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Review on the Instability Mechanism of Tunnel Center Diaphragm Under Blasting Action

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Abstract

Tunnel blasting is a complex and critical process in engineering geology and tunnel construction. The middle partition support structure and temporary support structure during the tunnel construction period are prone to vibration instability, which poses a great risk of damage to the tunnel. Therefore, investigating the mechanism of instability of intermediate partitions under explosive loads is of great significance for enhancing the safety and economy of tunnel projects. This paper provides a comprehensive overview of the characteristics of tunnel blasting loads, analyzes in detail the changes in the stress state of intermediate partitions under blasting actions, and summarizes the current research methods and achievements on the instability mechanism of intermediate partitions, including numerical simulation, field monitoring, and theoretical analysis. It aims to provide references for a deeper understanding of the instability issues of intermediate partitions and for improving the safety of tunnel construction.

Keywords

Tunnel Engineering, Intermediate Partition Damage, Blasting Engineering, Local instability.

1. INTRODUCTION

China features complex and diverse geological conditions, characterized by varied topographies and landforms as well as frequent occurrences of geological hazards. Tunnel excavation methods such as the Center Diaphragm (CD) method and the Cross Center Diaphragm (CRD) method, which are particularly suitable for complex geological conditions, have been widely applied in China. The center diaphragm, as a commonly used temporary support structure in tunnel construction, plays a crucial role in maintaining the stability during tunnel construction. However, under the repeated action of blasting loads, the center diaphragm may undergo instability and failure, thereby affecting the safety and progress of tunnel construction. Therefore, in-depth research on the instability mechanism of the center diaphragm under tunnel blasting has significant practical engineering significance. To sum up, this paper first introduces the propagation and vibration characteristics of tunnel blasting vibration loads, then conducts a detailed analysis of the stress variation characteristics of the center diaphragm under blasting action, systematically expounds the research methods and results regarding the instability of the center diaphragm, and provides prospects for future research. It offers a theoretical basis and scientific support for the stability evaluation of the center diaphragm, the adoption of effective measures such as key parameter evaluation for optimizing blasting design and vibration reduction technologies, as well as ensuring the safety of tunnel construction.

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2. TUNNEL BLASTING LOAD CHARACTERISTICS

Blasting stress waves are generated by the energy released from explosive detonation. The high-temperature and high-pressure gases produced by the explosion expand rapidly, forming initial shock waves that propagate through the rock mass. During the propagation of stress waves, the wave front is a compression zone, followed by a rarefaction zone. Rocks are compressed in the compression zone and stretched in the rarefaction zone. Stress waves include longitudinal waves (P-waves), shear waves (S-waves), and surface waves (R-waves). P-waves propagate the fastest and reach the center diaphragm first, causing longitudinal vibration of the particles in the center diaphragm; S-waves arrive subsequently, inducing transverse vibration of the particles; R-waves, with their energy relatively concentrated on the surface of the rock mass, have a significant impact on the part of the center diaphragm close to the surface of the surrounding rock. Through similar model blasting experiments and numerical simulation analysis using ANSYS/LS-DYNA, Zhang Teng [1] et al. found that the stress components of longitudinal and shear waves in different directions superimpose and cancel each other out with changes in the reflection coefficient, leading to stress concentration phenomena at different distances between the structural plane and the explosion source. Xu Peng [2] et al. focused on the interaction mechanism between blasting stress waves and explosion-induced cracks, and their research revealed that when blasting stress waves and explosion-induced cracks act in opposite and same directions, the explosive expansion waves inhibit and promote crack propagation, respectively, while shear waves promote and inhibit crack propagation, respectively. Guo Zhidong [3] et al. conducted model tests on concrete with different charge structures and found that with the increase of the distance from the explosion center, the blasting stress waves show exponential attenuation. The coupled charge structure consumes a large amount of energy in the crushing zone, resulting in uneven energy transfer, while the uncoupled charge structure exhibits slower energy attenuation and more uniform energy transfer. During the propagation of stress waves, their amplitude attenuates with the increase of propagation distance. Meanwhile, geological conditions such as the inhomogeneity of the rock mass and the presence of joints and fissures can cause reflection, refraction, and scattering of stress waves, further altering their propagation characteristics and their effect on the center diaphragm.

