Dynamic Response and Perturbation Design of Surrounding Rock in Blasting Construction of Small Radius Spiral Tunnel

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Abstract: To achieve a better blasting effect of ultra-long and deep buried spiral tunnel with a small radius, it is necessary to study the dynamic response and disturbance of blasting construction. As the engineering background with a poor engineering geological condition, this paper uses the Midi spiral-tunnel in Yunnan province that has a small radius of curvature, a large burial depth, and a large excavation distance. The blasting load is determined first by calculation. Under different blasting construction parameters, the deformation and dynamic vibration responses of the surrounding rocks are studied using the finite element numerical method. The damage mechanism of rock under the blasting load is analyzed. The tunnel engineering blasting is designed and calculated, and the small distance disturbance design of spiral tunnel blasting construction with a small radius is performed from the excavation method and blasting parameters. The results serve as a reference to reveal the surrounding rock dynamics in blasting construction of the spiral tunnel with a small radius.

Key words: Extra-long tunnel; small radius spiral; blasting construction; dynamic response; rock damage; perturbation design

1. Introduction
Highway tunnels, with large span and deep burial, are more likely to encounter hard rocks. Recently, conventional mechanical excavation is not applicable. The blasting construction method, under the current technical conditions, has high economic benefits and construction efficiency, so it has been widely used in the highway excavation [1–2]. A series of serious problems, such as cracking of surrounding buildings caused by blasting vibration, safety interference of the tunnel structure, and noise and vibration caused by blasting, must also be considered, especially for a spiral tunnel with a small radius. Hence, for the blasting construction of a spiral tunnel with a small radius, it is important to study the dynamic response of surrounding rocks and micro-disturbance design [3–5], which can effectively control the blasting vibration and ensure the safe and efficient completion of the tunnel project [6].

Domestic and foreign research scholars have carried out much useful research under different engineering backgrounds as regards the surrounding rock dynamic response and perturbation design problems of tunnel blasting construction. Duan et al. [7] studied the impact range of blasting disturbance under different surrounding rock grades, discussed and optimized existing prediction models, and analyzed the monitoring data to prove that the prediction model constructed by the piecewise function can improve the prediction accuracy well. The linear regression analysis of the tunnel blasting vibration field monitoring data was conducted by Feng Xiyong using the Sadovsky empirical equation, and then to establish a three-dimensional finite element numerical model of the corresponding tunnel engineering, they performed the time-history analysis using the finite element software MIDAS/GTS. Regarding the dynamic response of the blasting load of the buried tunnel construction to the surrounding rock and supporting structure of the tunnel [8], Luo Hao conducted a field test of the blasting vibration effect of the double-arch tunnel excavation, obtained the K and
S in the Sadofsky equation using the mathematical regression method value, and used numerical simulation to study the effect of blasting vibration on tunnel structure and ground under the conditions of the surrounding rock of grades IV and V, different burial depths, and different charges [9–12].

As the engineering background, this study uses the super-long Midi spiral-tunnel project in Yunnan Province, conducts an in-depth study on the dynamic response and micro-disturbance design of the small radius spiral tunnel blasting construction, and studies the damage mechanics of the rock mass under the blasting load. Our results will provide necessary reference for the follow-up engineers to conduct this kind of research.

2. Project Overview

This study is based on the Midi spiral-tunnel in Yunnan. The location of the tunnel is between the Goujie Interchange and the Longcha Interchange on the highway between Jianshui County and Yuanyang County. As shown in Figure 1, it is a two-line split tunnel. The left line is 3,830 m long, and the right line is 3,970 m long. The tunnel is a small radius spiral tunnel. Between the entrance and exit, the height difference is 80 m, the longitudinal slope is $-2.08\%$ (unidirectional slope), the maximum buried depth is 366 m, and the total length is more than 3,000 m. The tunnel area is dominated by granite according to the preliminary exploration of geological data, and the main rock structure comprises a series of folds and faults. Hence, the blasting construction method is used for tunnel excavation.

Figure 1. Schematic diagram of the Midi tunnel in Yunnan.

