Ventilation System in Tunnel during Construction Works

Yoshihiro Takano, Chiyoda Engineering Consultants, Co., Ltd, Tokyo, Japan

Preface

Construction works always involve danger and their environment is not always clean. In case of tunnelling works, especially in tunnels to be constructed with the drill and blast method, the problems on the safety and health such as the ones by dust and poison gas are serious subjects. This paper discusses the principle of ventilation system in tunnel during construction to provide good environment for tunneling works.

1. Safe and health in tunnelling works

In tunnelling works comprising drilling, blasting, excavation, shotcreting and mucking, appropriate measures are absolutely necessary to secure safe and healthy working environment. The ventilation system is the most effective method to settle the problem on the dust, smoke and gas in tunnel. In Japan, in accordance with the Labor Standard Law and other related regulations, this system is introduced to secure the safety and health of labors in tunnel.

2. Standard on ventilation in tunnel

The followings aggravate the working environment in tunnel.

1) Dust and gas caused by drilling, blasting, loading of excavated materials and shotcreting
2) Exhaust gas and smoke discharged by diesel
3) Poison gas made from explosive or organic solvent
4) Poison gas, flammable gas or oxygen shortage gas in ground
5) High temperature and high humidity

Where, carbon monoxide, nitrogen oxide, hydrogen sulfide and sulfurous acid gas belong to poison gas.

Carbon monoxide, hydrogen sulfide, methane belong to flammable gas.

Carbon dioxide causes anoxia, if it makes the density of oxygen becomes less than 18%.

Tables 2.1 and 2.2 show dust density caused by each tunnelling work and, volume of poison gas generated by explosive or diesel.

Table 2.1 Dust density caused by tunnelling works

Works	Density of dust (mg/m^3)
Excavation	10 - 1000
Loading of excavated materials	10 - 1000
Mucking (Transportation)	10 - 100
Drilling	1- 50
Blasting	100 - 300
Shotcreting	10 - 200

Table 2.2 Volume of generated poison gas

Explosive/ Diesel	Classification	Poison gas	Volume(m^3/kg) for CO (m^3/(min/piece) for NOx
Explosive	Enoki-dynamite No.2	Carbon monoxide	8×10^{-3}
	Other dynamite	Carbon monoxide	11×10^{-3}
	Slurry type	Carbon monoxide	2×10^{-3}
	Emulsion type	Carbon monoxide	5×10^{-3}
	ANFO	Carbon monoxide	30×10^{-3}
Diesel	Shovel	Nitrogen oxide	55×10^{-6}
	Dump truck	Nitrogen oxide	20×10^{-6}
	Others	Nitrogen oxide	20×10^{-6}

Quoted from Standard Specification for Tunnelling (Mountainous Tunnels) issued by Japan Society of Civil Engineers

Tables 2.3, 2.4 and 2.5 show the allowable densities of dust, poison gas and the relation between the density of gas and human health.

Table 2.3 Allowable density of dust

Category	Kinds of dust	Allowable density (mg/m^3)	
		Absorbent dust	Total dust
I	Tale, Soapstone, Kieselguhr, Aluminum, Bentnite, etc	0.5	2
II	Mineral dust, Iron oxide, Coal, Portland cement, Limestone, etc	1	4
III	Other organic or inorganic dust	2	8
Asbestos	Actinolite, etc	0.12	

Table 2.4 Allowable density of poison gas

Gas	Allowable density (ppm)
Carbon monoxide	100
Nitrogen oxide	25

Table 2.5 Relation between the density of gas and human health

Gas	Sudden death (%)	Durable for a half or one hour (%)	Durable for a long time (%)
Carbon monoxide	0.4	0.15 – 0.2	0.01
Nitrogen oxide	0.025 – 0.075	0.01 – 0.015	0.0033
Carbon dioxide	8	1	0.5

3. Measures to improve environment in tunnel

Measures to keep safety and health of labors from dust, gas, smoke and high temperature in tunnel during construction are classified into the followings.

1) Management to reduce the generation of dust, gas and smoke
2) Individual protection
3) Adoption of appropriate ventilation system

The selection of explosives generation less gas, the adoption of wet type shotcreting having less rebound, the adoption of mechanical excavation system without using explosive, etc, belong to the first measure.

The requirement to labors to use a goggle and a gas mask, or the adoption of remote control system belong to the second measure.

