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Tunnel Blasting Design Methods under Complex Environmental Conditions in Plateau Areas

Zhou Mingcong[1], Zhao Jun[1], Xiao Qinghua[2], Zhou Ling[1], Shi Chenchen[1], Yuan Hao[2,*]

[1]*China Railway No. 2 Engineering Group Co., Ltd., Chengdu, 610031, China*
[2]*School of Civil Engineering, Southwest Jiaotong University, Chengdu, 610031, China*
[*]*Corresponding author*

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Abstract: This study addresses the challenges faced in tunnel blasting construction under complex environmental conditions in plateau areas and proposes an optimized blasting parameter design method to tackle environmental issues such as high altitude, oxygen deficiency, cold climates, and ecological fragility. Through on-site experiments at a plateau tunnel, key parameters such as blast hole diameter, charge quantity, hole spacing, and initiation sequence were optimized and adjusted, resulting in the development of a blasting parameter design method suited to the characteristics of plateau tunnels. The results show that: (1) Oxygen deficiency and cold climates reduce the efficiency of energy release during blasting, weakening the fragmentation effect, while ecological fragility requires minimal environmental disturbance from the blasting process. (2) Increasing hole diameter, increasing charge quantity, shortening hole spacing, and adopting delayed initiation significantly enhance the stability of the surrounding rock, reduce over-excavation, and minimize environmental disturbance. (3) The optimized blasting scheme reduced the average over-excavation by 41.3%, validating the feasibility and effectiveness of the blasting parameter design method. It was also found that over-excavation increased with hole spacing and decreased initially with increasing hole diameter before rising again. The research provides strong technical support and reference for future blasting construction in plateau tunnels.

1. Introduction

Although there has been significant research on high-altitude tunnel blasting, the determination of blasting parameters and the design of blasting methods are still constrained by factors such as surrounding rock geology, cross-sectional shape, construction conditions, and the fragile ecology, leaving many issues unresolved.

Many scholars have conducted extensive research on tunnel blasting technology under complex geological conditions in high-altitude regions, achieving fruitful results. Xiao et al. [1] introduced 3D laser scanning technology into tunnel blasting and combined it with the BP neural network algorithm to optimize blasting parameters. Liu et al. [2] determined the controlled blasting parameters for the small cross-section tunnels in the second phase of the Yinjiang project under plateau hypoxia conditions, based on the principles of 'short advancement, weak blasting, and minimal disturbance. Xiao [3] studied smooth blasting technology for railway tunnels in plateau mountainous areas and found that it achieved good blasting results for long tunnels. Guan [4] believes that advanced geological forecasting is crucial for determining the blasting parameters of high-altitude railway tunnels. Wu et al. [5] revealed the tunnel blasting mechanism in high-altitude areas through computational fluid dynamics (CFD) and blasting simulations. Huang et al. [6] found that after tunnel blasting, the altitude is inversely proportional to the CO diffusion coefficient. Feng et al. [7] concluded that the high-altitude environment significantly affects the diffusion and concentration distribution of hazardous gases after tunnel blasting. Wang He et al. [8] studied the law of gas migration and ventilation effectiveness, discovering severe gas accumulation near the vault and waist of the tunnel face under non-ventilated conditions. Chang et al. [9] investigated the tunnel ventilation law through CFD numerical simulation and found that after tunnel blasting, a vortex zone forms near the tunnel face and at the intersection of the branch and main tunnels under ventilation. The generation and variation of the vortex continuously consume mechanical ventilation energy, reducing ventilation efficiency. Xu [10] studied the propagation characteristics of environmental noise on-site and discovered that the duration of blasting vibration and blasting noise pressure is roughly the same, suggesting that tunnel blasting in urban areas should simultaneously evaluate both vibration and noise levels. Hou et al. [11] used numerical simulation and theoretical analysis to study the impact of tunnel blasting on nearby ancient buildings, finding that as the charge per blasting cycle increases, the vibration velocity at monitoring points gradually increases, peaking and then gradually decreasing.

