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Original Paper

Comparison of Ventilation Schemes and Analysis of Implementation Effects for Construction Ventilation in Extra-Long Tunnels under High-Cold and High-Altitude Conditions —A Case Study of Tianshan Shengli Tunnel

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Abstract

To address the technical challenges of low air pressure, low temperature, long distance, and multiple working faces in the construction ventilation of extra-long tunnels in high-cold and high-altitude areas, this study takes the Tianshan Shengli Tunnel project as the engineering case and systematically investigates the comparison, optimization, and implementation effect of ventilation schemes by combining theoretical calculation, comparative analysis, and on-site systematic monitoring. Based on a construction organization arranged in two major stages and sixteen sub-stages, two ventilation modes are compared and analyzed: full-face simultaneous construction (Scheme I) and process-alternating construction (Scheme II). A required-air-volume calculation system is proposed with blast-fume exhaust as the controlling factor, yielding design values of 1980m³/min for the main tunnel by drilling and blasting method, 1500m³/min for the central pilot tunnel by TBM method, and 855m³/min for the shaft by drilling and blasting method. Combined with on-site conditions, Scheme II is further optimized to establish a combined ventilation mode of "forced ventilation in the main tunnel + drift ventilation in the central pilot tunnel + centralized smoke exhaust through the shaft," supplemented by refined on-site management. Compared with Scheme I, the total power is reduced by approximately 60% on average, with a maximum reduction of 74.9% during peak periods and the cumulative cost savings over the entire construction cycle amount to approximately 128.10 million RMB On-site monitoring results show that the wind speed at all sections meets the requirement of ≥0.3 m/s and the CO concentration is controlled below the allowable limit. In addition, a significant *blocking effect of the secondary lining trolley on pollutant transport is discovered, with a CO concentration difference reaching 3.96 times. The research findings can provide technical reference for the construction ventilation of extra-long tunnels in high-cold and high-altitude areas.*

Keywords

extra-long tunnel, construction ventilation, high-cold and high-altitude, ventilation scheme selection, dynamic optimization, Tianshan Shengli Tunnel

1. Introduction

The scale of construction of extra-long tunnels in the cold and high altitudes in western China continues to expand. By the end of 2021, 16 highway tunnels with a length of over 10 kilometers had been completed, 21 were under construction and 5 were planned [1]. In high-altitude areas, the air density is low and the air pressure is small. The air volume of ventilators decreases and the combustion of internal combustion machinery is incomplete, making the technical difficulty of construction ventilation extremely high [2]. The Tianshan Victory Tunnel, which is 22,105 meters long, is the longest highway tunnel under construction in the world. It is located in the middle of the Tianshan Mountains in Xinjiang, with an entrance elevation of about 2,767 meters and an exit elevation of about 2,900 meters. The extreme minimum temperature is -33.5 ° C and the maximum depth of permafrost is 5.0 meters. The tunnel adopts the “two main tunnel drilling and blasting method + middle tunnel TBM method” three-tunnel scheme, with four shafts for ventilation in five sections. During the peak period, nine working faces are under construction simultaneously, and the construction ventilation faces multiple extreme challenges such as low air pressure, high cold, long distance and multiple working faces [4].

In terms of existing research, Wu et al. [2] derived the wind pressure and power altitude correction coefficient formula $c_1=-0.0767H+1$ (H is altitude, km), indicating that the ventilation volume requirement at an altitude of 4,000 m is approximately three times that in plain areas. Wang Daoliang [3] systematically summarized the key technologies for the design of high-altitude highway tunnel civil engineering and pointed out that in high-altitude construction ventilation, the dual effects of air pressure reduction on air volume and internal combustion engine power should be considered. Qiao Hongyan [4] studied the cooling and thermal environment characteristics of super-long single-head construction in high-temperature tunnels and revealed the special requirements for construction ventilation in high-temperature environments. Shao Chun et al. [5] systematically summarized the influence laws of low-temperature environments on ventilation equipment. He et al. [6] studied the ventilation characteristics of extra-long tunnel construction in high-altitude areas through numerical simulation. Zhang et al. [7] studied the configuration of construction personnel and electromechanical equipment for extra-long tunnels in plateau and cold regions, providing basic data for the calculation of air demand.

However, existing studies have mainly focused on the optimization of a single tunnel and a single ventilation mode [8-10], and there is a lack of systematic methods for the comparison of ventilation schemes for simultaneous construction of multiple working faces under the “three tunnels + multiple shafts” combination mode, and the quantitative evaluation of implementation effects is insufficient. Wang et al. [8] studied the ventilation optimization of the inclined shaft construction section of the extra-long tunnel at high altitude, but did not cover the combined ventilation conditions of multiple shafts. Chen et al. [9] conducted an optimization study on the press-in ventilation combined with jet fan scheme for extra-long tunnels, and the conclusion was mainly applicable to double-bore tunnels. Duo Shengjun [10] studied the ventilation technology for long-distance TBM construction in railway tunnels, but there is no systematic report on the comparison of ventilation schemes for the “drill-and-blast +TBM” hybrid construction mode. Han Xianmin et al. [11] proposed the combined ventilation technology of partition and air duct, providing a new idea for air flow organization in complex conditions.

Based on the Tianshan Victory Tunnel project, this paper systematically conducts the comparison and implementation effect analysis of ventilation schemes for extra-long tunnels in high cold and high altitude, with a focus on the 16-stage power comparison of the two ventilation schemes, the optimization concept of alternating process construction, and the implementation effect verification based on field system monitoring.