Blasting vibration is manifested as changes in parameters such as vibration velocity, acceleration, and displacement. Vibration velocity is an important indicator for measuring the impact of blasting vibration on structures. According to the Sadovsky empirical formula, as shown in Equation (2-1), the blasting vibration velocity is related to factors such as explosive charge and distance from the explosion center.

$$v = k\left(\frac{\sqrt[3]{Q}}{R}\right)^{a} \tag{2-1}$$

Where: v is the particle vibration velocity (unit: cm/s); k is the coefficient related to the medium and blasting conditions; Q is the explosive quantity in a single simultaneous detonation (unit: kg); R is the distance from the explosion source to the measuring point (unit: m); and a is the vibration attenuation coefficient.

In tunnel blasting, the intensity of blasting vibration on the center diaphragm varies at different positions, with the vibration velocity of the center diaphragm on the side close to the blasting source often being higher. In addition, blasting vibration has obvious pulse characteristics, and its frequency components are relatively complex, covering the range from low frequency to high frequency. Vibrations of different frequencies have different impact mechanisms on the center diaphragm. Low-frequency vibrations may cause overall

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displacement and deformation of the center diaphragm, while high-frequency vibrations are prone to cause damage and cracking of the local concrete material of the center diaphragm. Through on-site vibration testing and time-frequency energy analysis, Hu Miaoliang [4] et al. found that as the blasting seismic wave propagates, the vibration energy gradually weakens but shows a tendency to concentrate in low frequencies, which may aggravate the adverse effects of vibration. Xiong Haitao [5] et al. constructed a tunnel blasting vibration waveform function to predict the vibration waveform. When the delay time is 10s and 20s, peak superposition occurs; when the delay time is 40s and 50s, the duration of blasting vibration will be prolonged. The optimal delay time for blasting vibration control and blasting vibration effect is 30s. By combining on-site monitoring and numerical simulation, Luo Yanping [6] et al. concluded that the vertical direction of building structures is most affected by blasting, with the main frequency being closer to the natural frequency of the building structure, while the vibration velocity in all directions decreases with the increase of the distance from the explosion center.

3. DAMAGE MECHANISM AND INSTABILITY MODE OF THE CENTER DIAPHRAGM UNDER BLASTING ACTION

3.1. Blasting Damage to the Center Diaphragm

When a blasting event occurs, the stress state of the center diaphragm undergoes a sudden and drastic change. Blasting stress waves and amplitudes first reach the side of the center diaphragm adjacent to the blasting source, generating significant impact loads there. These impact loads induce various stress distributions within the center diaphragm; in addition to compressive stress, tensile stress and shear stress are also generated. Since the tensile strength of concrete is much lower than its compressive strength, under the action of tensile stress, cracking may first appear on the surface concrete of the center diaphragm. Under the action of shear stress, structural shear deformation may occur inside the center diaphragm, reducing its load-bearing capacity.

After blasting, although stress waves and vibrations gradually attenuate, the internal damage already incurred by the center diaphragm will continuously affect its mechanical performance. Cracked concrete areas will reduce the effective bearing area of the center diaphragm, and the deformation and damage of the internal structure will alter the law of stress redistribution. During subsequent construction, under the action of surrounding rock pressure and other external loads, the stress state of the center diaphragm will further deteriorate, potentially leading to further crack propagation and even local or overall instability failure. Therefore, the damage mechanisms of the center diaphragm are mainly summarized as direct damage by stress waves, cumulative damage from blasting vibration, and damage induced by changes in surrounding rock stress, as shown in Table 1. Hao Lou [7] et al. derived the theoretical solution for the dynamic stress concentration factor (DSCF) of circular tunnels under the action of cylindrical and planar P-waves using the wave function expansion method. By combining Fourier transform and Duhamel integral, they determined the transient response of underground tunnels under near-field explosions and far-field earthquakes in both the frequency and time domains. It was found that the differences in the dynamic response and damage characteristics of underground tunnels are mainly attributed to two factors: the curvature of stress waves and the waveform of transient loads. Cui Yaozhong [8] conducted research on the cumulative damage law of retained surrounding rock under cyclic blasting. In the study, only the variable of excavation footage length was altered. The analysis revealed that periodic damage increases with the increase of excavation footage length, showing a linear increasing relationship; the length of the cumulative damage-affected area changes in the opposite trend to the excavation footage, i.e., as the excavation footage length increases, the length of the cumulative damage-affected area decreases, with a linear decreasing relationship.