In summary, many scholars have conducted extensive research on tunnel blasting parameters, design, ventilation, and environmental impact, achieving significant progress. However, certain limitations remain, such as the optimization of blasting parameters under different geological conditions and the lack of in-depth experimental verification for blasting design in high-altitude regions with ventilation restrictions and minimal impact on the surrounding ecology. Therefore, in light of the complex geological characteristics of plateau regions, further in-depth research is needed on how to design blasting under predefined conditions of high altitude, ventilation limitations, and ecological protection. This would not only improve the current theoretical framework but also provide scientific guidance for engineering practice, enhancing the safety and efficiency of tunnel construction. Based on this context, this paper studies a high-altitude tunnel, aiming to offer insights and references for similar projects and to promote the development and application of this field.

2. Characteristics of high-altitude tunnels and their impact on blasting

High-altitude tunnel construction faces unique natural conditions and ecological environments, particularly characterized by high altitude, oxygen deficiency, cold temperatures, and fragile ecosystems. These factors pose numerous challenges to tunnel blasting operations. In this section, we will discuss these characteristics in detail and analyze their specific impact on tunnel blasting.

2.1. High altitude and oxygen deficiency

In high-altitude regions, the oxygen content in the air is significantly reduced due to the elevation, leading to lower air density in the construction environment. This oxygen-deficient condition has profound effects on various aspects of tunnel blasting operations, as outlined below:

(1) Performance Changes of Blasting Materials: As altitude increases, atmospheric pressure gradually decreases, resulting in reduced detonation velocity and energy of explosives. At standard atmospheric pressure, the detonation velocity of commonly used explosives is about 7000 m/s. However, in high-altitude regions, such as at 4000 meters above sea level, the detonation velocity

drops to around 6500 m/s, weakening the blasting effect. To maintain effective blasting, parameters such as the charge amount and hole spacing must be adjusted according to the altitude.

(2) Diffusion of Dust and Harmful Gases After Blasting: In high-altitude environments, thin air and slower airflow make it difficult for dust and harmful gases generated by blasting to disperse. In tunnels at an altitude of 3500 meters, PM2.5 concentrations can reach 500 micrograms per cubic meter within five minutes of blasting, which is ten times the standard value. Therefore, enhanced ventilation measures are essential during construction to ensure worker safety.

(3) Decline in Machinery Efficiency: Oxygen deficiency also affects the operational efficiency of mechanical equipment, particularly rock drilling and excavation machines. Due to reduced combustion efficiency, equipment power can decrease by 20%-25%, directly slowing down the construction progress. Additionally, the maintenance and upkeep of equipment become more challenging, further increasing construction costs.

2.2. Cold climate

The cold climate in high-altitude regions has a significant impact on tunnel blasting operations, which is mainly reflected in the following aspects:

(1) Effect of Low Temperatures on Explosive Performance: In low-temperature conditions, the chemical reaction rate of explosives slows down, leading to incomplete explosions and reduced blasting efficiency. Moreover, low temperatures increase the brittleness of explosives and blasting equipment, which can result in blasting failures or accidental explosions during construction. Therefore, selecting explosives and blasting equipment that are suitable for cold environments is one of the key focuses in such operations.

(2) Impact of Temperature Differences on the Rock Mass: The large temperature differences between day and night in high-altitude regions cause stress concentration in the rock mass due to alternating heating and cooling, which increases the risk of rock instability after blasting. During construction, special attention should be paid to selecting appropriate blasting times, avoiding periods with significant day-night temperature differences, and applying proper rock support measures to maintain stability.

2.3. Ecological fragility

The ecological environment in high-altitude regions is extremely fragile, and even minor mistakes during tunnel construction could cause irreversible damage to the surrounding ecosystems. Therefore, tunnel blasting operations must be designed and implemented with strict adherence to environmental protection principles, minimizing disturbances to the surrounding ecosystem.

(1) Impact of Blasting on Soil and Vegetation: Vegetation in high-altitude areas grows slowly, and the soil structure is loose. Blasting operations can lead to soil erosion and vegetation degradation. As a result, blasting designs must strictly control the range of vibration to minimize damage to the surface vegetation and soil. When necessary, ecological restoration measures such as vegetation recovery and soil conservation should be implemented.