3. Selection of Calculation Parameters for Blasting Construction of Small Radius Spiral Tunnel

3.1. Rock mass and lining calculation parameters

The Midi spiral-tunnel has a larger range to pass through the surrounding rock of grade IV, and it is prone to damage or collapse of the surrounding rock during blasting construction because of its weak self-stability. Hence, for different blasting factors, the section of the surrounding rock of grade IV is selected. In Table 1, the finite element calculation of the surrounding rock damage of the construction, the constitutive calculation model adopted by the rock and soil body, modified using the Mohr–Coulomb model, and the calculated values of its physical and mechanical properties are shown [13–15].

| Lithology     | Surrounding rock classification | Granite |
|---------------|--------------------------------|---------|
| Severe (kN/m³) | 21.4                           |         |
| Elastic modulus ($10^4$ MPa) | 3.5                           |         |
| Deformation modulus (GPa) | 5                             |         |
| Poisson's ratio ($\mu$) | 0.25                          |         |
| Shear strength | $\Phi$ (°)                     | 32      |
| C (MPa)       | 0.55                           |         |
| Allowable bearing capacity of foundation (kPa) | 800                          |         |
The cross-sectional size of the tunnel model should be 6 to 10 times the diameter of the tunnel according to the principle of Saint Venan. In Figure 2, the three-dimensional solid finite element model of the tunnel and rock mass is shown, which is 140 m in width, 140 m in length, and 120 m in height [16]. The surrounding rock in this model is defined as a three-dimensional solid element, and the lining is defined as a plate element. The materials are all elastic. In Table 2, the physical and mechanical calculation parameters are shown. The tunnel lining is calculated using an elastic constitutive model.

![Figure 2. Calculation model and grid division: (a) overall model, (b) tunnel system, and (c) surrounding the rock system.](image)

| Material category | Density (kg/m³) | Elastic modulus (MPa) | Poisson's ratio | Shear modulus (MPa) |
|-------------------|----------------|-----------------------|----------------|-------------------|
| Concrete C30      | 2,300          | 30,000                | 0.20           | 102,000           |

### 3.2. Calculation load of blasting

Combined with the characteristics of three-dimensional numerical simulation software, after gathering the blasting holes in one place, it is assumed that this pressure acts on the imaginary surface of the blasting at the same time and the blasting pressure acts on the tunnel wall, considering that it is difficult to establish a single blasting hole unit at the blasting site. In the vertical direction, the burst pressure is calculated as follows [17]:

\[
P_{\text{det}} = \frac{4.18 \times 10^{-7} \times sge \times V_e^2}{1 + 0.8 sge}
\]

(1)

\[
P_B = P_{\text{det}} \left( \frac{d_e}{d_h} \right)^3
\]

(2)

where \( P_{\text{det}} \) is the burst pressure (KPa), \( P_B \) is the pressure on the wall of the hole (KPa), \( V_e \) is the blasting speed (cm/s), \( d_e \) is the gunpowder diameter (mm), \( d_h \) is the eyelet diameter (mm), and \( sge \) is the proportion of the gunpowder.

Using the given equation above, we calculated the dynamic pressure of air generated by blasting. However, in actual engineering, the dynamic pressure acting on the hole wall changes with time. Therefore, to calculate the Blasting load, the relevant time-history dynamic pressure equation given in Statfield can be used, and the calculation equation is as follows [18–20]:

\[
P_d(t) = 4P_B \left[ \exp \left( \frac{-Bt}{\sqrt{2}} \right) - \exp \left( -\sqrt{2}Bt \right) \right]
\]

(3)

In this equation, \( B = 163.38 \) is the load constant. The dynamic pressure generated per 1.0 kg charge can be calculated following this equation. Hence, the blasting load can be calculated according to Eqs. (2) and (3). The parameters in the equation are as follows. The density of the explosive is, the diameter of the roll \( d_e \) is...
32 mm, the diameter of the blast hole is 42 mm, and the blasting speed is 4,500 m/s.
The measured blasting vibration wave is used as the dynamic load in the calculation process of this study. The high-frequency part of the vibration wave will affect its propagation in the model. The wavelength of the high-frequency vibration wave needs to be smaller by 8 to 10 times the wave filtering than the mesh size in the model, so the Hilbert–Huang transform (HHT) wavelet processing method is used to process the high-frequency vibration wave. In Figures 3 and 4, the calculated blasting time history chart and spectrum chart are shown. The blasting dynamic load reaches the maximum value at approximately 6 ms, as shown in the figure.