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The research indicated that during the excavation of underground caverns, the dynamic loads generated by the blasting of the second circle of holes and peripheral holes are the main factors inducing cumulative damage to the surrounding rock. Through systematic research, Yang Renshu's [9] team established, for the first time, a quantitative relationship model between the cumulative damage range of surrounding rock and blasting parameters as well as dynamic response parameters, and derived a universal predictive function relationship. This function can accurately predict the cumulative damage range of surrounding rock at any distance from the explosion source based on the measured peak particle vibration velocity data. Peng Yaxiong [10] et al. constructed a tunnel mechanical model and took the Yaojia Tunnel in the Hunan section of the Shanghai-Kunming High-Speed Railway as the research object to conduct an in-depth analysis of the stability change law of layered surrounding rock under blasting action. It was found that the necessary and sufficient condition for sudden instability of layered surrounding rock tunnels is satisfying the bifurcation set equation, specifically, when the mutation eigenvalue $\Delta \le 0$, the system may undergo sudden instability. In addition, the cumulative effect of blasting will lead to a gradual decrease in the stiffness of the surrounding rock, and the increase in blasting charge will enhance the blasting vibration effect; both of these factors will significantly increase the instability probability of layered surrounding rock.

Table 1. Damage Mechanisms of the Center Diaphragm under Blasting Action

Damage Type	Causes of Damage	Damage Manifestations and Consequences
Direct Damage by Stress Waves	Blasting stress waves (P - waves, S - waves, R - waves) propagate. P - waves induce tensile stress to cause cracking on the surface of the center diaphragm; S - waves trigger shear stress to damage the internal structure; R - waves generate complex stress at the interface.	Surface cracks, internal structure damage, concrete spalling at the interface
Cumulative Damage from Blasting Vibration	The cumulative effect of multiple blasting vibration effects causes the development of micro - cracks inside the concrete.	Decrease in the stiffness of the center diaphragm, increase in deformation. When cumulative damage is severe, even small vibrations can cause further damage or instability.
Damage from Surrounding Rock Stress Changes	Blasting causes redistribution and relaxation of the surrounding rock stress, increasing the pressure on the center diaphragm and changing the contact state.	Uneven stress on the center diaphragm, resulting in damage such as concrete cracking and spalling

3.2. Instability Modes of the Center Diaphragm

After blasting, the concrete on the surface of the center diaphragm cracks first. The direction of the cracks is related to the propagation direction of the blasting stress waves and the stress state of the center diaphragm. Usually, transverse cracks perpendicular to the propagation direction of the stress waves appear on the surface of the center diaphragm on the side close to the blasting source. Oblique cracks also occur under the action of uneven extrusion and shearing between the center diaphragm and the surrounding rock. As the number of blasts increases, the cracks continue to penetrate and develop, leading to the spalling of the concrete

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cover of the center diaphragm. The exposure of steel bars reduces the load - bearing capacity of the center diaphragm. Under the action of blasting vibration and surrounding rock extrusion, overall deformation instability or local deformation instability may occur. Overall deformation instability means that the center diaphragm tilts toward the tunnel side as a whole or bends and deforms. When the deformation reaches a certain extent, the center diaphragm becomes unstable. Local deformation instability means that local structures of the center diaphragm, such as support members and connection parts, are damaged, resulting in the weakening of local load - bearing capacity and thus the overall instability of the center diaphragm. For example, the joint between the center diaphragm and the temporary invert is very likely to be loosened and damaged under the action of blasting loads, leading to the local instability of the temporary center diaphragm.