(2) Water Resource Pollution: Water resources in high-altitude areas are both precious and scarce. If untreated wastewater and chemicals from blasting operations are discharged directly, they could contaminate the water sources. Therefore, construction sites must be equipped with effective wastewater treatment systems to ensure that no water pollution occurs during blasting operations.

In summary, the challenges posed by high altitude, oxygen deficiency, cold climate, and ecological fragility in high-altitude tunnel construction demand higher standards for blasting operations. To address these issues, it is crucial to optimize blasting parameters, select blasting materials and equipment suitable for the local environment, and adopt necessary environmental protection measures to ensure the safety and sustainability of the construction process.

2.4. Responses to high-altitude tunnel blasting challenges

Due to the unique environment of high-altitude tunnels (characterized by high altitude, oxygen deficiency, cold temperatures, and ecological fragility), traditional blasting designs are no longer fully applicable. Therefore, it is necessary to optimize and adjust blasting parameters to address the challenges of high-altitude oxygen deficiency, cold climate, and ecological fragility. The specific countermeasures are as follows:

(1) Countermeasures for High-Altitude Oxygen Deficiency

To address the issues of insufficient energy release and slow diffusion of dust and harmful gases caused by oxygen deficiency at high altitudes, the following measures can be adopted: 1) Increase the blast hole diameter from the standard 45 mm to 50-55 mm to compensate for the reduced energy release due to oxygen deficiency. 2) Increase the charge amount per hole by 15% to 20%, while ensuring safety, to achieve sufficient rock fragmentation. 3) After blasting, immediately activate ventilation systems to ensure that dust and gases disperse to safe levels within 10 minutes. Additionally, use delayed detonation to reduce excessive dust generation from a single blast.

(2) Countermeasures for Cold Climate

To address incomplete detonation of explosives and reduced efficiency of machinery due to the low temperatures in high-altitude regions, the following measures can be taken: 1) Select cold-resistant explosives to ensure stable energy release. 2) Shorten the hole spacing slightly to ensure adequate rock fragmentation, as cold environments may increase internal stress within the rock mass. 3) Strengthen equipment maintenance and adopt antifreeze measures for machinery to ensure normal operation of drilling equipment.

(3) Countermeasures for Ecological Fragility

To address the slow vegetation growth, loose soil structure, and sensitivity to disturbances in high-altitude regions, the following measures can be implemented: 1) Use segmented delayed blasting to reduce the cumulative effect of vibrations. Set the delay interval between detonations to 25 ms to 50 ms to mitigate vibration stacking effects and reduce damage to the surrounding soil and vegetation. 2) Control the charge amount and shorten the hole spacing to better manage the distribution of blasting energy, minimizing the impact on the surrounding ecological environment.

3. Blasting design plan

To explore blasting design methods under the complex conditions of high-altitude regions, this study, based on a specific high-altitude tunnel project, proposes a blasting design method tailored to the characteristics of high-altitude tunnels. This method addresses challenges such as high altitude with oxygen deficiency, cold climate, and ecological fragility, ensuring that the blasting design is suitable for the unique conditions of high-altitude environments.