![Figure 3. Time history of blasting load.](image)

![Figure 4. Fourier spectrum of blasting load.](image)

4. Monitoring Results and Analysis
The construction of the Midi tunnel is extremely challenging because of its small curve radius, large burial depth, large excavation distance, and poor overall engineering geological conditions. Three-dimensional numerical simulations of different charging methods, blast hole spacing, and uncoupling coefficients of the tunnel are carried out in this study. To provide reference suggestions for the safe construction of Midi tunnels, we also explored the best blasting design parameters and mass dynamic response laws.

4.1. Charge structure
The charging structure refers to the way the explosive roll is placed in the blast hole and is one of the important factors that affect the blasting effect. Continuous charging and interval charging are the most commonly used charging structure. To study the deformation and vibration response law of surrounding rock during blasting construction under different charging conditions, a three-dimensional numerical calculation model of a single shot hole was established. The continuous charge and interval charge structures were taken, respectively. The hole diameter is 42 mm, the total length is 2 m, the charge amount is 2 kg, the length of the interval charge is 0.15 m, and the interval of charge is 0.26 m, as shown in Figure 5.
The calculation cloud diagram in Figure 6 shows that the maximum vibration velocity caused by the interval charging is 0.13026 m/s, and the maximum vibration velocity caused by the continuous charging is 0.134714 m/s.

![Figure 5. Models and blasting load under different charge structures: (a) intermittent charging and (b)](image)
continuous charging.

Figure 6. Vibration velocity of surrounding rock under different charge structures at 6 ms: (a) intermittent charging and (b) continuous charging.

The average wave velocities of rock masses with different depths of tunnel surrounding rocks under two charging structures, namely air interval charge and continuous charge, are shown in Figure 7.

Figure 7. Average sound wave velocity of rock mass at different depths of charge structure.

The wave velocity of rock mass has an obvious upward trend within the range of 0–9.8 m under continuous loading slope, as shown in Figure 7. The rock mass is damaged by violent blasting excavation. This area is the blasting-damaged area of the slope, and its wave velocity is the wave velocity \( c_d \) of the damaged rock mass. The average wave velocity of the rock mass fluctuates outside the damage zone, but on the whole tends to be stable. Outside the damage zone, the average value of the average wave velocity of each measuring point is recorded as the acoustic wave velocity \( c_{p0} \) of the undamaged rock mass. The depth of the blasting excavation damage zone and the sonic velocity of the undamaged rock mass in the interval and continuous charge slope rock mass are listed in Table 3. A statistical analysis of the peak wave velocity of the rock mass in front of and behind the tunnel was found. As shown in Figure 8, the peak wave velocity of the rock mass under the interval charge and continuous charge blasting structures also showed a clear difference.
Table 3. Depth of blasting damage area and wave speed of undamaged rock mass.

| Charge structure      | Damage area depth/m | Wave velocity of undamaged rock mass/(km/s) |
|-----------------------|----------------------|--------------------------------------------|
|                       | Calculated value     | Geological survey recommended value [17]  |
| Interval charge       | 17.1                 | 4.6                                        |
| Continuous charge     | 11.4                 | 3.8                                        |

Figure 8. Peak distribution of front and back vibration of palms with different charge structures.

In the interval charge, the depth of the damage caused by the blasting excavation is significantly smaller than that in the continuous charge rock mass. This is because the worse the rock mass, the less energy is consumed by the excavation of the rock mass. In addition, more explosions are observed on the retained rock mass of the slope, causing damage and destruction of the retained rock mass.

4.2. Blast hole spacing

There are two types of blast hole spacing: one is the spacing between the blasting hole and the empty hole, and the other is the spacing between the adjacent blasting holes. The effect of the spacing between adjacent blasting holes on rock blasting is the main topic under this section. A single blast hole model was established to study the deformation and vibration characteristics of surrounding rock during blasting construction under different blast hole spacing pieces. The blast hole spacings were 60, 80, and 100 cm, and the single hole charge was 2 kg. The model is shown in Figure 9.