Table 2. Instability Modes of Center Diaphragm under Blasting Loads

Instability Mode	Description	Influencing Factors
Bending Instability	Excessive local or overall bending moment causes bending deformation or cracking of the diaphragm.	Local action of blasting load, thickness of the diaphragm, flexural strength of materials, boundary conditions
Shear Instability	Shear stress exceeds the shear strength of materials, causing oblique cracks or slip instability.	Shear component of blasting load, shear strength of materials, geometric shape of the diaphragm
Buckling Instability	The diaphragm undergoes local or overall wavy deformation due to being thin - walled or insufficiently supported.	Slenderness ratio of the diaphragm, elastic modulus of materials, direction of blasting load, boundary constraint conditions
Fracture Instability	Sudden failure of the diaphragm due to brittle or ductile fracture of materials.	Toughness of materials, intensity of blasting load, stress concentration phenomenon
Dynamic Instability	Vibration or resonance induced by high - frequency blasting load causes instability or damage of the diaphragm.	Frequency of blasting load, natural vibration frequency of the diaphragm, damping characteristics of materials
Composite Instability	Superposition of multiple instability modes, such as the combined action of bending and shear causing damage.	Comprehensive stress state, material performance, structural form, load distribution

During the long - term construction of the tunnel, the center diaphragm is repeatedly subjected to multiple blasting loads, which will cause fatigue damage. Under the action of fatigue loads, the internal microstructure of the concrete material gradually deteriorates, and cracks continuously initiate and propagate, resulting in a decrease in the fatigue strength of the center diaphragm. When the cumulative fatigue damage reaches a certain level, even under the action of normal surrounding rock pressure, the center diaphragm may undergo fatigue failure. This kind of failure is often sudden and poses a great threat to the safety of tunnel construction. Shao Shengxuan [11] used a multi - factor analysis method to examine the influence of excavation technology, footage depth, and surrounding rock conditions on the dynamic characteristics of the center diaphragm, established a mathematical model for the attenuation of vibration velocity at the waist of the wall, and revealed the correlation law of the evolution of

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vibration velocity and tensile stress with the construction footage. Chen Xin [12] obtained the vibration velocity field data of the ground surface and the center diaphragm through synchronous monitoring technology, and analyzed the propagation characteristics of blasting seismic waves and the characteristics of structural dynamic responses induced thereby. Zhang Qingbin [13] et al. innovatively adopted a comparative research method, and summarized the universal laws of the influence of blasting construction of large - span double - arch tunnels on the center diaphragm through comparative analysis of vibration monitoring data of excavated sections and unexcavated sections.

In addition, the author summarized the instability modes of the center diaphragm under blasting loads by referring to relevant materials, as shown in Table 2.

4. RESEARCH METHODS FOR THE INSTABILITY MECHANISM OF THE CENTER DIAPHRAGM

The instability of the center diaphragm under blasting is due to the interaction of multiple factors, including blasting parameters, structural parameters of the center diaphragm, surrounding rock conditions, etc. The current research methods mainly include three categories: numerical simulation, on - site monitoring, and theoretical analysis.

4.1. Numerical Simulation Method

The extensive application of numerical simulation has greatly enhanced the safety of tunnel blasting excavation work. The simulation methods mainly include finite element simulation and discrete element simulation. For finite element simulation, corresponding software such as ANSYS and ABAQUS is used to establish a three - dimensional numerical model of the tunnel and the center diaphragm. The blasting load is applied to the model in the form of stress wave load or vibration load. Through the visual model, the stress, strain distribution and variation process of the center diaphragm can be intuitively displayed. By observing the influence of changes in blasting parameters, center diaphragm parameters, and properties of surrounding rock on the stress and deformation of the center diaphragm, it can provide reference opinions for optimizing blasting design, the structure of the center diaphragm, etc. Discrete element simulation such as PFC is suitable for the blasting process of rock mass tunnels with developed joints and fissures. It can better consider the discontinuity and fragmentation process of the rock mass, the interaction between rock mass blocks under blasting and the influence on the center diaphragm. Furthermore, it can study the damage and instability process of the center diaphragm under the impact of the movement of blasting rock mass blocks, and can reveal the influence laws and mechanisms of the discontinuity of the rock mass on the instability of the center diaphragm. Cao Ruijun [14] used the finite element software ANSYS to establish and perform mesh division, and then imported the model into FLAC software through the software for calculation. The displacement cloud diagrams and stress cloud diagrams of the model at various stages during the excavation process were obtained. By analyzing the displacement and stress of the key parts of the model, it was concluded that the observation in the vertical axis Z direction should be emphatically strengthened during construction. Zeng Mingliang [15], based on an actual engineering project, used numerical simulation technology to completely simulate the entire construction process of the CD method, and systematically analyzed the distribution characteristics of vertical displacement, bending moment, and axial force of the tunnel structure at each construction stage. The research results show that by optimizing the construction parameters, the structural deformation and internal force can be effectively controlled, and the response of each part can meet the design requirements, thus ensuring the overall construction safety. Yang Weiling [16] et al. adopted the discrete element numerical method to study the catastrophe mechanism of karst tunnels under the combined action of blasting dynamic load and transient unloading of ground stress. They focused on discussing the evolution of the