The adoption of ventilation system using a fan or blower, and dust collector belong to the third measure.

This paper present the third measure in detail as follows.

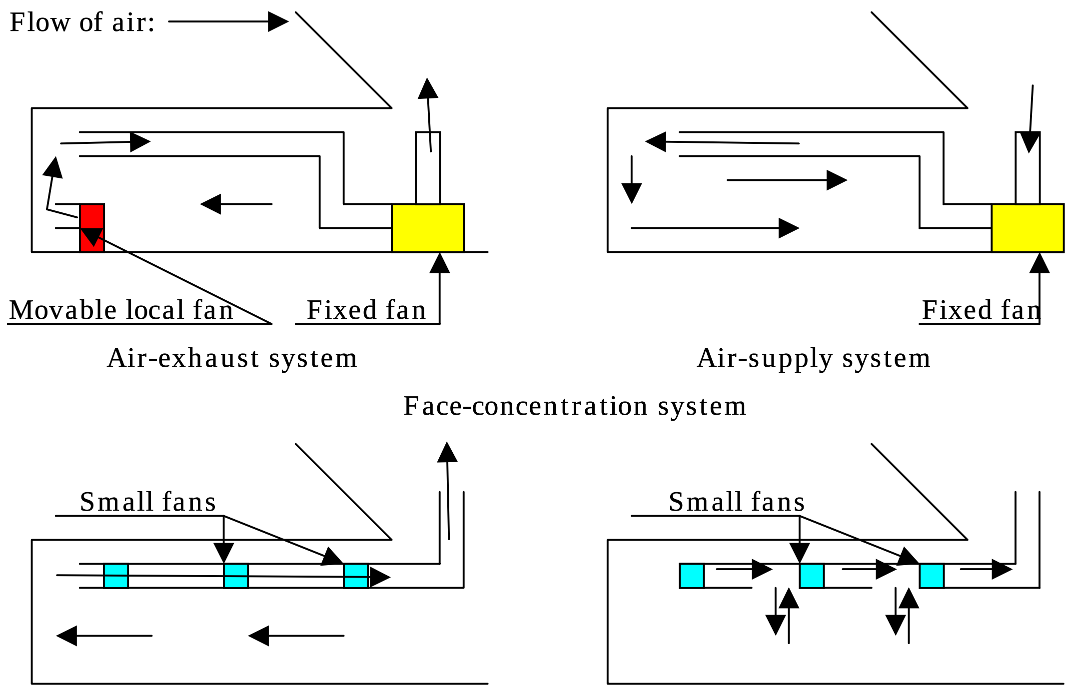
4. Ventilation system in tunnel

4.1 Classification of ventilation system

The principle of ventilation system is classified into the air-supply system and the air-exhaust system and the application method of it is done into the face-concentration system and the series connection system. The series connection system is sub-classified into the continuous system and the continual system. Table 4.1 compares several kinds of ventilation systems and Figure 4.1 shows each system.

Table 4.1 Merits and demerits of ventilation systems

Ventilation system		Merits	Demerits
Face-Con-cent-ration	Air-exhaust	1.Only air pipes to be extended 2.Easy maintenance 3.Little leakage	1.Gas flown to face 2.Only hard ventilation pipe available 3.Capacity of fan to be changed at portal 4.Lacal fan necessary at face
	Air-supply	Above-mentioned	1.Passage of dirty air in tunnel 2.Hard ventilation pipes to be used 3.Capacity of fan to be changed at portal
Series Con-nec-tion	Continuous (Air-exhaust /Air-supply)	1.Economical due to small fan	1.Leakage at joints 2.Hard ventilation pipe to be used 3.One fan to be affected by trouble of another
	Continuous (Air-exhaust /Air-supply)	Above-mentioned	1.Big leakage 2. One fan to be affected by trouble of another