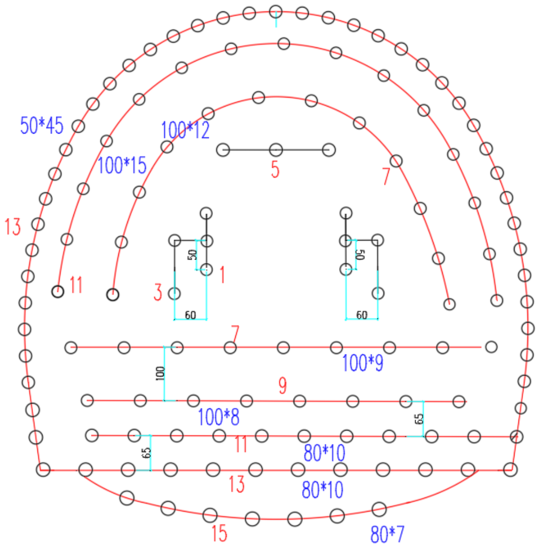
3.1. Engineering background

The tunnel in the high-altitude region has a total length of 25,595.52 meters and is located at an elevation of 3,800 meters. The construction method involves a combination of one inclined shaft, one cross passage, and the drilling-and-blasting method for the excavation of twin single-track tunnels. The surrounding rock is primarily classified as Grade IV and V. The maximum burial depth of the tunnel is 1,180 meters, and it crosses five faults and fracture zones, along with ten folds. The recommended water inflow throughout the tunnel is approximately 137,000 cubic meters per day, with a maximum inflow of about 207,000 cubic meters per day. Additionally, the tunnel is subjected to strong tectonic stress, with the presence of gas and harmful gases.

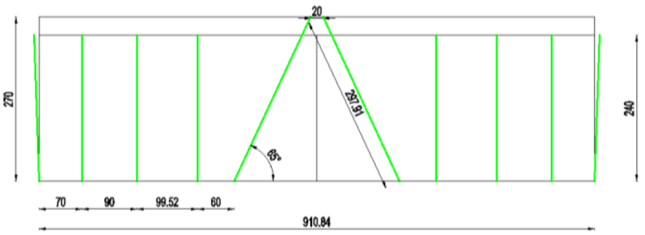
3.2. Blast plan

The rock surrounding the tunnel in the blasting section is classified as Grade IV, primarily composed of shale, with a clear cross-sectional dimension of 7.5 meters wide and 6.5 meters high (as shown in Figure 1) and an advance length of 2.4 meters. By applying the aforementioned countermeasures, the blasting plan for this experimental section is illustrated in Figure 2, and the blasting parameters are detailed in Table 1.

Figure 1: Internal environment of a high-altitude tunnel



(a) Schematic diagram of full-cross-section blast hole layout (Unit: cm)



(b) Cross-sectional schematic diagram of blast hole layout for full-cross-section excavation (Unit: cm)

Figure 2: Schematic diagram of the blasting plan

Table 1: Blasting parameters

Excavation Section	Blast Hole Name	Number of Holes	Hole Depth (m)	Hole Spacing (m)	Resistance Line (m)	Angle (°)	Charging Structure	Charging Amount				Stemming Length (m)	Electronic Detonator Delay Interval	Remarks
								Charging Length (m)	Charge per Hole (kg)	Actual Conversion to Sticks per Hole	Subtotal (kg)			
Full Cross Section	First-Level Cut Holes	6	2.98	0.5	/	65	Continuous	1.6	1.6	5.3	9.6	0.3	1	32mm explosive cartridge
	Second-Level Cut Holes	4	2.4	0.75	0.5	90	Continuous	1.4	1.4	4.7	5.6	0.3	3	32mm explosive cartridge
	Auxiliary Holes	3	2.4	1	1	90	Continuous	1.3	1.3	4.3	3.9	0.3	5	32mm explosive cartridge
	Auxiliary Holes	15	2.4	1	1	90	Continuous	1.3	1.3	4.3	19.5	0.3	7	32mm explosive cartridge
	Auxiliary Hole	12	2.4	1	1	90	Continuous	1.3	1.3	4.3	15.6	0.3	9	32mm explosive cartridge
	Auxiliary Hole	28	2.4	1	1	90	Continuous	1.3	1.3	4.3	36.4	0.3	11	32mm explosive cartridge
	Auxiliary Hole	9	2.4	1	1	90	Continuous	1.3	1.3	4.3	11.7	0.3	17	32mm explosive cartridge
	Floor Holes	7	2.4	0.8	0.65	90	Continuous	1.3	1.3	4.3	9.1	0.3	15	32mm explosive cartridge
	Perimeter Holes	45	2.4	0.5	0.6	92	Interval	/	0.4	2	18	0.3	13	25mm explosive cartridge
Total		129	/								129.4	comprehensive specific consumption :0.82kg/m^3		