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displacement field, the change of seepage characteristics, and the law of water pressure redistribution of water - resistant rock layers with different dip angles under dynamic disturbance. Their research results provide a theoretical basis for the optimal design of the center diaphragm method under complex geological conditions.

4.2. On-site Monitoring Methods

The on - site monitoring method refers to a method of directly observing and recording various parameters in the actual engineering environment. It is used to understand the operation status of the project, identify potential problems, and provide a basis for engineering design, construction, and maintenance. In the problem of tunnel blasting instability, the on - site monitoring methods mainly include vibration monitoring and stress - strain monitoring. Vibration monitoring arranges vibration sensors at different positions of the center diaphragm in the tunnel construction site to monitor the vibration response of the center diaphragm in real - time during the blasting process. It analyzes the time - history curves of vibration velocity and acceleration, evaluates the degree of influence of blasting vibration on the center diaphragm, and combines the on - site blasting parameters and geological conditions to establish a relationship model between the vibration response and the blasting parameters, providing a reference for on - site blasting control. Stress - strain monitoring embeds stress - strain sensors inside the center diaphragm to monitor the changes in stress and strain inside the center diaphragm before and after blasting, analyzes the evolution process of its stress state, judges whether there is abnormal stress concentration and deformation, and timely detects potential instability risks. Qin Hong [17] et al., in order to study the propagation law of vibration velocity in various directions under the corresponding surrounding rock grade during the blasting process, took the Liujialing Tunnel as the background, carried out vibration velocity monitoring in three directions X, Y, and Z on - site, and then combined with the numerical simulation data to analyze the on - site vibration velocity. This practice provides a reference for the blasting construction of similar small - clear - distance tunnel projects. Ye Lianchao [18] adopted the on - site monitoring method to describe the surrounding rock deformation and analyze the law of displacement change around the tunnel at each monitoring point of a tunnel section. It is concluded that the deformation mode can be summarized as: pre - deformation - rapid deformation - normal deformation - stable deformation. Yang Dezhi [19], relying on the Caomaoshan Tunnel Project of the Beijing - Zhangjiakou High - speed Railway, carried out blasting vibration monitoring and acoustic wave testing. Through data analysis and curve fitting, the cumulative damage range Rcr and the critical blasting vibration velocity PPVcr corresponding to the blasting construction were obtained respectively, and it was found that there is a good exponential function relationship between R_{cr} and PPV_{cr}.

4.3. Theoretical Analysis Methods

The theoretical analysis method parses the dynamic response and damage evolution process of the center diaphragm by establishing a mathematical model to obtain its instability mechanism, providing guidance for engineering design and safety evaluation. The theoretical analysis methods for the dynamic response instability problem of the center diaphragm include the dynamics theory and the damage mechanics theory. The dynamics theory is based on the dynamics theory of the blasting action on the center diaphragm. By establishing a dynamic model of the blasting action on the center diaphragm, and according to conditions such as the structural and material parameters of the center diaphragm and the application form of the blasting load, the vibration displacement, velocity, and acceleration of the dynamic response of the center diaphragm are calculated. Through theoretical parsing, the analytical or approximate solution of the dynamic response of the center diaphragm is obtained, providing a basis for understanding the dynamic behavior of the center diaphragm under blasting. The damage mechanics theory introduces the research on the damage evolution law. By establishing a

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damage constitutive model, and based on the damage of concrete under the action of blasting stress, through the damage evolution law of concrete with strain, the influence of the damage of the center diaphragm on its overall mechanical properties and instability is analyzed. Damage mechanics analysis can quantitatively predict the cumulative damage degree and the risk of instability of the center diaphragm under multiple blasting actions. Yu Yuanxiang [20] et al. established a stress model of the anchored surrounding rock unit under the action of dynamic and static loads. Based on the principle of coordinated deformation of the rod and rock and the attenuation law of the main frequency of blasting, derived the calculation formulas for the radius of the plastic zone and the fractured zone of the anchored surrounding rock after cumulative damage under the action of dynamic and static loads, and analyzed the evolution law of the deformation range of the anchored surrounding rock under the action of different factors.

