Studying on the characteristics of vibration effect of the blasting of excavating anchorage tunnels of Chishui River Super Bridge

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Abstract. The section of anchorage tunnels is large, there are variable contour and variable areas and small distance among anchorage tunnels and main tunnels, and easy to form unloading cracks or boulder to bias arch, so blasting excavation maybe easily damage the middle pillars and surrounding rock and to collapses the entrance of holes, which will affect the operation of bridge in the future. For the structure, spatial distribution state of anchorage tunnel and the highway tunnels, and spatial relationship among its, based on the topographic feature, geological structure, rock and lithology of the Sichuan bank of Chishui River Super Bridge, according to the correlation between blasting source factors and the energy density distribution characteristic of blasting seismic wave, combined with monitoring, the blasting vibration effect characteristics of tunnel anchorage excavation are studied on, the blasting technology is optimized, and the support are strengthen to ensure the stability of the surrounding rock, middle pillar and mouth, so that the construction will be done successfully.

1. Introduction

The grand suspension bridge spans over the deep gorge, and the anchor tunnel is most suitable anchoring form for vertical steep slopes [1], for example, the Chengdu shore of the Luding Super Bridge over the Dadu River.

The short-distance blasting excavation in the steep slope anchor tunnel and highway tunnel can easily damage the septum rock pillar and the entrance. Regardless of whether the anchor is located above or below the highway subgrade, the vibration can damage the septum pillars and make the surrounding rock of vertical or horizontal adjacent tunnels unstable, thereby increasing the risk of suspension bridges.

The tunnel anchorage is widely used with the extension of the high-speed railway and expressway networks in the west. Research on the blasting excavation of anchor tunnels focusing on the vibration experiment monitoring targeting a certain specific sections with the determined height has emerged, aiming to explore the cumulative effect and stress distribution characteristics of the blasting vibration of the septum by means of information fitting and numerical simulation [2]. The above research enriches the experience of anchor excavation blasting and improves the excavation and blasting technologies targeting anchor tunnel and highway and railway tunnels.
Based on the structure of anchor tunnel and highway tunnel, the spatial relationship, features of the surrounding rock and surface geology, this paper explores the lasting vibration response characteristics of the uncoupled rock stratum of steep slope, boulder of biased arch, septum rock pillar, tunnel studding and the surrounding rocks by adopting the theories of stochastic complex wave mechanism and non-stationary stochastic compound wave as well as rock mechanics, using existing numerical simulation and monitoring data for review. This paper aims to optimize the source factor and determine the best geometric dimensions and propulsion lines on the working face and the minimum safety interval between the anchor tunnels.

The Chishui River Super Bridge, with a span of 1200 m, is the first suspension bridge in the mountainous area in Asia. In this area, the wind comes from multiple directions with sharp peaks, and the rock is seriously corroded. The effect of tunnel anchor blasting excavation is directly linked to the safety of the Bridge.

Since there are many similar situations in the anchorage of high-speed railway and expressway tunnels in the west, it is necessary and significant to analyze the characteristics of the blasting vibration effect of the tunnel excavation of the Chishui River Super Bridge.

2. Project Overview

The starting and stopping stake number of the Chishui River Super Bridge on the Jiangxigu Expressway is:

The Sichuan shore of the Bridge has a height difference of 1250 m. The tunnel anchor is located on the mountainside. At the entrance of the tunnel, there are three sets of rock layers on the steep slope. The unloading crack is 10 m from the tunnel entrance with the tension width of about 30 cm. The entrance section is continuous and unsymmetrical loaded.

The surrounding rock stratum of the anchor tunnel consists of calcareous mudstone and limestone. The rock formation changes from $315^\circ \pm 35^\circ$ to $270^\circ \pm 15^\circ$, and is in III and IV monoclinic structure.