4. Implementation of the blasting plan and result analysis

To ensure the smooth implementation of the blasting plan, real-time measurements of blast hole parameters were conducted on-site (as shown in Figure 3), and the results were fed back to the technical team to allow for adjustments as needed, reducing errors. In actual operations, site preparation followed the designed blasting plan, using the latest hydraulic rock drilling machines. The blast hole diameter was 50 mm, with a drilling depth controlled at 2.5 meters, and a perimeter hole spacing of 50 cm. According to the construction plan, a total of 129 blast holes were required for each operation. During drilling, it was essential to maintain precise hole spacing to avoid uneven blasting effects caused by over- or under-spacing. The delayed detonation sequence was set with a 50ms interval to minimize vibration stacking effects. After detonation, on-site monitoring was conducted to assess overbreak and underbreak conditions, and the resulting rubble was promptly cleared. Additionally, the proper functioning of the tunnel ventilation system was ensured to maintain safety during the blasting operation.

(a) Blast hole parameter measurement (b) Explosive data collection

Figure 3: On-Site blasting parameter collection

The overbreak and underbreak results measured after blasting, following the steps outlined above, are shown in Figure 4.

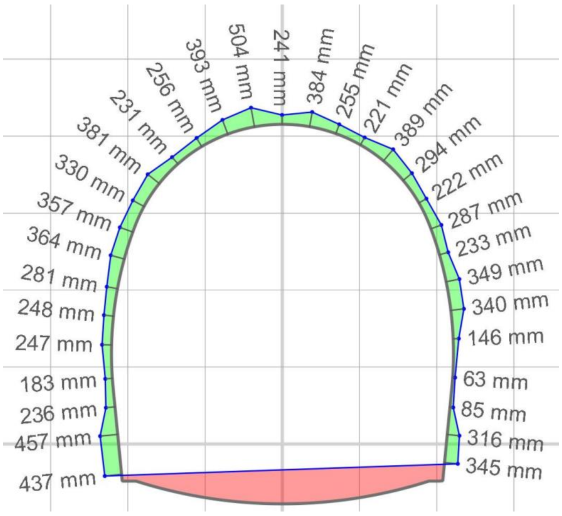


Figure 4: Schematic Diagram of the First Tunnel Overbreak and Underbreak Results

As shown in Figure 4, the average linear overbreak from this blasting operation was 292.802 mm, indicating room for optimization. Based on the previously discussed blasting parameter design, the following adjustments were made to optimize the blasting parameters: 1) Increase the blast hole diameter to 55 mm; 2) Reduce the perimeter hole spacing to 45 cm, and decrease the auxiliary hole row spacing to 60 cm, using a 25 ms delayed detonation; 3) Control the outward angle of the perimeter holes and increase the distance between the steel arch and the tunnel face. The adjusted plan was communicated on-site, and real-time monitoring of the blasting parameters was conducted. The results of the optimized overbreak and underbreak are shown in Figure 5.

