect” caused by the side-through tunnel and the shift of the surface diffusion center of the lower part together led to the peak velocity of the lower measuring point of the Yangliu tunnel being much higher than that of the higher measuring point.

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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