3. Analysis of characteristics of blasting vibration response of tunnel excavation

3.1. Analysis of vibration response of blasting excavation of steep rock slope with good integrity

The paper on the blasting vibration stability of the consequent rock slope [3] believes that the safety factor of the slope should cover the vibration frequency, damping and vibration frequency. Experiment shows that when the blasting excavation is performed at the front edge of the slope, the response on the
front side is stronger than that on the back side. The frequency domain widens with the increase of the span ratio and the height ratio of the shallow tunnel. The surface response is enhanced with higher frequency \[4, 5\]. When excavation is not performed at the front edge of the slope, due to the viscous soil filtering, the frequency domain is narrowed with lower main frequency. When the self-vibration frequency of the hillside is relatively high, the two factors above will move backward. Therefore, it is necessary to study the characteristics of blasting vibration response of the steep slope in order to better explore the collapse risks.

The geological body is regarded as viscoelastic, the tunnel contour and the surface are free surfaces, and the other interfaces are infinite bodies. This paper conducts numerical simulation of geological blasting dynamics based on the equivalent source factors, equivalent distances and similar geological conditions. The forced dynamic balance equation is:

\[
[M] \ddot{\mathbf{u}} + [C] \dot{\mathbf{u}} + [K] \mathbf{u} = [M] \ddot{f}(t)
\]

In the equation, \([M]\) represents the matrix of geological body mass; \([C]\), damping matrix of geological body; \([K]\), matrix of geological body stiffness; \(\mathbf{u}\), seismic displacement of geological body; \(\dot{\mathbf{u}}\), particle vibration acceleration; \({\ddot{f}(t)}\), acceleration of geological body due to blasting.

The numerical simulation conducted using the physical mechanics model for vibration enhancement analysis has the effect of amplifying vibration. Due to the fact that the excavation is near the entrance, the seismic wave propagation path is short, and that the geotechnical filtering effect is weak, the frequency fails to meet the natural vibration frequency of the tunnel entrance, but rebounds due to resonance. The vibration of the overlying layer leads to the vibration of the overburden layer, which is located at the free end. The seismic wave doubles its intensity after meeting the surface, leading to the increase of vibration. When the peak of the blasting vibration meets a certain level, there will appear shallow unloading cracks at the tunnel, which will develop until the collapse occurs.

### 3.2 Analysis of vibration effect on excavation of deep unloading crack in steep slope

The seismic wave propagates due to the mutual traction of the geotechnical particles, and the unloading crack or the increased void of the faulted rock hinders the sustainability of high-frequency short waves. If the filler is highly viscous, then it can block high-frequency waves; in this way, only low-frequency long wave can propagate.

The main seismic wave has high frequency and short wavelength. Therefore, there exist significant differences between the vibration characteristic of the upper and lower rock layers and that of the inner and outer layers. The vibration mode is inconsistent with the lower rock mass, the vibration frequency is reduced, the amplitude is increased, and the relative displacement is presented. Under this circumstance, the vertical crack becomes larger, the relative vibration is more obvious, and the crack develops faster. In this way, the vibration response of the cover layer or the residual formation is relatively stronger, showing an amplification effect, leading to large-scale landslide at the outer rock mass.

### 3.3 Analysis of characteristics of blasting vibration mechanics of giant dangerous rock of unsymmetrical loading tunnel

The vertical "X" intersecting secondary faults are formed at the entrance, which tends to form axial and transverse cracks, leading to unstable arch distortion.

The blasting tunneling can aggravate the mechanical parameters of the deteriorated boulder bias arch.
The unsymmetrical loaded giant rock is located at the far end, and is not subject to the tractive effect, but only the thrust. When the entrance is affected by the blasting seismic wave, the rock will inevitably damage the arch, resulting in instability of the rock mass and even collapse of the entrance.

3.4 Entrance protection and monitoring

After studying the unloading cracks, it is confirmed that the tunnel of the Chishui River Super Bridge is an anchor tunnel with unsymmetrical loaded giant rock.