2. Overview of the Project

The Tianshan Victory Tunnel, located in Hejing County, Bayingolin Mongolian Autonomous Prefecture, Xinjiang, is a key project of the G0711 Urumqi-Weili section expressway. The left line is 22,131 meters long and the right line is 22,122 meters long. The designed speed is 80 km/h, the building clearance is 10.25 meters wide and 5.0 meters high, and the maximum burial depth is 1,115 meters [12].

The tunnel site has a typical alpine and cold climate, with a multi-year average surface temperature of -0.8 to -5.7 ° C, an extreme minimum temperature of -33.5 ° C, a maximum permafrost depth of 3.0 to 5.0 m, and a freezing period of up to 8 months each year. There are 16 fault zones in the tunnel site area, with normal water inflow ranging from 35,652 to 37,114 m^3/d and rockburst sections of 3,940 m. The F6 fault fracture zone is about 100 m long in the tunnel body, the fracture influence zone is about 345 m long, and the maximum in-situ stress is 21.8 MPa [13].

The tunnel adopts the “three shafts and four shafts” construction scheme. The two main tunnels will be constructed using the drilling and blasting method, while the middle approach tunnel (service tunnel) will be constructed using the TBM method (8.43m diameter, with two TBMS advancing in opposite directions), and a working face will be added to the main tunnel through the vehicle cross passage to achieve “long tunnel short excavation”. Four ventilation shafts (No. 1 to No. 4) are set up for ventilation in five sections, as shown in Table 1. Among them, No. 2 shaft is 707 m deep and is the deepest highway shaft in the country. Vehicle transverse tunnels are spaced 750 to 1,000 meters, and pedestrian transverse tunnels are spaced 250 to 350 meters. During the peak construction period, a total of 9 working faces were arranged simultaneously (6 main tunnels + 2 TBMS + 1 shaft), and the construction ventilation conditions were extremely complex [12].

Table 1. Shaft Parameters of Tianshan Shengli Tunnel

Shaft	Well depth /m	Net diameter /m	Wellhead altitude /m	Functional positioning
1 #	575	9.0	2 970	Ventilation and smoke exhaust
2 #	707	9.0	3 150	Ventilation and smoke exhaust (the deepest highway shaft in China)
3 #	476	9.0	2 893	Ventilation and smoke exhaust
4 #	321	9.0	2 850	Ventilation and smoke exhaust

2. Comparison of Ventilation Schemes for Long Tunnels in Cold and High Altitudes

2.1 Required Air Volume Calculation

2.1.1 Method of Calculation

The required air volume for construction ventilation is calculated separately by the following four methods, and the maximum value is taken as the design air volume [14] :

(1) By the number of workers required: $Q_1=n\times q$, where n is the maximum number of workers in the tunnel; q is the air volume required per person, taken as 4 $m^3/(min\cdot person)$.

(2) According to the air volume required to remove blast smoke: $Q_2=(7.8/t)\times\sqrt[3]{(AL^2S^2)}$, where A is the amount of explosives used in one blast, kg; L is the length of ventilation that needs to be improved after blasting, m; S is the cross-sectional area of the tunnel, m^2; t is ventilation time, min.

(3) Air volume required for the minimum allowable wind speed: $Q_3=60\times v_{m\ m\ n}\times S$, where $v_{m\ n\ n}$ is the minimum allowable wind speed, take 0.3 m/s for the main tunnel, 0.5 m/s for the service tunnel, and 0.15 m/s for the shaft.

(4) According to the air volume required to dilute the exhaust gas of the internal combustion engine: $Q_4=k\times\Sigma P$, where k is the coefficient of air volume required per unit power of the internal combustion engine, take 3-4.5 $m^3/(min\cdot kW)$; ΣP is the total power of the internal combustion engine, kW.

Among the above four methods, the dilution of internal combustion engine exhaust gas method has the largest calculation result, but the coefficient k has a wide range of values and does not take into account the impact of the decrease in internal combustion engine power and the increase in emissions at high altitudes. Therefore, this paper takes the calculation results of the internal combustion engine exhaust gas as a reference, uses the blast smoke exhaust air volume as the control factor for the main tunnel, and uses the minimum wind speed as the control factor for the service tunnel and the shaft to comprehensively determine the design air volume.

2.1.2 Calculation Results of Air Demand for each Work Area

The excavation cross-sectional area of the main tunnel by drilling and blasting method is 110 square meters, that of the service tunnel by TBM method is 50 square meters, and that of the vertical shaft by drilling and blasting method is 95 square meters. After high altitude correction (average altitude about 3,200 m, correction factor c_1=0.7546), the calculation results are shown in Table 2.

Table 2. Calculation Results of Required Air Volume

Work area type	By personnel /(m³·min⁻¹)	By blast exhaust /(m³·min⁻¹)	By minimum wind speed /(m³·min⁻¹)	By internal combustion engine /(m³·min⁻¹)	Design values /(m³·min⁻¹)	Control factors
Main hole drilling and blasting method	88	1 980	1 980	1 012.5	1 980	Blast exhaust
Service Tunnel TBM method	72	0	1,500	0	500	Minimum wind speed
Shaft drilling and blasting method	72	855	855	430.8	855	Minimum wind speed

The main tunnel is controlled by blast smoke (1,980 m³/min), and the service tunnel and shaft are controlled by minimum wind speed (1,500 m³/min and 855 m³/min, respectively). After high-altitude correction, the actual air requirement for the main tunnel reached 2,633 m³/min.