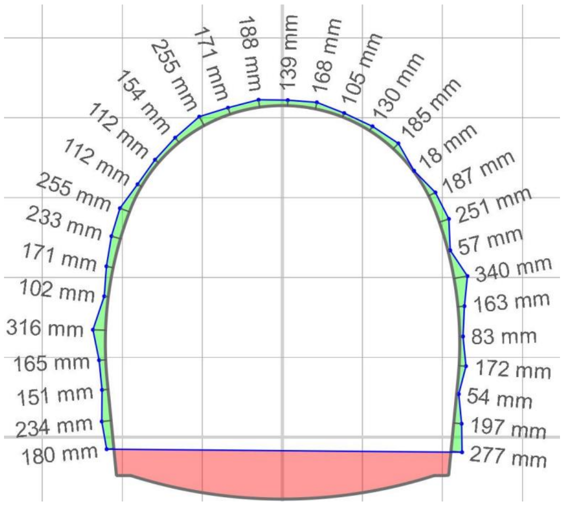
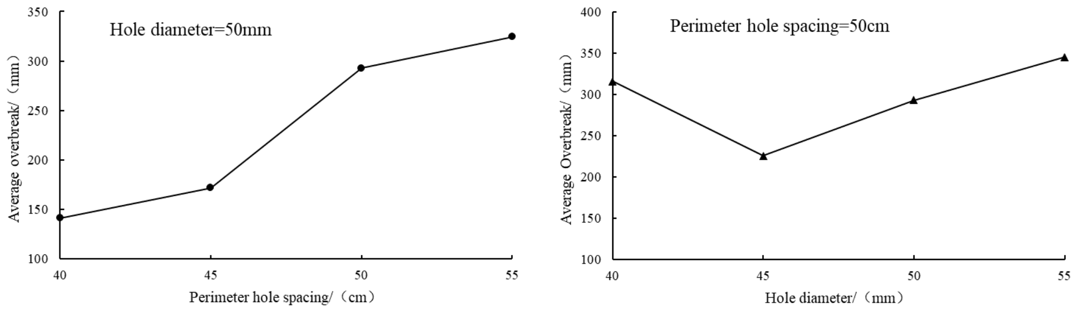


Figure 5: Schematic diagram of the optimized tunnel overbreak and underbreak results

As shown in Figure 5, the optimized average linear overbreak and underbreak was reduced to 171.731 mm. Compared to the pre-optimization overbreak, this represents a 41.3% reduction, indicating a significant improvement in blasting performance. This demonstrates the feasibility of the optimized plan and confirms the validity of the chosen blasting parameters for high-altitude tunnels. To further analyze the impact of blast hole parameters on overbreak and underbreak, a sensitivity analysis was conducted on the perimeter hole spacing and blast hole diameter. The final statistical results are shown in Figure 6.



(a) Impact of perimeter hole spacing (b) impact of blast hole diameter

Figure 6: Sensitivity analysis of blast hole parameters

As shown in Figure 6, when the hole diameter remains constant, the overbreak increases as the perimeter hole spacing increases. This indicates that smaller perimeter hole spacing results in a more concentrated distribution of blasting energy in the rock mass, leading to more uniform rock fragmentation and reduced overbreak. When the perimeter hole spacing remains constant, the overbreak initially decreases and then increases as the hole diameter increases. This suggests that when the blast hole diameter is relatively small, the blasting energy is weaker, and the amount of explosives is insufficient to fully fragment the rock, leading to localized underbreak. However, when the diameter becomes too large, the blasting energy becomes excessive, resulting in increased overbreak. Therefore, selecting appropriate blasting parameters is crucial for controlling tunnel overbreak. These parameters should be determined based on a comprehensive analysis of the tunnel's geological conditions, construction environment, blasting objectives, and economic costs.

5. Conclusions

Based on the characteristics of tunnel blasting under complex geological conditions in high-altitude regions, a series of blasting parameters were proposed and optimized to address the environmental challenges of high altitude, oxygen deficiency, cold temperatures, and ecological fragility. Through field trials and data analysis, the effectiveness of the optimized blasting design in practical engineering was verified. The specific conclusions are as follows:

(1) The characteristics of high-altitude tunnels, including high altitude, oxygen deficiency, cold climate, and ecological fragility, significantly affect blasting operations. Low oxygen levels and cold temperatures reduce the energy release efficiency of explosives, weakening the fragmentation effect. Ecological fragility necessitates minimal environmental disturbance during blasting.

(2) In response to the environmental characteristics of high-altitude tunnels, measures such as increasing hole diameter, increasing charge amounts, shortening hole spacing, using delayed detonation, and enhancing ventilation systems were proposed to improve rock stability, reduce overbreak and underbreak, and minimize environmental disturbances.

(3) Through the implementation and adjustment of the blasting plan, the average overbreak was reduced by 41.3%, verifying the feasibility and effectiveness of the blasting parameter design. It was also found that overbreak increases with the increase in perimeter hole spacing and initially decreases, then increases with the increase in hole diameter.

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