High and steep slopes are not suitable for slope cutting or dangerous stones removal because of not only the huge amount of engineering work, but also the risk of entrance collapse.

The deep bedding unloading crack is suitable to adopt grouting anchor support and multi-level interception and drainage treatment. The boulder biased arch is suitable to adopt gap grouting, arch and the second layer thickening. In addition, concrete can be used on the bolder so as to form a strong and holistic structure at the entrance.

4. Mechanical analysis of vibration response of septum rock pillar

4.1 Analysis of blasting vibration characteristics of the septum rock pillar of proceeding tunnel

Analysis of axial vibration characteristics

Numerical simulation and experimental research show that as the blasting excavation of the anchor tunnel continues, the vibration response of the rock pillar in the proceeding tunnel gradually increases [6].

The vibration response characteristics of the septum rock pillar must be affected by the boundary constraints and the spatial excitation factors or characteristics. Along the axis of the anchor tunnel, the section continuously expands, the height-thickness ratio of the septum increases with lower thickness is reduced and higher flexibility. In this way, the amplitude of swing inevitably increases, and the vibration response of the rock pillar in the proceeding tunnel is also gradually enhanced.

Higher intensity of the vibration source will lead to the increase of swing of the entire septum.

The self-vibration mode frequency, the intrinsic property of the studied structural system, is inversely related to mass and positively related to stiffness. The stiffness is positively correlated with...
the degree of freedom of the natural boundary and the boundary constraint. When the forced vibration frequency is closer to the frequency of the self-vibration and the fundamental frequency, the amplitude of swing will be larger.

The blasting seismic wave belongs to the non-stationary random composite wave. When its frequency is closer to the self-vibration frequency of the rock and the fundamental frequency, the vibration amplitude of the rock will be higher. Due to the damping effect of the soil, the advanced mode of seismic wave is more likely to attenuate.

However, the vibration response of the septum rock pillar in the proceeding tunnels gets stronger along the axis of the tunnel from the excavation site, and then it gradually decreases to zero. The constraint of the following tunnels on the septum rock pillar changes suddenly. If the boundary constraint is removed, the flexibility of the septum is enhanced. Since the influence of the tunnel excavation is weakened, the amplitude of vibration and vibration response gradually increase. When the blasting seismic wave propagates away from the source, it is inevitably attenuated due to the loss and dispersion of the energy.

The septum rock pillar is not constrained in radial direction, with large exposed area. It has no boundary constraints in the axial direction, but strong boundary constraints in the vertical direction. Then, the vibration response along the lateral, axial and normal directions is inevitably weakened. As the wave gets away from the source of the explosion, the three components gradually get slower and more consistent due to the loss and dispersion of the seismic wave energy.

The blasting seismic wave mainly propagates along the normal direction of the center of the blasting packet, and it attenuates slowly in this direction within 15m-20m. Therefore, it is necessary to reserve some space between two blasting surfaces to ensure the construction safety.

In order to avoid excessive vibration response, it is necessary to improve the dynamic distribution of the blasting vibration response in the axial direction and reserve more space between two excavation surfaces. In addition, it is feasible to advance in the “L” shape to increase the boundary constraints of the septum pillar and optimize the blasting parameters.

![Figure 6. Propulsion of "L" Bench Blasting Excavation](image)

(2) Analysis of section vibration characteristics

The vibration response peak of septal rock pillar decreases more rapidly from the arch foot to the pillar top than from the arch foot to the pillar foot [6].

The seismic wave moves away from the source of the explosion in the radial direction, and the stress is concentrated in the proceeding tunnel, and then the wave gradually restores its original propagation characteristics. The proceeding tunnels may be damaged due to stress concentration. The septum rock pillar is at the explosive side with low boundary constraints; therefore, it is where the peak of stress concentration locates. The distal column has strong constraints, thus the weakest amplitude of swing.

