Technologies on Safe Construction Ventilation of Long-large Shield Tunnel with Low Gas in Metro

Wei Zhao¹, Qingming Meng², Qi Liu¹, Mengheng Zhang³ and Wei LI⁴,*

¹ Sinohydro Bureau 5Co., LTD., Sichuan, China
² Power China Railway Construction Co., Ltd, Beijing, China
³ Shanghai No.1 Metro Operation Co., Ltd, Shanghai, China
⁴ Shanghai Institute of Technology, Shanghai, China.

*Corresponding author e-mail: weiliyy@usst.edu.cn

Abstract. Taking the project of long-large shield tunnel with low gas in Xingtian section of Chengdu Metro Line 18 as an example, A new construction ventilation method is established, which includes: the main tunnel ventilation with axial fans installed at the entrance of the tunnel and the local ventilation with jet fans installed in the shield and at the upper part of the bridge and the top of the 4# trailer for the rear supporting system; the connecting passage ventilation with a jet fan installed on the wall; the crossing ventilation with a jet fan installed in the middle of tunnel. The ventilation technology for safe construction of Metro long-large shield tunnel with low gas is established after detailed calculation of the fan selection, which is applied to finish safely and quickly construction task, and which provides reference for similar projects in the future.

1. Introduction

There are disasters such as explosions, poisoning and even suffocation caused by gas in the construction of tunnels, so the safety risk level of gas tunnel construction is very high, and there have been many major gas accidents at home and abroad. Chinese gas accidents mainly occur in the coal mine industry. Wang Jianguo and others conducted cross-coupling statistical analysis from multiple angles such as the grade, type, occurrence time and geographical distribution of large and higher gas accidents in coal mines in China, and concluded that large and above gas accidents occurred in coal mines in China from 2012 to 2016 [1].

With the construction of railways and highway networks, there are more and more tunnels crossing the coal seam, and gas disaster accidents in tunnel construction are also increasing, which seriously restricts the construction and development of my country's transportation infrastructure. Therefore, there is an urgent need to study effective tunnel gas disaster prevention and mitigation technologies. Zhao Tieshan took the Lanzhou-Chongqing railway super-high gas Meilingguan tunnel as an example, conducted a detailed analysis of the construction ventilation technology experience, and proposed that a good ventilation system is the key to ensure the smooth progress of the tunnel construction [2]. Especially in high-gas tunnels, ventilation is the main method to dilute and discharge gas, and is a key process to prevent gas accidents and protect the physical and mental health of construction workers. Qin Renpei carried out calculation of ventilation wind speed and air volume and ventilation arrangement...
based on the measurement of gas and hydrogen sulfide content in Tanjiazhai Tunnel of Zhongdian Expressway, proving that ventilation is an effective way for the construction of gas tunnels [3].

With the construction of subways in China, the geological and environmental conditions encountered are becoming more and more complicated. For example, the section of Suzhou Line 3 from Heshan Road Station to Suzhou Leyuan Station passes through a 108m-long upper and lower soft composite stratum, resulting in difficult to control the line shape and tool wear [4]. At present, the construction impact of subway tunnels with small spacings passing through large urban underground structures is particularly prominent [5], and the study of safety construction control technology is significance [6].

In recent years, there have been more and more urban rail transit gas tunnels. For example, the shield tunnel between Hankou Station and Fanhu Station of Wuhan Rail Transit Line 2 Phase 1 Project passes through low gas strata [7]. In order to avoid the occurrence of gas accidents in tunnel construction, it is necessary to strengthen the safety construction and ventilation work. However, at present, most people only realize that high-gas tunnels need to be strengthened for safe construction and ventilation, and they just ignore the danger of low-gas tunnels, which has caused major construction accidents. For example, at 11:30 pm on February 1, 1993, a gas explosion occurred at the site of the Tokyo Metropolitan Water Authority’s water pipeline shield project, killing 4 people and injuring 1 person [8]. The main cause of the accident after investigation was the problem of shield tail sealing and insufficient ventilation. It was speculated that at 23:30, an explosion occurred due to electrical sparks near the palm face contacting the gas that reached the explosion limit.