2.2 Ventilation Scheme One: Simultaneous Construction of the Entire Face

2.2.1 Ventilation Phase Division

According to the construction organization design, the ventilation process is divided into 16 stages based on the construction progress of each face and the sequence of crossing passage connection [12]. The phase division is marked by the opening of each transverse passage and the advancement of each face. Take the left line as an example: The first stage is opening excavation (single working face); The second stage is the formation of two working faces after the No. 1 transverse passage is connected; The third stage is the formation of three working faces after the No. 2 transverse passage is completed; And so on until the end of the single working face in the sixteenth stage.

2.2.2 Power Calculation for Each Stage

The ventilator power is calculated as N=Q×p/(60×η), where η is the fan efficiency. The total power calculated for each stage of Scheme 1 is shown in Table 3.

Table 3 Calculated Total Power of each Sage for Scheme I

Stages	Left line total power /kW	Right line total power /kW	Stage characteristics
Stage 1	155.22	155.22	Opening excavation, single working face
Phase 2	583.13	583.13	1# cross passage through, 2 working faces
Phase 3	1 908.54	1 115.83	2# cross passage through, three working faces
Phase 4	687.75	687.75	The opening section of the main hole ends
Stage 5	2 643.09	1 523.46	3# cross passage through, 4 working faces
Phase 6	1 021.56	1021.56	1# Main hole ends
Stage 7	4 410.69	2 698.72	4# cross passage through, 5 working faces
Phase 8	4 241.87	2 513.55	Shaft No. 1 was connected, and smoke exhaust was initiated using the shaft
Phase 9	**5,757.21**	**3 398.71**	**5# transverse channel through, power peak period**
Phase 10	1 732.07	1,156.38	Press-in + jet roadway combined ventilation
Phase 11	4 969.62	3 015.28	6# cross passage through
Phase 12	4 371.13	2 518.96	Shaft No. 2 is through
Phase 13	3 250.68	2 105.44	9# cross passage through
Phase 14	2 590.02	1,852.17	Cross passage No. 10 is connected
Phase 15	1 564.63	1 185.33	12# and 13# cross channels are connected
Phase 16	143.91	143.91	Single work face closure

As shown in Table 3, the peak power of Scheme 1 occurs in stage 9, with 5,757.21 kW on the left line and 3,398.71 kW on the right line. With the increase in the number of working faces and the extension of ventilation distance, the power rose sharply. Phases 7 to 9 are the peak periods for multiple working faces, and the power remains high. There are three main reasons for the sharp increase in power: (1) multiple working faces are operating at full capacity simultaneously. Each working face is calculated based on the blast smoke exhaust air volume of 1,980 m^3/min, and the total air volume increases linearly with the number of working faces; (2) The extended ventilation distance leads to a significant increase in frictional resistance along the way, and the ventilation resistance increases approximately in a quadratic relationship with the ventilation length; (3) When multiple fans operate in series, the system efficiency decreases as the number of series increases.

2.3 Ventilation Scheme 2: Alternate Construction of Processes

2.3.1 Optimization Concept

The core idea of Scheme 2: When multiple faces are under construction simultaneously during peak hours, the newly opened auxiliary working faces (such as faces 3# and 5# or faces 4# and 6#) shall be constructed with alternating processes or partial alternating construction methods. At one of the faces, only human operations (arch erection, drilling, etc.) are carried out, and there are no internal combustion mechanical equipment operations and high air-consuming processes such as blasting, slag removal, and spraying. At this time, the face is supplied with air based on the required air volume of the construction personnel (400 m^3/min), which significantly reduces the required air volume compared to the full-load calculation in Scheme One.

For example, in the third phase, the 1# main tunnel, considering only personnel operations, requires air from 1,980 m^3/min to 400 m^3/min, the ventilation resistance of this section is reduced from 182.77 Pa to 7.46 Pa, and the corresponding power is reduced from 16.91 kW to 0.14 kW, a reduction of 99.2%.

2.3.2 Power Calculation for Each Stage

Scheme 2 optimizes and adjusts the air demand for non-main construction faces based on Scheme 1. The total power calculated at each stage is shown in Table 4.

Table 4. Calculated Total Power and Reduction rate for Scheme II

“Stage	Left line total power /kW	Right line total power /kW	Lower rate /% compared to Scheme 1
Phase 1	155.22	155.22	0
Phase 2	583.13	583.13	0
Stage 3	**745.21**	**508.88**	**61.0/54.4**
Stage 4	687.75	687.75	0
Stage 5	**1 083.93**	**746.40**	**59.0/51.0**
Stage 6	1 021.56	1 021.56	0
Stage 7	**1 800.84**	**1 404.68**	**59.2/48.0**
Stage 8	**1 616.57**	**1 341.25**	**61.9/46.6**
Stage 9	**2 288.84**	**1 852.17**	**60.3/45.5**
Phase 10	**722.59**	**671.55**	**58.3/41.9**
Stage 11	**1 988.21**	**1 626.49**	**60.0/46.1**
Stage 12	**1 095.72**	**1 021.56**	**74.9/59.5**
Stage 13	**1 392.32**	**1 185.33**	**57.2/43.7**
Stage 14	1 341.25	1 185.33	48.2/36.0
Stage 15	**484.49**	**484.49**	**69.0/59.1**
Stage 16	143.91	143.91	0

According to Table 4, during the multiple working face simultaneous construction phases (Phases 3, 5, 7 to 15) of Scheme Two, the power reduction rate is 45% to 75%. Stage 12 has the greatest reduction (74.9%), and stage 14 has the smallest reduction (48.2%). In the single-face phase (Phases 1, 2, 4, 6, 16), the power of the two schemes is the same. In the case of stage 3, the total power of the left line in Scheme 1 is 1,908.54 kW, and in Scheme 2 it drops to 745.21 kW, a reduction of 61.0%. The mechanism of the power reduction is as follows: After considering only personnel operation, the air volume required at the face of the No.1 main tunnel drops from 1,980 m^3/min to 400 m^3/min, the resistance of the ventilation pipe section drops sharply from 182.77 Pa to 7.46 Pa, and the corresponding fan power drops from 16.91 kW to 0.14 kW, a reduction of 99.2%.

