Effect of Construction Ventilation Scheme on Pollutant Transport in a High-Speed Railway Tunnel

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Abstract. To find out the distribution of dust and harmful gases and check the effect of ventilation and dust prevention after blasting in tunnel construction with the drilling and blasting method, the wind velocity, dust concentration and the concentration of harmful gas in You-zhu-shan tunnel of Gui-Guang high-speed railway were studied by CFD simulation and field test. The ventilation scheme optimization was carried out and the optimum scheme of main tunnel as air intake while parallel heading as air outlet is put forward. The results showed that the concentration of CO in the tunnel working area is reduced to 24ppm after ventilation 24minutes. Dust concentration maximum lies in the working tunneling side which involves no direct air flow from air duct. And it will be reduced by the continuous dust discharging, trapping and settling along the tunnel due to turbulent diffusion and entrainment of jets. The dust concentration is of a large variation range between trolley and the tunnel portal. It is in high number in tunnel face due to the influence of trolley through the accumulation of the dust around, which will result in a poor working environment.

1. Introduction

The construction ventilation which is of great importance under the environment of drilling blasting method and trackless transportation has become the bottleneck in rapid tunnel construction [1]. Specifically, the ventilation and air purification are becoming more and more prominent in long tunnel construction. Against the background of highly mechanized construction level, long distance tunnel ventilation is of great impact on not only the tunnel construction period, but also the line survey, route selection, engineering design, construction segmentation, scheme determination, machinery and equipment selection, project progress and investment [2]. Due to the differences of tunnel length, nowadays, the application of duct ventilation, gallery ventilation and the combination of both are much more common than that of dust removal technology [3]. Lots of research regarding tunnel construction ventilation has been done across the world. Ferro V et al. [4] has introduced some relevant method in Cesena Municipal tunnel application, longitudinal ventilation, shaft ventilation, electrostatic cleaning system. Research involving the model of gas dilution after blasting and the condition in which workers can return to the blasted area has been developed based on CFD [5]. Some semi-empirical equations have been proposed to calculate the effective length of the airflow impacting by means of CFD [6, 7]. Hargreaves and Lowndes [8] constructed a series of steady-state models to replicate the ventilation flow patterns at the head end of a drivage. Considering the influence of time, dust behavior in auxiliary ventilation systems has been studied [9]. Zhang et al. [10] studied the pollutant diffusion of underground cavern group. Klemens et al. [11] established a two-dimensional laminar model to simulate the dust deposition in a rectangular coal mine roadway with upper obstacles.
Zhang et al. [12] employed a three-dimensional transient two-phase Eulerian model to simulate velocity fields and dust diffusion of the heading face in a diversion tunnel.

2. Project background
Gui-Guang high-speed railway, the first one-stage-completion high speed railway in karst mountain areas with high standard and long line in China, is occupied with Design speed and reserved one separately 250km/h and 300km/h. As part of the Gui-guang railway, You-zhu-shan Tunnel, overall length 9896m and maximum buried depth around 720m, is the controlling project crossing Qiannan mountainous area where steep terrain bears. It was designed as the double track tunnel with the clearance section area being 92m², the construction length of tunnel exit 5296m. Located 30m away from the left side of the tunnel, the exit parallel heading is 2250m with space size being 4.7m×6m (length×width). Three stages are arranged in construction ventilation in accordance with the main tunnel length of You-zhu-shan tunnel.

Stage 1: When main tunnel length is less than 1000m: forced axial fans should be adopted separately for ventilation. Ventilation arrangement is depicted in Figure 1.

Stage 2: When main tunnel length is between 1000m and 2500m: parallel heading construction is priority. Specifically, the combination of forced axial fans and gallery ventilation should be applied to guarantee the air quality first in parallel heading where both personnel and machinery are gathered. Ventilation arrangement is depicted in Figure 2.

Stage 3: when the length of parallel heading is 2250m (no more construction needed): using parallel heading as air inlet, the main tunnel ventilation is worked by the forced ventilation of 2×110kW axial flow fan, which needs to be located at the junction of the parallel heading and the main tunnel with 1.5m diameter PVC zipper duct. 75kW jet fan is installed every 500m in the main tunnel to discharged the polluted air. Ventilation arrangement is depicted in Figure 3.

3. Numerical simulation
3.1. Ventilation scheme optimization
In stage 3, the construction of parallel heading face is finished. The personnel with the machinery mainly are concentrated in the main tunnel, where the polluted air lies in a long time in accordance with the scheme regarding main tunnel as air outlet (see Figure 3). Hence the main tunnel is regarded as the fresh air entrance and the parallel heading as the outlet passage. (parallel heading is worked as
the ventilation drainage rather than the transport passage in stage 3). A 135kW×2 axial fan with 1.5m-diameter duct to be installed at the main tunnel, and two 75kW jet fans respectively in the small mileage of 4#、5# parallel heading. Meanwhile, 1#～4# cross passage should be closed. See optimized ventilation arrangement in Figure 4.

For optimizing design, a comparative simulation analysis has been made regarding on the two ventilation schemes (main tunnel air intake and outlet) of stage 3. The commercial computational fluid dynamics (CFD) software ANSYS FLUENT was employed to solve numerical models. The three-dimensional unsteady component transport model was used to solve the governing equations and the standard two-equation k-ε turbulence model. Numerical simulation parameters are shown in Table 1.