At present, the current status of ventilation management of low-gas tunnel construction in my country is insufficient construction safety awareness, relatively backward ventilation management technology; unreasonable ventilation system design, ventilation equipment and facilities need to be further improved; gas detection work is not in place, and the management and supervision of the gas tunnel is insufficient [9].

The section between Xinglong Station and Tianfu New Station of the 4th civil construction of Chengdu Metro Line 18 is a low-gas shield tunnel with a length of 507.484m and tunnel diameter is 8.3m. The design speed is 140km/h. This section is the first low gas length in the southwest area Large shield tunnel. Long tunnels increase the surface area of gas spills, increase the probability of gas outburst and the volume of gas, resulting in increased construction safety risks and increased difficulty in ventilation technology. Therefore, it is of great significance to study and solve the technical problems of safe construction and ventilation of metro tunnels with long gas shields.

2. Overview of the project

The shield section of Xinglong Station ~ Tianfu New Station (Xing~Tian Section) of the 4th civil construction of Chengdu Metro Line 18 is located east of Longquan Mountains, northeast of Hejiang Town Township, west of Taihe Road, and the mileage of the section is YCK34+030.585 ~YCK39+105.469, with a total length of 507.484m. As shown in Figure 1, after leaving the Xinglong Station, the line is laid from the west to the east along the planned road, and the line successively passes through the south extension line of Hongxing Road, Luxi River Bridge, and Chengzilu Expressway. The current status on both sides of the section is mainly farmland and woodland, the terrain is undulating, with a maximum height difference of 40m. Because the interval is too long, the middle air shaft is set at YDK35+860.709 and doubles as the shield starting shaft. The shield-crossing strata in the Xing~tian interval are dominated by mudstone and sandstone, and they are divided into low-gas shield intervals according to the results of geological surveys within the influence range of the Luodai gas field and the Sugang gas field.
A total of four composite earth pressure balance shield machines were used for tunnel construction in Xing-Tian interval: two from Xinglong Station and Xing-Tian interval wind shaft receiving; two from Xing-Tian interval air shaft, Tianfuxin Station reception. From the middle wind well to the Tianfu New Station shield section, the right line has a starting distance of YDK35+860.709 and an ending distance of YDK38+575. It is the longest shield tunneling length of 2714.291m. One shield machine was put into tunneling construction. Xing-Tian section is constructed with ZTE8600 earth pressure balance shield machine developed by China Railway Construction Heavy Industry Group Co., Ltd. The cutter head diameter is 8.65m, the main machine does not include the screw machine length is 10.5m, including the screw machine length is about 16.5m, shield The total length of the machine and its supporting equipment is 114m.

The minimum longitudinal slope of Xing-tian tunnel is 2‰, and the maximum longitudinal slope is 24.115‰. The maximum buried depth of the tunnel is about 45.2m, the smallest buried depth is about 4.2m, and the smallest plane curve radius is 1200m. The structural size of the starting shaft of the middle air shaft is 25m long and 28m wide. The inner diameter of the section tunnel is 7500mm, the thickness of the segment is 400mm, and the width of the segment is 1500/1800mm.

3. Construction of safe construction ventilation method

3.1. Principles of ventilation
The principles of safe construction and ventilation are as follows:
(1) Follow the coal mine ventilation requirements, the current relevant regulations and specifications of railway tunnels, and refer to the current relevant regulations and specifications of highway tunnels;
(2) The designed tunnel construction ventilation system is safe, stable, reliable, and economic. The air volume of each wind site should be reasonable, and the air volume, wind speed, gas and other toxic and harmful gas concentrations should meet the requirements;
(3) Adopt multi-level speed-adjusting axial flow fan, and select larger diameter ventilation ducts;
(4) The types and specifications of the ventilation equipment on each working surface of the same work area should not be too much or too complicated, and the number of jet fans should not be too much. Explosion-proof fans and local fans should be explosion-proof;
(5) The tunnel construction ventilation design should be comprehensively considered according to the tunnel length, construction method, and construction equipment support;
(6) Adhere to the design principle of "people-oriented, improve the environment, ensure safety, save energy, save investment".