2.4 Scheme Comparison

Further, indicators such as peak total power, average stage power, number of main wind turbines, and life-cycle cost were selected for comparison of technical feasibility and economic rationality, and the results are shown in Table 5.

Table 5. Comparison of Technical and Economic Indexes

Comparison indicators	Option 1 (Simultaneous construction of the entire face)	Option 2 (Alternate construction process)	Rate of difference
Peak maximum total power /kW	5,757.21	2 288.84	-60.3%
Average stage power /kW	1 850	740	-60.0%
Number of main fans per unit	6	6	0
Life cycle cost/ten thousand yuan	21 450	12 980	-39.5%
Payback period/year	—	—	1.2

Option 2 reduces peak power by 60.3% compared to Option 1, average power by 60.0%, and life cycle cost by 39.5%. From the perspective of life cycle cost (LCC), the cumulative savings in operating costs over the 6-year construction period of Plan 2 have exceeded the initial investment difference, and the payback period is only about 1.2 years.

The technical advantage of Plan 2 lies in: (1) achieving “management for energy consumption” through the optimization of construction organization, significantly reducing ventilation energy consumption by merely arranging construction procedures without increasing investment in ventilation equipment; (2) It avoids the “big horse pulling a small cart” phenomenon that occurs during the peak hours of multiple working faces in Scheme One, and the operating conditions of the fans at each stage are closer to the rated conditions, and the system efficiency is higher; (3) The total air volume in the tunnel was reduced, and the average wind speed in the main tunnel was lowered from 1.2 m/s in Scheme 1 to 0.85 m/s, improving operational comfort.

As shown in Table 6, the power configuration of each fan is compared below.

Table 6. Comparison of Fan Power Configuration

Fan position	Service Range	Option 1 Power /kW	Scheme 2 Power /kW	Reduction rate /%
Fan No. 1	Left hole No. 1 face	647.07	647.07	0
2# Wind turbine	Service Tunnel TBM+ Left Tunnel No. 2 and No. 3 faces	3 215.09	1 427.85	55.6
Fan No. 3	Right hole 2# and 3# faces	2 787.99	613.00	78.0
4# Fan	Right hole 1 face	610.72	610.72	0

As shown in Table 6, the power reduction of wind turbines No. 2 and No. 3 (55.6% and 78.0% respectively) is the main contributor to the energy saving of Scheme 2. 1# and 4# wind turbines serve a single working face, and the power of the two schemes is the same.

Considering both technical feasibility and economic rationality, the ventilation of the Tianshan Victory Tunnel construction is recommended to adopt Scheme Two (alternating process construction mode), but it should be noted that the implementation of Scheme Two poses higher requirements for on-site construction organization and management. The process arrangement of the auxiliary working face needs to be coordinated with the main working face, and the complexity of construction scheduling has increased. In actual operation, the following measures should be supplemented on site: (1) Construction scheduling at each face should give priority to ensuring full-load operation at the main face, and low-air consumption processes should be arranged at the auxiliary face; (2) Be equipped with mobile local ventilation equipment to provide supplementary ventilation for sudden high-air consumption operations on site.

3. Dynamic Optimization and Refined Management of Ventilation Schemes

3.1 Problems with the Original Ventilation Scheme

The traditional pure press-in ventilation scheme was adopted in the early stage of construction. As the tunnel excavation depth increased and the intermediate shaft was gradually completed, the following problems were exposed in the original scheme [12]: (1) The imported axial fan was installed on the steel structure support. During operation, it was found that the fan resonated with the support at a frequency of 40 Hz, and the vibration amplitude exceeded the allowable value, making it impossible to operate at full load; (2) There is a distance of about 200 m between the air inlet of the relay fan and the air outlet of the previous fan. Polluted air is mixed in this section, causing the CO concentration in the fresh air actually delivered by the relay fan to exceed the standard, resulting in secondary pollution. (3) The self-made duct tees are connected by a reduced pipe diameter transition method, and the local resistance coefficient at the tees is as high as 1.5 to 2.0, resulting in less air supply for the working faces further in, and the air volume distribution among the working faces is seriously uneven; (4) The main tunnel is connected to the middle tunnel through the vehicle cross passage, and some of the cross passages are not separated by air doors, resulting in irregular air flow among the three tunnels and severe mixing of fresh air and polluted air.

3.2 Four-stage Dynamic Ventilation Optimization

In response to the above issues, this paper proposes a four-stage dynamic ventilation optimization method to achieve a precise match between the ventilation system and the construction schedule, in combination with the construction progress and the sequence of shaft penetration.

(1) First stage: Before the shaft is completed (cumulative advance ≤ 3,000 m). In this stage, there are only two tunneling faces at the inlet and outlet ends, and the ventilation distance is relatively short, basically maintaining the original press-in ventilation scheme. Key optimization measures: Set up canvas air curtains on the No. 1 and No. 2 vehicle crossings for temporary closure to prevent the flow of fresh air and polluted air; Adjust the installation position of the fans and add vibration pads between the fans and the brackets to eliminate resonance; One relay axial fan and two jet fans will be added to the service tunnel to prepare for the tunnel ventilation after the middle tunnel is completed.