Air-exhaust system Air-supply system

Face-concentration system

Continuous system Continual system

Series connection system

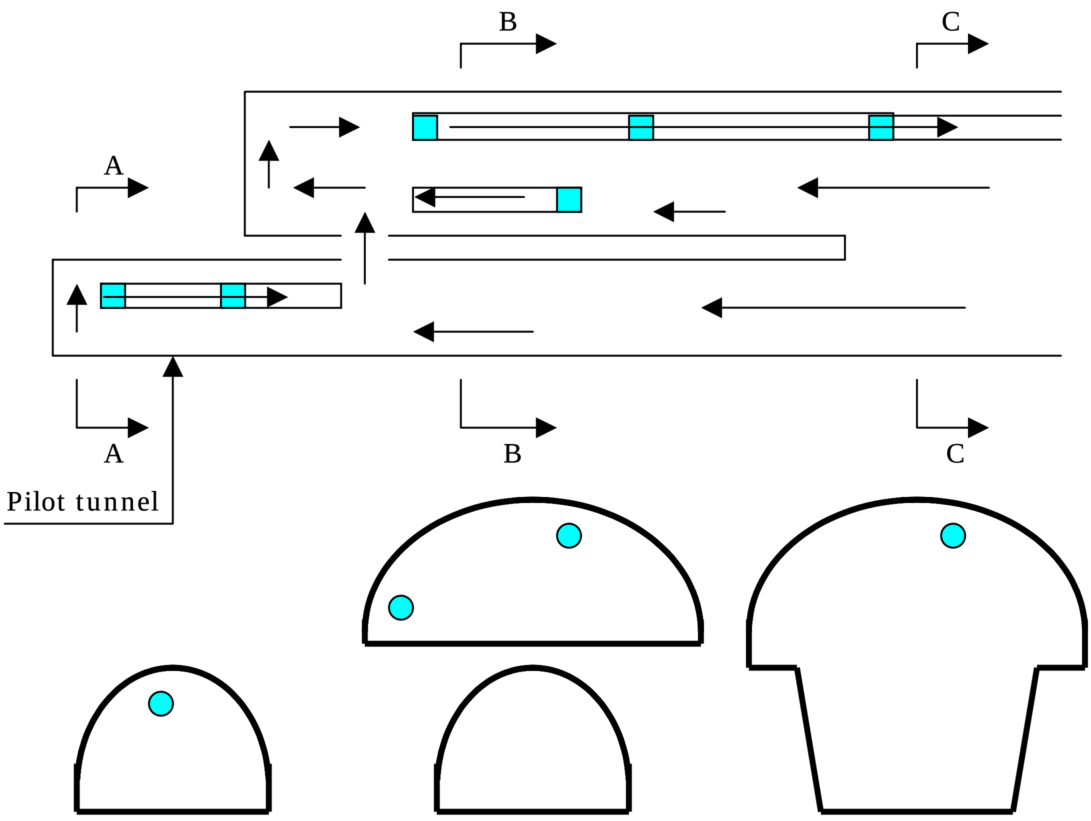
Figure 4.1 Ventilation systems

4.2 Application of ventilation system in tunnel

The application of ventilation system depends on excavation method. Figure 4.2 shows the ventilation systems applied to the tunnel excavation method using pilot tunnel and the full-face excavation method.

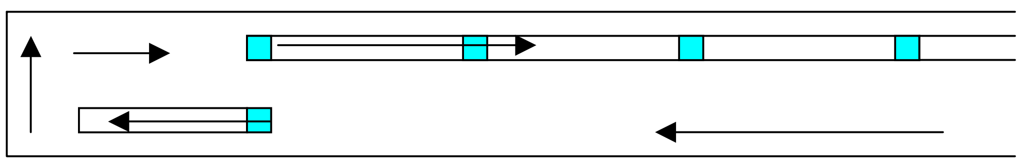
Flow of air:

Fan:



Section A-A Section B-B Section C-C

Ventilation system applied to tunnel excavation with pilot tunnel



Ventilation system applied to full-face tunnel excavation

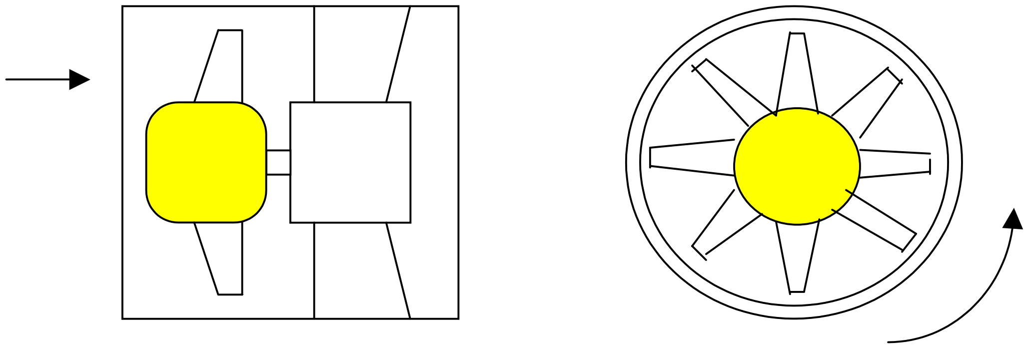
Figure 4.2 Ventilation system in tunnel

5. Facilities and equipment of ventilation

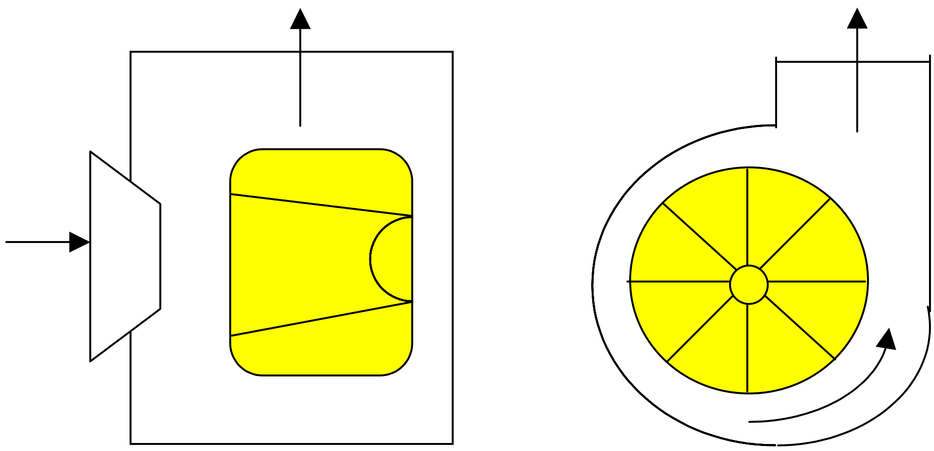
5.1 Fan

The axial fan or the centrifugal fan is used for the ventilation system in tunnel. Figure 4.3 shows them.

Flow of air: ⟶



Schematic drawing of axial fan



Schematic drawing of centrifugal fan

Figure 4.3 Fans for tunnel ventilation

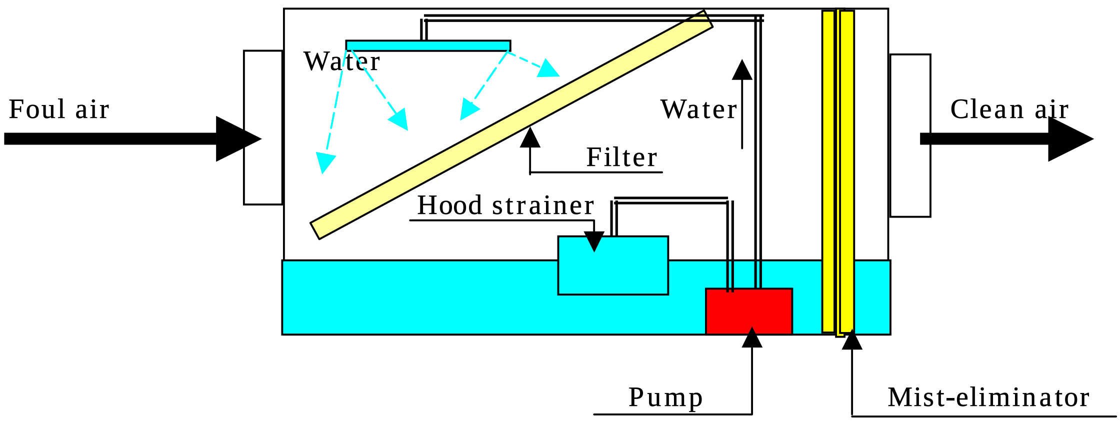
5.2 Ventilation pipe

Ventilation pipes used in tunnel are classified into hard pipe and soft pipe. Steel pipe, plastic-aluminum composite pipe and fiber-reinforced vinyl pipe belong to the former and vinyl pipe belongs to the latter. Soft pipe is portable and flexible but less rigid. Due to the less rigidity of vinyl pipe, the negative pressure by suction reduces possibly its area. In this case, steel reinforcement ring shall be installed inside pipe. Hard pipe is rigid and durable and has small friction loss but it is relatively expensive.