3.2. Standard of ventilation
According to the ‘Code for Construction of Railway Tunnels’ (TB10204-2002), the ventilation standards for safe construction are as follows:
(1) Oxygen content in air: not less than 20% by volume;
(2) The maximum allowable concentration of harmful gases: the maximum allowable concentration of carbon monoxide is 30mg/m³;
(3) The temperature in the tunnel should not exceed 28°C;
(4) Carbon dioxide should not exceed 0.5% by volume;
(5) The noise in the tunnel should not be greater than 90dB;
(6) Tunnel construction ventilation should be able to provide the minimum air volume required for various operations in the tunnel, and each person should be supplied with fresh air of 4m³/min.

3.3. Construction of ventilation
(1) Safe construction and ventilation of the main tunnel

The ventilation mode of the main tunnel adopts a combination of main ventilation and local ventilation. Axial fans are used to push in fresh air at the tunnel entrance, as shown in Figure 2. The shield equipment structure accounts for 30% of the effective cross-section of the tunnel. In order to meet the return air velocity in the tunnel $\leq 0.5$ m/s, a local fan should be added. The ventilation of the local fan should not exceed 0.3 times the tunnel pressure. The air supply duct of the tunnel adopts zipper polyethylene ventilation pipe, the diameter of the duct is $\varnothing 1800$ mm, and the duct is antistatic and anti-flame retardant.

Local ventilation setting: add a 2.2kW jet fan on the left and right sides of the upper platform of the shield body, the air volume is 3.2m³/s, aim at the area where the gas is easily collected on the upper part of the shield body, and accelerate the air convection in the shield body; on the upper part of the connecting bridge Add a 15kW jet fan, the outlet speed of the fan is 39m/s, and the effective distance is about 91.26m. The fan blows toward the tail of the shield trailer to prevent gas from forming a gas belt at the top of the tunnel; add one on the top of the 4# trailer 15kW jet fan, the outlet speed of the fan is 39m/s, the effective distance is about 91.26m, the fan blows in the direction of the tail of the shield trailer, to prevent the formation of gas belt at the top of the tunnel.

![Figure 2. Ventilation arrangement/mm](image)

(2) Ventilation of communication channels

Under the tunnel construction environment, the ventilation channel is worse than the main channel, so gas accumulation is more likely to occur. A 15kW jet fan is set 20m before the opening of the communication channel in the tunnel. The fan is fixed on the side wall of the tunnel, and the air is sent from the air duct of the jet fan to the palm surface of the communication channel to ensure the normal ventilation of the communication channel.
(3) Ventilation through the tunnel
The permeability of gas is 1.6 times that of air, so there is still a certain risk of gas penetration through the tunnel. At the same time, after the use of the through tunnel, if there is gas accumulation, there will be operational risks. A 22kW jet fan is installed in the middle of the through tunnel to ensure smooth air flow in the tunnel, and the wind speed is not less than 0.5 m/s. According to the actual wind speed measured on site, if it is less than 0.5 m/s, add a jet fan.

4. Selection of safe construction fan

4.1. Calculation parameters
The boundary conditions and related parameters required for the calculation of air volume and wind resistance are: tunnel cross-sectional area of 44.2 m²; the maximum number of people working in the cave is 40, and each person needs fresh air of 4 m³/min; the air volume of two welding machines is 50 m³/min; the minimum return air speed is 0.5 m/s, the average air leakage rate of the duct is 0.5% per 100 meters, and the duct resistance coefficient is 0.0125; the absolute gas emission is calculated according to the maximum emission of the low gas tunnel of 0.5 m³/min.

4.2. Calculation of ventilation air volume
(1) Calculate the air volume according to the minimum allowable return wind speed in the tunnel
\[ Q_1 = VS = 1326 \text{ m}^3/\text{min} \]
In the formula: \( V \)—taking 30 m/min, namely 0.5 m/s; \( S \)—44.2 m²;

(2) Calculate the air volume according to the breathing and electric welding in the tunnel:
\[ Q_2 = (qN + q_dN_d)\gamma_1 = (4 \times 40 + 50 \times 2) \times 1.2 = 312 \text{ m}^3/\text{min} \]
In the formula: \( q \)—the amount of fresh air required by each person in the cave, taking 4 m³/min; \( N \)—the maximum number of people working in the tunnel at the same time, taking 40 people; \( q_d \)—the amount of fresh air required by each welding machine in the hole, take 50 m³/min; \( N_d \)—aerobic equipment (the number of welding machines used in the tunnel at the same time, take 2); \( \gamma_1 \)—safety factor, take 1.2.