(2) Phase 2: After the shaft is completed (cumulative advance of 3,000 to 5,000 m). With the opening of shaft No. 1, ventilation conditions are significantly improved. Core optimization measures: Move the large axial flow fan at the inlet end (French ECE, 2×160 kW) forward near the 3# - 4# vehicle cross passage and shorten the air supply distance at the inlet end working face to within 3,500 m; The service tunnel is officially used as a fresh air supply tunnel, and the TBM is equipped with exhaust fans to deliver fresh air from the middle tunnel to each cross-passage opening; Permanent air doors are installed on all connected vehicle crossings No. 3 to No. 4, leaving only two crossings as intake and return air channels; The stale air is discharged through shaft 1, and the “chimney effect” of the shaft increases the exhaust efficiency by about 40 percent compared to the traditional tunnel exhaust method.

(3) Phase 3: Construction away from the shaft (cumulative footage 5,000-7,000 m). As the work progresses towards the middle, gradually move away from the shaft, and the ventilation distance increases again. Take the following measures: Use the left line + service tunnel as the supply air channel and the right line as the drainage channel to form a transverse air flow organization of “left line supply air - work face operation - right line exhaust air”; Move all the jet fans originally placed on the left line to the right line to form a directional diversion air flow within the right line and accelerate the discharge of polluted air; Install reverse deflector fans in the cross passage between the left line and the service tunnel to direct fresh air from the left line to the working face of the right line to make up for the insufficiency of air supply from the right line.

(4) Phase 4: Combined ventilation of double shafts (cumulative footage > 7,000 m). When No. 2 shaft is put into use, a combined ventilation pattern of No. 1 and No. 2 shafts is formed, and the ventilation conditions are significantly improved. Continuous optimization measures: The polluted air in the middle section (between shafts 2# and 3#) can be discharged nearby through shafts 2# and 3# respectively, shortening the discharge distance to within 3,500 meters; Variable frequency speed control devices are added at each shaft opening to adjust the fan speed in real time based on the monitoring data of air quality inside the shaft for on-demand ventilation; Establish a rotation operation system for the shafts, dynamically adjust the exhaust load of each shaft according to the construction progress, and balance the wear of the equipment.

Table 7. Summary of Four-stage Dynamic Ventilation Optimization Measures

Stages	Range of footage /m	Core Measures	Ventilation methods	Shaft utilization
Phase 1	≤ 3,000	Add relay fans + jet fans and close the cross passage	Press-in	Unused
Phase 2	3,000 to 5,000	Move the fan forward, supply air through the middle guide hole, and close the vehicle passage	Press-in + tunnel type	Single shaft exhaust
The third stage	5,000 to 7,000	Lateral airflow organization, directional flow diversion	Mainly roadway type	Single shaft exhaust
Phase 4	> 7,000	Double shafts combined, variable frequency on demand ventilation	Combined	Double shaft combination

3.3 Refined Management Measures

(1) Pipeline management. Air duct hoisting follows the four-word principle of “flat, straight, stable, tight”; Sheet air ducts (30-50 m) are set inside the vehicle passage to facilitate a smooth transition between the main tunnel air ducts and the middle tunnel air ducts and reduce local resistance; Anti-scratch plates are installed on concrete mixer trucks and slag discharge trucks to prevent vehicle collisions from damaging the air ducts.

(2) Air flow isolation management. For vehicle/person access without ventilation ducts, canvas air curtains are used for temporary closure, which are only briefly opened when personnel and equipment pass through and immediately reopened after passing through; Air curtains + jet fans guide the exhaust route of polluted air to avoid air short circuits; The intake and exhaust air volumes are configured at a ratio of 1.0 to 1.2 to ensure a slightly positive pressure state in the main tunnel and prevent the dirty air

from flowing back into the fresh air area through the cross passage.

(3) Equipment operation and maintenance management. The wind turbine operates on a “monthly minor maintenance, quarterly major maintenance” system: minor maintenance includes cleaning the blades, checking the fasteners, and lubricating the bearings; Major maintenance includes disassembling and inspecting impellers, replacing seals, and testing motor insulation. Before the cold season arrives, conduct a thorough inspection of the fan heating system, bearing temperature monitoring device, and motor insulation resistance; Preheat the heating system 30 minutes in advance to ensure that the fan starts normally in a low-temperature environment. Install wind speed, CO concentration and temperature sensors at key sections inside the tunnel, and transmit data in real time to the dispatch center; Set the CO concentration alarm threshold at 24 ppm and the wind speed alarm threshold at 0.15 m/s, and automatically alarm and adjust the fan speed when the limits are exceeded.

(4) Special management measures for extremely cold environments. During winter construction, 50 mm thick polyurethane insulation boards are laid on the outer wall of the tunnel lining within 1,000 m of the tunnel entrance section to reduce the impact of low temperature on the environment inside the tunnel; The concrete mixing plant uses fully enclosed insulated sheds, which are equipped with warm air fans to ensure that the temperature inside the sheds does not fall below 9 ° C in winter; The outer wall of the concrete transport tank truck is wrapped with a cotton blanket insulation layer to shorten the transport time to within 30 minutes and ensure that the temperature of the concrete entering the formwork is not lower than 5 ℃. A prefabricated house is built in the fan room outside the tunnel to preheat the fresh air sent into the tunnel, ensuring that the temperature of the fresh air sent into the tunnel in winter is not lower than 5 ℃, avoiding the impact of low-temperature fresh air on the working environment inside the tunnel. All internal combustion machinery is equipped with diesel particulate filters (DPF) + selective catalytic reduction (SCR) systems, using vehicle urea solution to reduce CO emissions by approximately 25% and NOx emissions by approximately 40%.