Table 1. Numerical simulation parameters

| Area   | Perimeter | Explosive quantity | Casting distance | CO production | Initial concentration |
|--------|-----------|--------------------|------------------|---------------|-----------------------|
| 99.27 m² | 37.27m    | 250kg              | 65m              | 9.6 m³        | 1551ppm               |

3.2. Air intake scheme of main tunnel

Figure 5 is a change curve of CO concentration for different time in the central line of You-zhu-shan tunnel. It shows that CO is advancing to the tunnel exit as time goes by, and the tunnel dangerous zone (CO high concentration area) varies in different time. In the light of this, the numerical calculation results should be considered to avoid personnel damage caused by the dangerous zone entrance in construction. Figure 5 shows that CO can be exhausted through parallel heading after 20-min ventilation. And basically, the main tunnel is in a relative safe area, where the personnel are allowed to construct accordingly.

![Figure 5. Change curve of CO concentration for different time in the central line](image)

3.3. Air outlet scheme of main tunnel

Figure 6 is a change curve of CO concentration for different time in the scheme regarding main tunnel air intake of You-zhu-shan tunnel. It shows that CO is advancing to the tunnel exit as time goes by, and the tunnel dangerous zone (CO high concentration area) varies in different time. In the light of this,
the numerical calculation results should be considered to avoid personnel damage caused by the danger zone entrance in construction. CO is kept in the main tunnel in the process of ventilation, which is disadvantaged for the safety of personnel carrying on the subsequent construction (eg: the second lining; drainage ditch; cable duct).

Figure 6. Change curve of CO concentration for different time in the scheme regarding main tunnel air intake

It is concluded that the scheme of air outlet in the main tunnel is inferior than intake do through contrastive analysis, which can be shown in the following aspects: ① It's harder for the jet fan to form air flow into the same direction due to the large section of main tunnel. ② Working personnel will be interfered by the noises of jet fan and the polluted air going through the main tunnel. ③ The numerous subsequent constructions would be influenced by the operation of several jet fans installed in the main tunnel. The scheme of air intake in the main tunnel is carried out on site based on the calculation results. And Figure 7 is a partial jet fan arrangement on site regarding main tunnel as an air intake, and Figure 8 shows the exhausting condition of parallel heading.

Figure 7. 75KW Jet fan in cross passage

Figure 8. Polluted air in parallel heading exit
3.4. Dust diffusion law
An analysis concerning dust diffusion rule in tunnel face has been made based on 3D numerical simulation, whose model is presented in Figure 9. Figure 10 shows the air flow velocity under the condition of forced ventilation. Accordingly, the air flow velocity, going through tunnel by forced ventilation, will reach its maximum in air outlet area, then form into cyclone after tunnel face spray and go roundabout to the tunnel exit. And it will get slower in closer area of the tunnel portal. Track and retention time of dust in tunnel under forced ventilation is shown in Figure 11. It can be concluded that the tunnel air flow formed by forced ventilator comes into cyclone after tunnel face spray, which will result in the dust spiral around the air outlet area as the dust is mainly gathered on the working surface of the lower right side.

Dust diffusion regularities are concluded from the simulation results: ① Dust concentration maximum lies in the working face side which involves no direct air flow from air duct; whereas the relatively minimum is formed on the side which bears the direct air flow. ② The turbulent diffusion and entrainment of the working surface after the air flow formed by the spray of air duct will make the dust continuously discharged, trapped and settled along the tunnel. And therefore, the dust concentration here decreases gradually. By contrast, the section far away from the air duct, which involves in relatively large dust concentration, together with working surface, has formed the largest dust concentration area in tunnel. ③ Dust concentration, which appears in a clear "cluster" shape due to the unbalanced and discontinuous spatial distribution, will decrease along the tunnel exit.

4. Field test of pollutant
Field test concerning the concentration of the harmful gas as CO, SO$^2$, H$_2$S in tunnel is made with LD-3C and PortaSens II Gas-Leak Detector. And the testing points include tunnel face, secondary trolley area, ventilator intake, tunnel portal and cross passage. See all the 13 testing points in Figure 12 and tests results in Figure 13~Figure 16.
The results show: ① The dust concentration is of a large variation range between trolley and the tunnel portal. It is in high number in tunnel face due to the influence of trolley through the accumulation of the dust around, which will result in a poor working environment; ② Little difference of dust concentration between the junction of main tunnel and parallel heading and parallel heading exit makes the dust removal effect is better in parallel heading. ③ Dust removal equipment is recommend to be installed in measuring points 7, where large dust concentration has accumulated due to the serious dust flow impediment by trolley II. ④ The efficiency of dust removal in gallery ventilation is much higher than forced ventilation in accordance with the comparison of the two periods before and after.

5. Conclusions
After 20-min optimized scheme of air intake in main tunnel, the concentration of CO in the tunnel working area is reduced to the statics which is below the safe concentration (24ppm); Dust concentration maximum lies in the working tunneling side which involves no direct air flow from air duct. And it will be reduced by the continuous dust discharging, trapping and settling along the tunnel due to turbulent diffusion and entrainment of jets.
The dust concentration is of a large variation range between trolley and the tunnel portal. It is in high number in tunnel face due to the influence of trolley through the accumulation of the dust around, which will result in a poor working environment; Little difference of dust concentration between the junction of main tunnel and parallel heading and parallel heading exit makes the dust removal effect is better in parallel heading.
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