(3) Calculate the air volume by eliminating the accumulation of gas in the top layer
\[ Q_3 = V_w \times S = 60 \times (3.14 \times 7.5^2/4) = 2649.38 \text{ m}^3/\text{min} \]
In the formula: \( V_w \)—The minimum wind speed required to eliminate the top gas in the tunnel is 1 m/s; \( S \)—The cross-sectional area of the tunnel is 44.2 m².

(4) Calculate the air volume according to the tunnel gas concentration not exceeding the limit
\[ Q_4 = G_w/C = 0.5/0.005 = 100 \text{ m}^3/\text{min} \]
In the formula: \( G_w \)—The highest gas emission rate of low gas in the tunnel is 0.5 m³/min; \( C \)—the highest gas concentration after dilution is 0.5%.

The minimum air volume at the ventilation outlet takes the maximum value above, and the minimum value of the air volume at the outlet of the primary ventilation is \( Q_{min} = 2649.38 \text{ m}^3/\text{min} = 44.12 \text{ m}^3/\text{s} \).

4.3. Calculation of air volume and pressure required by the fan
(1) Ventilation volume
According to the average air leakage rate of the air duct being 0.5%, the air volume at the primary fan:
\[ Q_1 = Q_{min}/[(1 - \beta)\gamma(L/100)] \gamma_2 = 2649.38 \times 1.1/[ (1 - 0.005) \gamma 27.143] = 3339.06 \text{ m}^3/\text{min} = 55.65 \text{ m}^3/\text{s} \]
In the formula: \( \beta \)—the air leakage rate of the tunnel duct at 100 meters, 0.5%; \( L \)—the length of the tunnel, 2712.291 m; \( \gamma_2 \)—the safety factor of the air volume required by the fan 1.1.

(2) Wind pipe resistance and wind pressure loss
\[ P_d = \lambda \times L/d \times \rho \times V_p^2/2 = 0.0125 \times 2714.291/1.8 \times 1.293 \times 21.87^2/2 = 5828.54 \text{ Pa} \]
In the formula: \( \lambda \)—the friction coefficient of the duct resistance, taken as 0.0125; \( d \)—the diameter of the duct, 1.8m; \( \rho \)—the density of the air, taken as 1.293kg/m³; \( V_p \)—the average wind speed of the duct, \( V_p = Q_1/(60 \times \pi \times d^2/4) = 3.339.06/(60 \times 3.1416 \times 1.8^2/4) = 21.87 \text{ m/s} \).

(3) Loss of tunnel resistance wind pressure

\[
P_D = \lambda_T \times L/d \times \rho \times V_t^2/2 = 0.025 \times 2714.291/7.5 \times 1.293 \times 1.26^2/2 = 9.286 \text{ Pa}
\]

In the formula: \( D \)—the inner diameter of the tunnel, 7.5m; \( V_t \)—the average wind speed of the tunnel, \( V_t = 55.65/(3.14 \times 7.5^2/4) = 1.26 \text{ m/s} \); \( \lambda_T \)—the resistance coefficient of the tunnel.

Reynolds coefficient of the fluid in the tunnel: \( Re = \rho V_t D/\mu = 1.293 \times 1.26 \times 7.5/1.79 \times 10^{-5} = 6.826 \times 10^{-5} \). \( \mu \) is the aerodynamic viscosity coefficient, taking 1.79\( \times 10^{-5} \text{ Pa}\cdot\text{s} \).

The relative roughness of the inner wall of the tunnel is \( \delta \varepsilon = \varepsilon/d = 20\text{mm}/7500\text{mm} = 2.66 \times 10^{-3} \). \( \varepsilon \) is the relative roughness of the ventilation pipe, and the relative roughness of the zippered polyethylene ventilation pipe is 20mm.

Check the graph (the relationship between the drag coefficient and the Reynolds coefficient and relative roughness) to find the tunnel drag coefficient \( \lambda_T = 0.025 \).