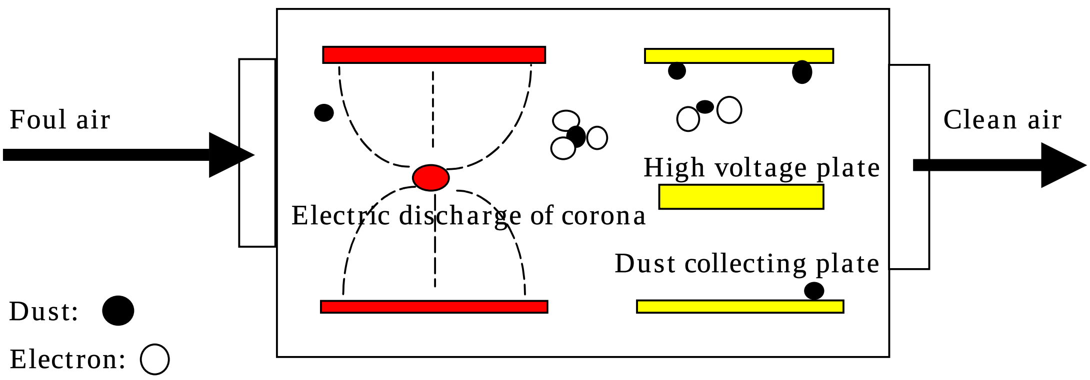
If tunnel is excavated with the pilot tunnel, hard pipe shall be used because soft pipe is vulnerable and has much possibility to make a problem on leakage.

5.3 Dust collector

Dust collectors are classified into the wet type and the dry type. The filter type duct collector belongs to the former. The electric duct collector and the centrifugal duct collector belong to the latter. Conventionally, the filter type duct collector has been used in tunnel. Recently, the electric duct collector has been used in tunnel because it has high performance to collect very small-sized particle (7 – 10 μm). Figure 4.4 shows the principle of duct collectors of these two types.



Principle of filter type dust collector

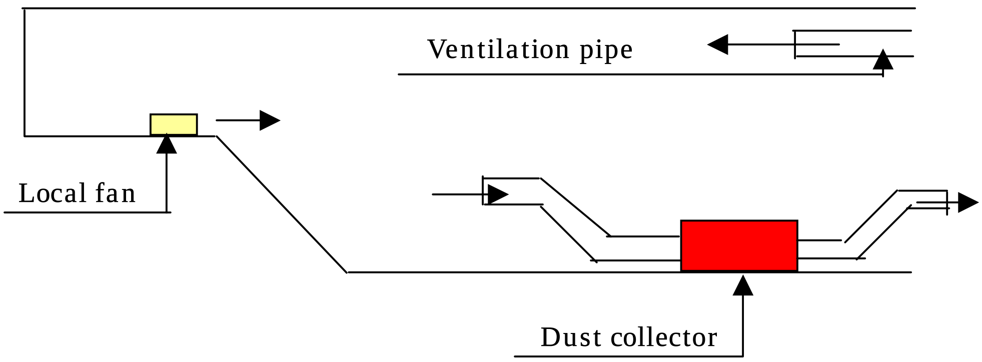


Principle of electric dust collector

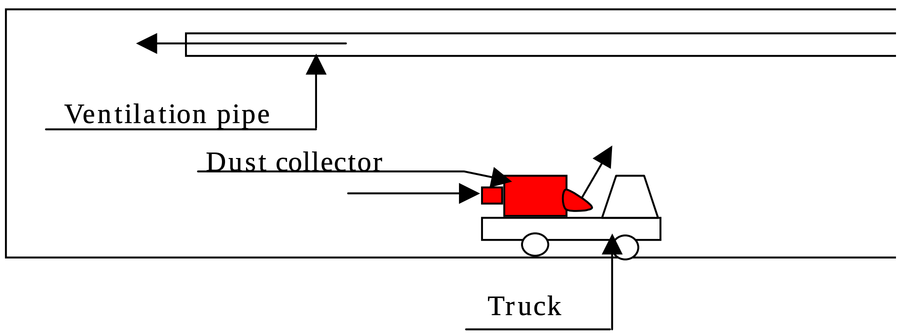
Figure 4.4 Principle of dust collector

Figure 4.5 shows an example of application of dust collector in tunnel.