4. Conduct an Effect Analysis

4.1 Monitoring of the Air Flow Field Inside the Cave

4.1.1 Monitoring Scheme and Instruments

To verify the implementation effect of the ventilation scheme, systematic monitoring of the air flow field and air quality in the cave was carried out during the construction period [17]. The monitoring instruments included: AZ9871 portable anemometer (range 0 to 30 m/s, accuracy ±0.1 m/s), American Thermo Fisher i series gas analyzer (CO/NOx/SO_2, accuracy ±1%FS), TSI 8530 dust meter (PM2.5/PM10) Accuracy ±0.1 mg/m³), CCHG1000 dust concentration measuring instrument (direct reading).

Monitoring section layout: Section 1 at the opening of the right tunnel, Section 2 at the service tunnel, Section 3 at the connecting passage, Section 4 at the bottom of the shaft, Section 5 at the shaft opening. The monitoring methods include: (1) static monitoring - recording every 3 minutes near the face; (2)

Dynamic monitoring - set up sections every 20 m along the longitudinal direction of the tunnel, and set up measurement points at four heights of the arch top, left and right arch waist, and road surface at each section; (3) Vehicle-mounted continuous testing - the monitoring vehicle travels at a constant speed of 20 km/h and records every 2 seconds; (4) Fixed-point supplementary testing - set up fixed measurement points every 500 m and record 4 times a day (after blasting, during slag discharge, after shotcrete and during normal operation).

4.1.2 Wind Speed Monitoring Results

According to Table 8, the wind speed at each monitoring section met the requirement of ≥0.3 m/s. The maximum wind speed at the wellhead of the shaft reached 10.0 m/s, demonstrating a good "chimney effect"; Service tunnel wind speed 0.5 to 1.0 m/s meets TBM construction environment requirements; The maximum wind speed of the connecting passage is 4.0 m/s, indicating smooth air flow organization.

Table 8. Monitoring Results of Wind Speed at each Section

Monitoring sections	Location	Wind speed /($m \cdot s^{-1}$)	Wind direction	Whether it satisfies ≥0.3 m/s
Section 1	Right hole opening	0.3	Enter the hole	is
Section 2	Service Tunnel	0.5 ~ 1.0	Enter the hole	is
Section 3	Contact passage	Up to 4.0	Bidirectional	is
Section 4	Bottom of the shaft	Larger	Out of the hole	is
Section 5	Shaft wellhead	Maximum 10.0	Out hole	is

4.1.3 Temperature Monitoring Results

The temperature monitoring results inside the tunnel showed that the temperature at each section was stable at 20-21 ° C, meeting the requirements of the Technical Specifications for Highway Tunnel Construction. When the temperature outside the tunnel is -20 ° C in winter, the temperature inside the tunnel remains above 5 ° C, and the cold protection and heat preservation measures are effective. The main reasons for the stable temperature are: (1) Ground temperature heating - the tunnel is buried deep, and the surrounding rock ground temperature has a continuous heating effect on the air inside the tunnel; (2) Heat dissipation from equipment - heat generated by construction machinery and lighting equipment inside the tunnel; (3) Ventilation and insulation - The external fan sets up movable prefabricated houses to supply fresh air at temperatures above 5 ° C, avoiding the impact of low-temperature fresh air on the environment inside the cave.

4.2 Monitoring of Pollutant Concentrations and Migration Patterns

4.2.1 Monitoring Results of Various Pollutant Concentrations

The monitoring results of various pollutant concentrations are shown in Table 9. It is not difficult to see that the peak concentrations of all pollutants occurred in the left tunnel. The main reason is that the ventilation distance in the left tunnel is longer, and before the shaft was connected, it mainly relied on forced ventilation, and the drainage efficiency was relatively low. The right tunnel is connected to the middle tunnel and the shaft. The “chimney effect” has accelerated the discharge of pollutants, and the concentrations of all pollutants are lower than those in the left tunnel. The overall SO_2 concentration was lower (only 0.089 ppm in the right tunnel), indicating that the sulfur content in diesel was well controlled.

Table 9. Monitoring Results of Five Pollutants

Pollutants	Left hole peak	Right hole peak	Control standard	Emergence stage	Main Sources
CO	311.65 ppm	236.36 ppm	≤24 ppm	30 minutes after blasting	Internal combustion engine exhaust, blasting
NOx	17.91 ppm	15.03 ppm	≤5 ppm	Discharge stage	Exhaust gas from internal combustion engines
SO_2	2.46 ppm	0.089 ppm	≤5 ppm	Shotcrete	Diesel contains sulfur
PM2.5	285 μg/m³	220 μg/m³	≤75 μg/m³	Residue removal stage	Blasting, slag removal
PM10	412 μg/m³	350 μg/m³	≤150 μg/m³	Residue removal stage	Blasting, slag removal

4.2.2 Time Variation Pattern of CO Concentration

The variation pattern of CO concentration is closely related to the construction process: within 0 to 5 minutes after blasting, the CO concentration rises rapidly from the baseline value to the peak (average 311.65 ppm in the left hole), because a large amount of CO is produced at the moment of blasting and has not yet been diluted by fresh air; Within 5 to 20 minutes, under the effect of forced ventilation, the CO concentration rapidly decays to below 15 ppm at a rate of approximately 2.0 ppm/min; Within 20 to 60 minutes, the CO concentration gradually tends to a stable baseline value (about 8 to 10 ppm), which is mainly affected by the vortex zone and dead corners inside the cave.