In Figure 10, the calculation results indicate that due to the superposition, the smaller the distance between the blast holes, the greater impact range of vibration after blasting. However, the figure also indicate that the displacement value is $6 \times 10^{-5}$ m, which the surrounding wall rock formed before and after superposition; therefore, the impact caused by vibration superposition is mainly reflected in the range of impact on the surrounding rock.

Figure 9. Blast hole models at different spacings: (a) 60 cm, (b) 80 cm, and (c) 100 cm.
Figure 10. Displacement clouds of different hole spacings at 6 ms: (a) 60 cm, (b) 80 cm, and (c) 100 cm.

The wave velocity of the rock mass (m) has a clear upward trend, as shown in Figure 11, which indicates that the rock mass in this range has been damaged by violent blasting excavation. This area is the damaged area of the blasting excavation of the slope. In Table 4, the depth of the blasting damage zone of 80 and 100 cm slope rock mass and the sound wave velocity of undamaged rock mass are listed. The effect of blasting is also affected by the amount of single-hole charge. Therefore, in addition to selecting by determining the blasting range, it needs to be appropriately adjusted according to the amount of charge to select the blast hole distance.

![Wave velocity of rock mass](image)

Figure 11. Distribution of average vibration wave velocity of rock mass with different blast hole spacings.

| Borehole spacing | Damage area depth/m | Undamaged rock mass wave speed/(km/s) |
|------------------|---------------------|--------------------------------------|
|                  |                     | Calculated value | Geological survey recommended value |
| 60 cm            | 21.3                | 4.9                  | 4.1–4.6                             |
| 80 cm            | 14.6                | 3.8                  |                                     |
| 100 cm           | 7.3                 | 2.7                  |                                     |

Table 4. Depth of blasting damage area and wave speed of undamaged rock mass.

A statistical analysis of the peak wave velocity of the rock mass in front of and behind the tunnel was found, and when the blast hole spacing was different, the peak wave velocity of the rock mass also showed a clear difference, as shown in Figure 12.

![Peak wave velocity distribution](image)

Figure 12. Peak vibration wave velocity distribution of front and back of rock mass with different hole spacings.

4.3. Uncoupling coefficient

By changing the uncoupling coefficient of the explosive, the blasting effect of the explosive can be controlled, and the blasting energy of the explosive can be reduced. The over-undercutting phenomenon of blasting...
construction can also be controlled. To study the mechanical characteristics of the surrounding rock of the tunnel blasting construction under different uncoupling coefficients, the step method is adopted to construct the blasting construction for uncoupling coefficients 1.2, 1.3, and 1.4, respectively, and the numerical simulation results are analyzed.

![Cloud graphs under different uncoupling coefficients at 6 ms.](image)

**Figure 13.** Cloud graphs under different uncoupling coefficients at 6 ms. (a) The side section of uncoupling coefficient is 1.2, (b) the front section of uncoupling coefficient is 1.2, (c) the side section of uncoupling coefficient is 1.3, (d) the front section of uncoupling coefficient is 1.3, (e) the side section of uncoupling coefficient is 1.4, and (f) the front section of uncoupling coefficient is 1.4.

The results from the numerical simulation show that the impact of the explosive on the surrounding rock decreases with the increase of the uncoupled coefficient when the uncoupled charge is used. This is because, under the uncoupled condition, the gap plays a certain role in the explosion buffering effect. Therefore, if this project wants to avoid over-undercutting caused by the tunnel, considering the economic cost (Figure 13, it is recommended to use the uncoupling coefficient of 1.4.

As shown in Figure 14, the peak value of vibration velocity is extracted at different distances from the position of the tunnel face under the conditions of each uncoupling coefficient.
Figure 14. Peak vibration wave velocity distribution of front and back of rock mass with various uncoupling coefficients.