Flow of air: →



Fixed dust collector applied to top heading and bench method



Dust collector loaded on track applied to full-face excavation method

Figure 4.5 Application of dust collector in tunnel

In case of full-face excavation method, large dust collector is necessary because area of tunnel is large. In this case, dust collector loaded on a truck, which can be moved to face when excavation or shotcreting is done, is convenient.

During tunnel excavation, dust density shall be measured with dust-meter.

6. Design of ventilation system

6.1 Calculation of discharge volume of ventilation

The discharge volume of ventilation in tunnel is calculated as follows.

$Q=Q_1+Q_2+Q_3+Q_4$ (Unit: Volume per time) --------------------------------- (Equation 6.1)

Where, Q=Total discharge volume of ventilation

Q_1=Discharge volume of ventilation necessary for labors and engineers in tunnel=$q_1 \times N_1$

Where, q_1=Discharge volume of ventilation per one person

N_1=Maximum number of labors and engineers in tunnel

Q2=Discharge volume of ventilation for dust caused by blasting

$=(V_{21}/T)\{1-(K_2 \times V_{21})/V_{22}\}$

Where, V_{21}=Volume of tunnel where ventilation is necessary

$=A_2 \times L_2$

Where, A_2=Area of tunnel,

L_2=Tunnel length where ventilation is necessary

T=Time during ventilation

K_2=Allowable density of poison gas (Refer to Table 2.4.)

V_{22}=Volume of poison gas generated by blasting

(Refer to Table 2.2.)

Q_3=Discharge volume of ventilation for dust generated by shotcreting

$=q_3/K_3$

Where, q_3=dust weight per time generated by shotcreting

K_3=Allowable density of dust (Refer to Table 2.3.)

Q4=Discharge volume of ventilation for poison gas generated by cars to transport excavated materials=$Q_{41} \times \alpha \times N_4/K_4$

Where, Q_{41}=Discharge volume of exhaust gas generated by one car

$= \beta \times V_{41} \times N_{41}$

Where, β=Coefficient decided by type of engine

=0.4 to 1.2 for meter-minute unit

V_{41}=Engine displacement (Volume)

N_{41}=Number of rotation of engine (rpm)

α=Content of poison gas in exhaust gas (Volume ratio: Poison gas divided by exhaust gas)

N_4=Number of cars

K_4= Allowable density of poison gas (Refer to Table 2.4.)

If we can do blasting, shotcreting and usage of cars separately without lapped works, and ventilate tunnel in each interval, Equation 6.1 can be replaced with the following equation 6.1'.

$Q=Q_1+Max(Q_2,Q_3,Q_4)$ (Unit: Volume per time) --------------------------- (Equation 6.1')

6.2 Design of fan and ventilation pipe

The power of fan and the size of ventilation pipe are designed by the application of Bernoulli's theorem, as follows.

$V=Q/A$ --- (Equation 6.2)

$h=\lambda(L/D)\times(V^2/2g)\times\gamma$ --- (Equation 6.3)

$N=Q\times g\times h\times\rho_w$ --- (Equation 6.4)

$B=(N/\eta)\times\alpha$ -- (Equation 6.5)

Where, V=Velocity of air

Q=Discharge volume of ventilation (Refer to Equation 6.1.)

A=Area of ventilation pipe h=Friction loss of head (Aqua)

λ=Coefficient of friction loss

D=Diameter of ventilation pipe

L=Length of ventilation pipe

g=Acceleration of gravity γ=Specific gravity of air=0.0012

N=Theoretical power of fan ρ_w =Density of water

B=Actually necessary power of fan

η=Efficiency of power of fan α=Safety factor=1.15 to 1.2

As a reference, in a tunnel in Japan having the area of 75 m^2 and the length of 4000m, the air exhaust system comprising a main fan with the capacity of 2000 m^3/min and a local fan with the capacity of 1500 m^3/min was adopted.

7. Conclusion

The facilities and equipment for the safety and health including the ventilation system shall be designed and installed in accordance with the related laws and regulations. But they prescribe the lowest level and the minimum requirements for the safety and health. After the NATM (New Austrian Tunnelling Method) was introduced into tunnelling works of mountainous tunnels, dust in tunnel shotcreting is increased by shotcreting. Tunnelling engineers in charge shall pay much attention to environment in tunnel, research geology, select the excavation method to minimize the negative impacts and design the appropriate ventilation system in tunnel during construction.