It is necessary to improve the blasting vibration dynamic distribution of the existing anchor tunnels and optimize the blasting parameters of the following ones. At the same time, it is feasible to reduce the blasting height of the upper steps and control the maximum amount of the explosive.

4.2 Analysis of vibration response characteristics of excavation of following tunnels

(1) The influence of the distance between the source and the septum rock pillar

Low explosive speed, weak shock wave intensity, distant and disperse explosive packages, low explosive volume, and long time delay can lead to weaker vibration response.
Entrance characteristics and parameters, network parameters, initiation sequence, delay characteristics, gutter, pre-crack state, form of light explosion, and uncoupling coefficient determine not only the characteristics of the explosive package and its spatial lattice state, but also the time and state of detonation, the concentration and amount of charge, the concentration of packages, and the spatial position of the septum, which ultimately determines and affects the response and stability of the septum and surrounding rock pillars. Sphere-like and large packages, high concentration, coupled charges, and the gutter near the septum rock pillar should all be avoided.

(2) Change the form of blasting excavation
In order to reduce the vibration damage of the tunnel surrounding rock and septum rock pillar and ensure the excavation stability and progress, it is feasible to move the blasting site away from the septum rock pillar, adopt asymmetric vertical trapezoidal trough, and combine pre-split and smooth blasting.

4.3 Analysis of blasting vibration response of septum rock pillars in proceeding tunnels.

5. Analysis of interaction between blasting excavation of highway tunnel and anchor tunnel
5.1 Analysis of mechanical characteristics of vibration response of proceeding highway tunnels
The separated and small-distance highway tunnels are vertically symmetrical and are evenly located on the left and right oblique lower sides of the anchor tunnel, with the closest distance from the rear anchor chamber of 23 m, which is much smaller than the specified distance of 54 m. In addition, the underground space of the rear anchor chamber reaches 460 m². From discrete numerical simulation, it is believed that the wave attenuates faster in the vertical direction than in the horizontal direction [7]. Though the upper or lower tunnel experiment, it is considered that the vibration response of the dome is the strongest. Therefore, it is necessary to study the vibration excitement of the anchorage chamber and the studding, and the vibration response of the septum rock pillar.

Small section performs better than large section in the aspects of mechanical rigidity and many other mechanical properties. The highway tunnel will be less affected if the anchor tunnel is excavated later.

5.2 Analysis of mechanical characteristics of vibration response of proceeding anchor tunnel
Since the small-distance anchor tunnel with a rear anchorage chamber is as large as 460 m² is located obliquely above the highway tunnel, its surrounding rock, septum rock pillar and studding tend to be damaged due to strong vibration.
The anchor tunnel near the highway tunnel suffers strong vibration, especially its studding. The vibration speed in this situation is stronger than that in the situation where the highway tunnel is excavated first.

To avoid the damage of the two tunnels, it is necessary to conduct excavation of the highway tunnel first and at the same time, optimize the factors of the explosion source.

6. Conclusion
Optimized blasting factors and appropriate reinforcement measures based on theoretical analysis and previous practice monitoring can meet the requirements of design and construction. The blasting excavation of the anchor tunnel of Chishui River Super Bridge has been successfully completed, which can provide reference for similar projects.

(1) Inclined unloading cracks on deep and shallow bedding rocks and biased arches gradually aggravate the vibration response of the anchor tunnel, it is feasible to adopt crack grouting and anchoring, strengthen arching, and intercept flooding so as to maintain the stability of the entrance.

(2) Study on the mechanical characteristics of the blasting response of the septum rock pillar based on the theory of geotechnical dynamics and the existing physico-mechanical model can help to optimize the blasting factors, adjust the blasting section, and improve the mechanical distribution characteristics of the surrounding rocks and septum rock pillars of the highway tunnel and anchor tunnel.

(3) The distance shall be determined based on the response intensity of proceeding and following tunnels.

(4) Highway tunnel shall be excavated before the anchor tunnel.

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