Figure 14 shows the vibration response law in a certain range of the face and the front and back of the blasting excavation with different uncoupling coefficients. With the continuous advancement of the face of the excavation, the vibration response area is roughly divided into three areas: (a) the surrounding rock position at the vault within the range of 0–1D hole diameter in front of and behind the face of the palm produces a large vibration during the tunnel blasting process, forming an area with obvious dynamic influence; (b) the surrounding rock position at the vault within the 1–2D hole diameter in front of and behind Zhangzi produces general vibration during the blasting process of the tunnel, which forms a general area with dynamic influence; and (c) weak vibrations occur at the location of the surrounding rock at the vault within the diameter range, forming areas with weak dynamic impact.

The analysis indicates that the damaged area of the rock was mainly concentrated in the obvious impact area, and on the slope surface, the rock mass damage was the most serious, and its deformation modulus was reduced by 50%. Figure 15 shows the decay law of deformation modulus of rock masses with different uncoupling coefficients. Hence, it is shown that as the depth \(d\) increases, the deformation modulus of the damaged rock mass increases linearly until reaching the deformation modulus \(E_{rm0}\) of the undamaged rock mass.

Figure 15. Deformation modulus \(E\) of rock mass in the damage zone with depth.

5. Optimization Calculation of Design Blasting Parameters

The blasting conditions with interval charge structure, 40 cm blast hole spacing, and an uncoupling coefficient of 1.4 were used to optimize the blasting parameters of the Midi tunnel following the aforementioned numerical calculation results, focusing on the calculation of the number of blast holes around the arch and the bottom of the tunnel.

5.1. Eye around the arch
The eye around the arch is smooth blasted with a φ32 mm medicine roll. According to the commonly used empirical equation of peripheral eye spacing proposed by Persson (1973),

\[ D = k \cdot d \]  

(4)

where \( D \) is the distance between the peripheral eyes (m); \( k \) is the empirical coefficient, generally, 12–15, and this project adopts 12; and \( d \) is the diameter of the hole (mm), this project uses 40 mm.

Then, the peripheral eye distance \( D = 0.042 \times 12 = 0.504 \) m.

Taking the blast hole density coefficient \( K = 0.8 \), the minimum resistance line is

\[ V = \frac{D}{K} = 0.63 \text{ m} \]  

(5)

The relationship between the concentration of charge per meter in the blast hole and the diameter \( d \) of the blast hole is

\[ l = 90d^2 \]  

(6)

Then, the minimum concentration of smooth blasting is approximately \( l = 900.042^2 \approx 0.16 \) kg/m.

The minimum charge concentration of peripheral eyes is 0.30 compared with the original plan, which is significantly greater than the calculated minimum charge concentration.

The number of eyes around the arch is calculated using the following equation:

\[ N_1 = \frac{B_1 - B}{a} + 1 \]  

(7)

where \( B_1 \) is the perimeter of the tunnel excavation section, \( B_1 = 35.5 \) m in this project; \( B \) is the width of the tunnel excavation, \( B = 11.2 \) m in this project; and \( a \) is the distance between the surrounding eyes, \( a = 0.5 \) m in this project.

Then, \( N_1 = 50 \) is calculated. That is, the eye distance around the arch \( D = 40 \) cm, the resistance line \( V = 63 \) cm, and the number of eyes around the arch \( N_1 = 50 \).

5.2. Eye at the bottom of the tunnel

For the eyes at the bottom of the tunnel, a proper blasting effect can be achieved by appropriately reducing the distance between the eyes around the bottom due to the larger clamping effect of the rock. Here, the bottom eye distance is 40 cm.

Then, the number of bottom eye blast holes is

\[ N_2 = \frac{B}{a} + 1 \]  

(8)

Substituting the data to calculate \( N_2 = 26 \), the peripheral eyes have a total of \( N = N_1 + N_2 = 76 \).

6. Small Radius Spiral Tunnel Perturbation Drilling and Blasting Construction Design

This design is for the excavation method of blasting construction, setting of blasting parameters, corresponding supporting methods, and emergency plans for special situations.

6.1. Excavation parameter design

According to the previous analysis, it is recommended to use the three-step method for the surrounding rock of grade IV with relatively unstable rock properties, and the excavation cycle footage is controlled by 1 to 2 steel supports. The construction process and related parameters of the three-step method are shown in Figures 16 and 17.