(4) Wind resistance loss of local resistance of air duct

\[
P_R = \sum \xi \times \rho \times V_p^2/2 = (0.09 + 0.75 + 0.09) \times 1.293 \times 21.87^2/2 = 287.57 \text{ Pa}
\]

\( \xi_1 \)—The coefficient of resistance of the variable diameter of the air pipe, the outlet becomes larger (the end of the fan), taking 0.09; \( \xi_2 \)—The resistance coefficient of the variable diameter of the air pipe, the resistance coefficient of the 90° standard elbow, taking 0.75; \( \xi_3 \)—The coefficient of resistance of the variable diameter of the air pipe, the outlet becomes larger (the end of the wind belt), taking 0.09.

(5) Air pressure required by the fan

\[
P = \gamma (P_d + P_D + P_R) = 1.1 \times (5828.54 + 9.286 + 287.57) = 6 \text{737.93 Pa}
\]

In the formula: \( \gamma \)—safety factor 1.1

4.4. Selection of safe construction fan

The selection of the fan model mainly considers three conditions: the air volume generated by the fan cannot be less than the theoretically calculated air volume; the diameter of the fan and the diameter of the selected ventilation pipe cannot be too different; the total pressure of the fan \( \preceq \) the total resistance of the pipe.

According to the calculation of the maximum air volume of 3 339.06 m³/min and the maximum air pressure of 6 737.93 Pa, the axial fan SDF (B)-№14 is selected to meet the ventilation requirements. The technical parameters are listed in Table 1. Two fans are configured in one section, that is, one should be used for one spare. Adopt flame retardant polyethylene ventilation pipe, its diameter is 1.8m, and the maximum length is 2714.291m. The photo of on-site fan layout is shown in Figure 3.

**Table 1. Technical parameters of main Fan**

| Model     | Technical Parameters | Rotating speed (r/min) | Wind pressure (Pa) | Air volume (m³/min) | Efficient air volume (m³/min) | Configuration power (kW) | Highest point power (kW) |
|-----------|----------------------|------------------------|--------------------|---------------------|-------------------------------|--------------------------|--------------------------|
| SDF (B) - №14 |                       | 1480                   | 1078–6860          | 2113–4116           | 3361                          | 160\times2               | 360                      |
Since this project is a low-gas tunnel, in order to ensure that the axial flow fan can operate normally to ventilate in the power grid during the power outage, a 300kw internal combustion generator set is installed in the power distribution room on the left and right of the tunnel to supply the ventilator. Install a reverse knife gate at the output of the distribution panel to ensure that it is isolated from the local power grid when the internal combustion generator is used to prevent accidents. After the internal combustion generator set is installed and tested, the professional electrician of the project department will check whether it is a qualified backup power supply and confirm that it is a qualified backup power supply before it can be used. At the same time, check the standby generator every week, and start once a week to ensure the normal use of the generator equipment.

5. Conclusion
A new construction ventilation method is established, which includes: the main tunnel ventilation with axial fans installed at the entrance of the tunnel and the local ventilation with jet fans installed in the shield and at the upper part of the bridge and the top of the 4# trailer for the rear supporting system; the connecting passage ventilation with a jet fan installed on the wall; the crossing ventilation with a jet fan installed in the middle of tunnel. The tunnel construction ventilation air volume calculation was carried out according to the minimum allowable return air speed in the tunnel, breathing and welding, eliminating the accumulation of gas in the top layer and the gas concentration not exceeding the limit. On the basis of detailed calculation of the fan demand and wind pressure, the metro shielded the tunnel with low gas. The main tunnel safe construction and ventilation selected the model of the fan, and established the "Ventilation Technology for Safe Construction of Metro Low Gas Long Shield Tunnel". This technology successfully solved the technical problems of safe construction and ventilation of low-
gas shield tunnels on Xing–tian section of Chengdu Metro Line 18, and completed the construction tasks safely and quickly. The left line planned to complete the tunnel in 55 days in advance, and the right line planned a total of 67 in advance. The completion of the tunnel through the sky greatly improves the efficacy and creates good social and economic benefits, which can provide a reference for similar projects in the future.

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