Nonlinear fitting of the decay process of CO concentration after blasting revealed that the change of CO concentration C(t) with time t conformed to the Lorentz function:

$$C(t)=C_0+\frac{2A}{\pi}\times\frac{w}{4(t\text{-}t_c)^2+w^2} \quad \text{Equation (4-1}$$

In the formula: C_0 is the baseline concentration, ppm; A is peak area (concentration-time integral), ppm·min; w is peak width (half-height full width), min; t^c is the peak center position (the moment the concentration reaches its peak), min. Left hole fitting parameters: C_0=8.35 ppm, A= 28,450 ppm·min, w=68 min, t^c=32 min, correlation coefficient R^2=0.95; Right hole fitting parameters: C_0=6.72 ppm, A= 22,180 ppm·min, w=55 min, t^c=28 min, correlation coefficient R^2=0.98. Both the left and right lines fit well, and the fitting results are shown in Table 10.

Table 10. Fitting Results of CO Concentration in Left and Right Tunnels

Fitting parameters	Left hole	Right hole
C_0/ppm	8.35	6.72
A/(ppm·min)	28 450	22 180
w/min	68	55
T^c / min	32	28
R^2	0.95	0.98

Comparing the CO decay curves of Scheme 1 and Scheme 2, Scheme 2 reduced the peak CO concentration by approximately 28% compared to Scheme 1 due to a more reasonable total air supply volume and smoother air flow organization. The time required to decay to a safe concentration was reduced from 35 minutes to 22 minutes, and the ventilation efficiency was improved by 37%.

4.2.3 The Blocking Effect of the Secondary Lining Trolley

An important engineering phenomenon was discovered during the test: the secondary lining trolley (concrete lining trolley) has a significant hindering effect on the spatial migration of pollutants [18]. The secondary lining trolley is located about 50 to 150 m behind the face, with dimensions of approximately 12 m×10 m×8 m (length × width × height), occupying about 70% of the cross-section of the tunnel, leaving only narrow gaps at the arch top and on both sides. The specific comparison of pollutant concentrations at the end of the secondary lining trolley near the face (windward side) and the end far from the face (leeward side) is shown in Table 11.

Table 11. Comparison of Pollutant Concentrations on Both Sides of Secondary Lining Trolley

Pollutants	Concentration on the windward side	Leeward concentration	Multiple differences	Main effects
NOx	12.35 ppm	4.79 ppm	2.58	Retained NOx
SO_2	2.85 ppm	1.41 ppm	2.02	Retained SO_2
CO	**158.20 ppm**	**39.95 ppm**	**3.96**	**Retained CO**

Pollutants	**Concentration on the windward side**	**Leeward concentration**	**Multiple differences**	**Main effects**
PM2.5	285 μg/m³	135 μg/m³	2.11	Trapping dust
PM10	412 μg/m³	233 μg/m³	1.77	Trapping dust

As shown in Table 11, the difference in CO concentration on both sides of the secondary lining trolley is the greatest, reaching 3.96 times, the difference in NOx is 2.58 times, and the difference in PM2.5 is 2.11 times. The mechanism of this phenomenon is as follows: After the secondary lining trolley occupies most of the cross-section, the air flow is forced to pass through the arch top and the narrow gaps on both sides. The reduction of the cross-section leads to an increase in local wind speed, while the vortex area behind the trolley prolongs the residence time of pollutants, and the concentration gradually accumulates. In response to this, the influence of the secondary lining trolley should be fully considered in the subsequent ventilation design for the corresponding tunnel construction, and local ventilation measures should be strengthened by adding jet fans or installing mobile ventilation ducts, etc., to eliminate the retention of pollutants as soon as possible.

4.3 Quantitative Evaluation of the "Chimney Effect" in the Shaft

To quantitatively evaluate the improvement effect of the shaft on ventilation [15], the differences in ventilation effects before and after the opening of shaft No. 1 and between the left line (unconnected shaft) and the right line (connected shaft) were compared.

After the opening of shaft No. 1, the drainage path of this section was shortened from 14,000 m along the main tunnel to 3,500 m through the shaft, and the drainage distance was reduced by 75%. Measured data showed that the average CO concentration in the shaft decreased from 35.6 ppm to 12.3 ppm after the shaft was connected, a reduction of 65.4%; The average dust concentration dropped from 45.2 mg/m³ to 18.6 mg/m³, a reduction of 58.8%.

Comparing the pollutant concentrations on the left line (with the main tunnel's forced ventilation only) and the right line (with the transverse passage connecting the middle tunnel and the shaft) : The CO concentration on the right line decreased by approximately 48.2% compared to the left line, the NOx concentration decreased by approximately 35.6%, and the dust concentration decreased by approximately 42.3%. The discharge efficiency of the right line (connected to the shaft) is approximately 1.93 times that of the left line (not connected to the shaft). The accelerated decline in concentration within the 70 m range of influence of the shaft validates the significant effect of the shaft "chimney effect" on improving ventilation.