![Figure 16. Schematic diagram of three-step](image)

![Figure 17. Three-step method construction](image)
excavation design.

The construction parameters are as follows:

1. When steel support is used for the upper steps, the arch foot can be enlarged and the anchor pin can be applied to reduce the deformation of the top of the tunnel. In addition, during the initial support, the supporting steel supports on the upper and lower sections of the steps should be smoothly connected, and the bolt connection should be firm.

2. During the construction of the tunnel, if the stability and integrity of the surrounding rock are poor, the lower section can be excavated by staggering, and the lower section can be reduced by excavating the lower section after the sprayed concrete of the upper section reaches certain strength, impact on the upper surrounding rock and support.

3. To control the axis of the tunnel and the pre-excavation of the tunnel, the tunnel footage should be 1–1.5 m, and the initial support shall be applied immediately after the construction falls.

4. After the blasting construction, the back arch should be applied in time to make the support closed into a ring.

6.2. Blasting parameter design

The effective design of blasting parameters is the key to control the construction period and ensure the excavation contour in tunnel construction. The blasting construction of rock damaged by vibration is reduced to give full play to the stability of surrounding rock. The design of blasting parameters was to achieve the best blasting effect according to the aforementioned optimization calculation results, form a clean and smooth excavation part, and reduce over-underexcavation.

This tunnel blasting uses a plastic detonator and a millisecond detonator initiation system. The millisecond detonator uses seven different millisecond detonators and uses a detonator to initiate. Given the complex groundwater conditions in the study area, 2# rock emulsion explosives are used, and two specifications of Φ25 and Φ32 can be used. The peripheral vision explosive volume is Φ25 (to reduce the amount of peripheral eye charge, 32 mm explosives can also be used, and air space is used, medicine). The digging eye medicine volume is Φ32, continuous charge. For a detailed charge parameter design, see Figure 18.

In summary, under the optimal conditions of the numerical model, the principle is mainly to use and create an empty surface for the micro-disturbance blasting and reduce the disturbance of blasting to surrounding rock, following the poor surrounding rock conditions in the study area, abundant groundwater, and prone to pre-excavation.

1. Using smooth blasting technology, we filled the surrounding eyes with air space and finally detonated.

2. The first step is to conduct the blasting of the guide hole first and then use the free surface created by the guide hole to blast.

3. There is no cut-out hole in the lower steps and invert arches. The free surface created by the upper steps to set up caving holes can be used.

7. Conclusion and Discussion

This paper takes the Midi spiral-tunnel in Yunnan province with poor engineering geological conditions as
the engineering background, which has a small radius of curvature, a large burial depth, and a large excavation distance. The relevant loads imposed by blasting were determined through calculation, and the deformation and dynamic vibration responses of surrounding rock were studied with the three-dimensional finite element method. The mechanical mechanism of rock damage under the blasting load was analyzed. The blasting design of the Midi tunnel project was calculated according to the results, and the small-distance perturbation of the blasting construction of the small radius spiral tunnel was designed. Specific research conclusions are as follows.

1. The influence ranges of continuous charge and interval charge are 0–17.1 m and 0–9.8 m. The depth of the rock mass damage caused by the interval charge is smaller than the continuous charge.
2. When the blast hole spacing is different, the peak wave velocity of the rock mass is different, and the effect of blasting is also affected by the single hole charge. Therefore, it is also necessary to make appropriate adjustments according to the charge amount to choose the appropriate blasting distance, in addition to the selection of the blasting influence range.
3. The rock damaged area is mainly concentrated in the explosive impact area, and the rock damage is the most serious on the side of the facing surface, with the deformation modulus reaching 50%. With the increase of depth, the deformation modulus of the damaged rock mass increases linearly until the undamaged rock mass.

Author Contributions
During the whole thesis writing process, ZBF conceptualized and presented the draft of the whole thesis. QY and XDS mapped the paper, polished the language, and analyzed some data. XXZ, XL, and NQ were responsible for the revision and logical thinking adjustment of the first draft of the paper.

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Conflicts of Interest
The authors declare no conflict of interest.

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