In fact, to study the instability of the center diaphragm under blasting, the above methods are not carried out independently. More often, scholars will use two or more methods to verify each other, so that the results obtained are more convincing. Jian Bingxi [21], to explore the dynamic response law of the support structure under the blasting action of the double - arch tunnel, adopted methods such as combining numerical simulation, theoretical analysis, and on - site tests to find the optimal design scheme for the blasting construction of the double - arch tunnel. Wang Xiao [22] comprehensively used methods such as on - site testing, theoretical analysis, and numerical simulation to conduct research on aspects such as "the propagation and attenuation law of stress in the surrounding rock of adjacent tunnels under blasting action, the prediction of the instability and sliding mechanism of rock blocks in the surrounding rock of adjacent tunnels, and the safety criteria for blasting vibration of the surrounding rock of adjacent tunnels".

5. CONCLUSION

This paper summarizes the current achievements in the research on the instability mechanism of the center diaphragm under tunnel blasting, including the characteristics of blasting loads, changes in the stress state of the center diaphragm, research methods for instability mechanisms, failure modes, and influencing factors. However, several key issues in this field still require further investigation:

(1) Limited Research on Indirect Effects: Existing studies primarily focus on the propagation characteristics of blasting stress waves and their direct impact on the center diaphragm. There is a notable gap in understanding the complex stress states arising from the interaction between blasting loads and surrounding rock, as well as their indirect effects on the center diaphragm. Factors such as rock heterogeneity and the development of joints and fissures can significantly alter the propagation path and intensity of blasting loads, thereby influencing the stress distribution in the center diaphragm. Current research has not adequately addressed the comprehensive effects of these factors.

(2) The instability of the center diaphragm results from the coupled effects of multiple factors, including blasting loads, surrounding rock conditions, structural parameters of the diaphragm, and construction techniques. Existing studies primarily focus on single or a few factors, lacking in - depth exploration of the instability mechanism under multi - factor coupling. Systemic theoretical frameworks are yet to be established for issues such as the coupling effect of blasting vibration and surrounding rock stress redistribution, and the synergistic influence of material property degradation and structural form changes in the center diaphragm.

(3) In long - tunnel projects, the adjacent center diaphragm is subjected to repeated blasting loads, and the cumulative damage from multiple blasts significantly impacts long - term stability control. Current research mainly focuses on single - blast damage, with limited studies on the

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evolution of cumulative damage under repeated blasting and its effects on the long - term stability of the adjacent diaphragm. There is a lack of quantitative assessment methods and indicators for cumulative damage, making it difficult to accurately predict the long - term instability risk of the adjacent center diaphragm.

(4) Although numerical simulation, on - site monitoring, and theoretical analysis are the primary research methods for adjacent instability, they all have certain limitations. Numerical simulations rely on model assumptions and parameter selections, failing to reflect the complexity of actual engineering. On - site monitoring is affected by construction conditions and the precision of monitoring equipment, making it difficult to obtain comprehensive data. Theoretical analyses involve overly idealized assumptions and cannot be applied to practical engineering. How to further improve research methods to enhance their accuracy and applicability is a critical issue that needs to be addressed in current research.

In subsequent research, interdisciplinary approaches can be adopted to further explore the instability mechanism under the combined action of factors such as adjacent blasting loads and surrounding rock pressure. Strengthen the summary and analysis of actual engineering cases, and further apply the research results to engineering practice. Provide a more scientific and reliable basis and guarantee for the similar design, construction, and maintenance of adjacent blasting and surrounding rock pressure during tunnel construction, and improve the safety of tunnel construction.

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