The mechanism of the "chimney effect" in the shaft is as follows: The shaft acts as a vertical passage, and the temperature difference between the inside and outside generates a thermal pressure difference (thermal pressure $\Delta P=g\times H\times\Delta\rho$, where g is the acceleration due to gravity, H is the height of the shaft, and $\Delta\rho$ is the difference in air density between the inside and outside), and the thermal pressure difference drives the polluted air to enter through the bottom of the shaft from inside the shaft and exit through the shaft opening. The No. 1 shaft of Tianshan Victory Tunnel is 575 m high. In winter, the temperature inside the shaft is about 5 to 8 ° C, and the temperature outside the shaft opening is about -15 to -20 ° C. The temperature difference is about 25 ° C, resulting in a thermal pressure difference of about 45 Pa, equivalent to the lift pressure of a medium-sized jet fan.

4.4 Economic Benefit Analysis

4.4.1 Benefits of Ventilation Scheme Optimization

The total power calculated at the peak of Scheme 2 was 2,288.84 kW, which was 60.3% lower than that of Scheme 1 at 5,757.21 kW. Based on a construction period of 6 years, an annual effective ventilation time of 6,000 hours, and an electricity price of 0.55 yuan /(kW·h), the total electricity cost savings for the entire construction period are approximately 104.13 million yuan [14].

4.4.2 The Benefits of Moving the Fan Forward into the Tunnel

In the second stage, the fan was moved forward to 3,500 m inside the tunnel, and the actual operating power of the fan was reduced by approximately 35% after the air supply distance was shortened. Based on a two-year operating period after the move forward, electricity costs were saved by approximately 15.17 million yuan.

4.4.3 Summary of Comprehensive Benefits

The summary of comprehensive economic benefits is presented in Table 12. It can be seen that through ventilation scheme comparison optimization, dynamic optimization and refined management, the cumulative cost savings throughout the entire construction period were approximately 128.1 million yuan. In addition, the ventilation scheme optimization reduced the temperature fluctuation range inside the tunnel, improved the curing conditions of the concrete, and increased the quality qualification rate of the lining by about 5%; The reduced wind speed decreased the resistance of the slag-carrying vehicles and indirectly increased the slag-removal efficiency by about 8%.

Table 12. Summary of Economic Benefits of Ventilation Optimization

Optimization program	**Original plan/ten thousand yuan**	**Optimization plan/ten thousand yuan**	**Save/ten thousand yuan**
Ventilation scheme optimization (full cycle electricity bill)	19 880	9 467	10 413
Move the wind turbine forward into the hole (2-year electricity bill)	2 650	1 133	1 517
Fine management (6-year cumulative)	4 880	4 000	880

Optimization program	Original plan/ten thousand yuan	Optimization plan/ten thousand yuan	Save/ten thousand yuan
Combined	**27 410**	**14 600**	**12 810**

4.4.4 Social Benefits

(1) The working environment has improved significantly. The average daily concentration of CO in the tunnel decreased by 65.4% and the average daily concentration of dust decreased by 58.8%, effectively safeguarding the occupational health of construction workers. (2) Construction efficiency is enhanced. The waiting time after blasting was reduced from 45 minutes to 25 minutes, one more cycle of operation was added per day, and the monthly footage was increased by about 15%. (3) Energy savings and carbon reduction contributions. Based on the savings of 18,933 MW·h of electricity and 0.335 kg/(kW·h) of standard coal consumption for thermal power, approximately 6,343 tons of standard coal were saved throughout the construction period, and about 16,700 tons of CO_2 emissions were reduced, which is in line with the current “dual carbon” strategic goals.

5. Conclusions

(1) In view of the construction organization characteristics of the “three tunnels and four shafts” of the Tianshan Victory Tunnel and the extreme environmental conditions of low air pressure and high cold, a ventilation scheme comparison method based on the 16-stage construction schedule was established. The air demand calculation results show that the air demand for the main tunnel drilling and blasting method, the middle pilot tunnel TBM method, and the shaft drilling and blasting method is 1,980 m^3/min, 1,500 m^3/min respectively. The main tunnel is controlled by blasting smoke exhaust, and the middle pilot tunnel and the shaft are controlled by minimum wind speed.

(2) An optimized ventilation scheme based on alternating process construction was proposed (Scheme Two). By rationally arranging the low-air consumption processes of the auxiliary face, the total power calculated at peak hours was reduced by 60.3% compared with the simultaneous construction mode of the entire face (Scheme 1), the power reduction rate at each stage was 45% to 75%, the life cycle cost was reduced by 39.5%, and the payback period was only 1.2 years.

(3) A four-stage dynamic ventilation optimization method and a refined management system were proposed. After the shaft was connected, the “chimney effect” was utilized to accelerate smoke exhaust, and the discharge efficiency was increased by approximately 93%, with the discharge efficiency of the right line being 1.93 times that of the left line.

(4) The air flow field system monitoring in the tunnel verified the implementation effect of the scheme: the wind speed at each section met the requirement of ≥ 0.3 m/s, the average daily concentration of CO was 12.3 ppm, the average daily concentration of dust was less than 10 mg/m^3, and the air quality in the tunnel met the requirements of the Technical Specifications for Highway Tunnel construction. It was

revealed that the time variation of CO concentration was in accordance with the Lorentz function law ($R^2=0.95$ for the left tunnel and $R^2=0.98$ for the right tunnel), and a significant blocking effect of the secondary lining trolley on pollutant transport was found (CO concentration difference reached 3.96 times). The total cost savings over the entire construction period amounted to approximately 128.1 million yuan, and CO_2 emissions were reduced by approximately 16,700 tons, with significant overall benefits.

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