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RESEARCH ARTICLE

Construction risks of Huaying mount tunnel and countermeasures

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ABSTRACT The Chongqing-Guang'an motorway is planned to cross Huaying mount at Jingguan town of Chongqing city. The whole mount is a colossal anticline whose core is consisted of coal measure strata (upper Permian Longtan formation P_2l) and the limbs are limestone strata (middle Triassic Leikoupo formation T_2l and lower Triassic Jialingjiang formation T_1j). The tunneling is full of risks of collapse, gas explosion or gas outburst, water (mud) inrush, gas inrush because of existence of faults, high pressure gas, karst tectonics and coal goafs around the tunnel. In order to cope with the high risk, two main countermeasures were taken to ensure security of construction. One is geology prediction, and the other is automatic wireless real-time monitoring system, which contains monitoring of video, wind speed, poisonous gas (CH_4, CO, H_2S, SO_2), people location, and automatic power-off equipment while gas contents being more than warning threshold. These ascertained the engineering safety effectively.

KEYWORDS tunnel construction, gas outburst, geology prediction, automatic monitoring system

1 General situation of project

Huaying mount tunnel is the most dominant engineering of Chongqing-Guang'an (Yuguang) motorway. The 5009 m long tunnel is designed as separated twin-tube one with 6 lanes in bidirection and the running speed of motors is 100 km/h. Its deepest point to the ground surface is 448 m (see Fig. 1).

Huaying mount is a colossal anticline tectonics of the folded zones, which is called Guanyinxia anticline. Figure 1 shows the whole mountain is consisted of two gorges sandwiched by three ranges. The morphology is caused by particular strata arrangement. See Fig. 2.

Symmetrically occurred from core to limbs, the strata include Longtan formation (P2l) Changxing formation (P2c) of Permian, Feixianguan (T1f), Jialingjiang (T1j), and Leikoupo (T2l), Xujiahe (T3xj) formation of Trias, Zhenzhuchong (J1z) formation of Jurassic system, among which the Jialingjiang (T1j) and Leikoupo (T2l) formation consist mainly of strongly soluble limestone and thereby form two large deep gorges. The Longtan formation (P2l) and Xujiahe formation (T3xj) are coal strata (including shale, sandstone and coal) and the Feixianguan (T1f)

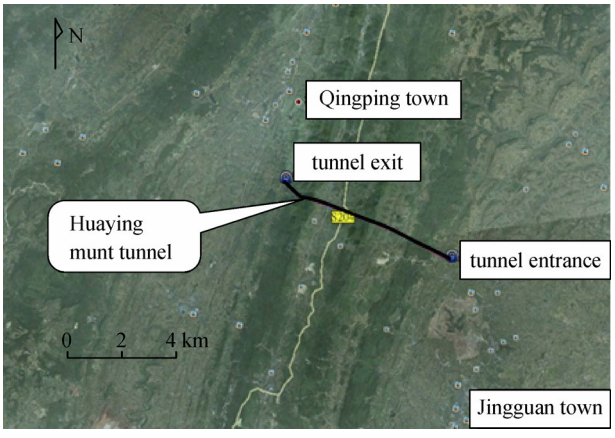

Fig. 1 Tunnel position map

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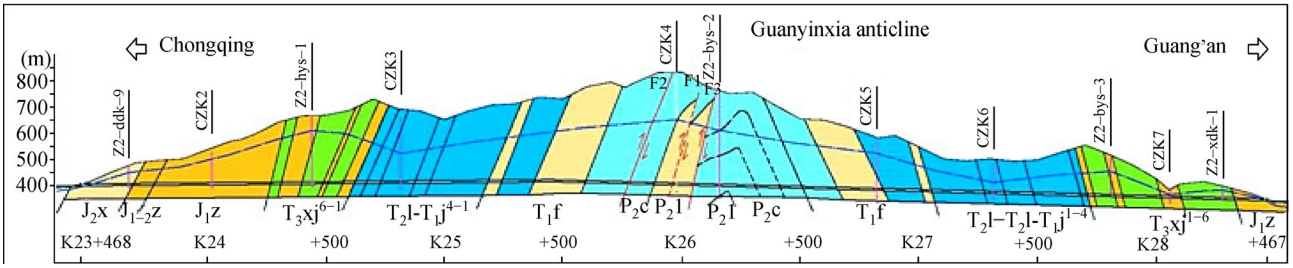

Fig. 2 Strata and tectonics of Huaying mount tunnel

formation includes marlite, limestone, shale and mudstone. Changxing formation (P2c) is made up of limestone. Zhenzhuchong (J1z) formation consists of mudstone sandwiched by sandstone.

Three large faults named F1, F2 and F4 exist in the core part of Guanyinxia anticline. Their influence ranges are 50−140 m, 60 m, 110 m.

The underground water flows from north to south. The whole tunnel is situated under the regional groundwater level. The tunnel entrance is located mid-deep, deep horizontal circulation zone and the exit is located shallow horizontal circulation zone. It is estimated the stable water inflow is 60000 m^3/d, the biggest water inflow may reach 190000 m^3/d for water from karst caves and underground river.

2 Engineering challenges and analyses to geology risks

Because of complicated strata and tectonic conditions, the Huaying mount tunnel engineering is full of geology risks, the challenges mainly includes the follows:

(1) Both the depth and the length of tunnel are big. With over 5 km in length and 448 m in depth, the tunnel belongs to deeply buried and particularly long tunnel.

(2) The tunnel width of excavation ranges from 16.62 m to 19.78 m. The Huaying tunnel is designed as three lane tunnel, so belongs to typical large section tunnel. The excavation width can reach from 16.62 m to 19.78 m according to different rock mass class from III, IV and V.

(3) The tectonics are developed and rock mass is broken. Fault tectonics are developed around the tunnel rock mass. The overall tunnel is located in Guanyinxia anticline. Squeezed by horizontal stress, at least five large faults were detected in Huaying mount, because of this the rock mass is broken. According to exploration data, 75% rock mass belongs to class IV and V. This is very disadvantaged for large section tunnel. Risk of collapse and roof fall would be very high.

(4) Soluble strata distribute widely and Karst flaws are developed. The exploration data show the strongly soluble strata account for 40% rock mass, which on one hand easily form zones with rich groundwater, on the other hand the insoluble strata occur alternately with soluble formation, this structure is very advantaged for karst flaws to form. This has been proved by similar project going through Huaying mount. As several large scale accidents of water inflow and mud burst had broken out [1–5].

(5) High risk of gas outburst or explosion. Tunneling would cross coal layers on several occasions, among which the Longtan formation (P2l) owns high gas pressure. Gas outburst accidents had happened many times in coal mine that exploited the same coal layer. Investigation shows there are seven coal mines in tunnel site, 3 of which exploit coal in Xujiahe (T3xj) formation and the rest exploit ones in Longtan formation (P2l). Xujiahe formation coal belongs to low gas coal and the possibility of gas outburst, coal dust explosion, spontaneous combustion of coal are all small. But Longtan formation coal is high gas one, which is prone to gas outburst, coal dust explosion and coal spontaneous combustion. According to statistics, over 30 times of gas outburst had taken place in Liujiagou coal mine while exploiting the Longtan formation coal. The amount of coal burst reached to over 10000 tons, and the biggest amount of gas outburst was 350000 m^3.

(6) Eight coal goafs situated around tunnels. Tunneling would go from above, behind or through coal goafs in eight positions. Such disasters as inflow of underground water, gas accumulated and cave-in would be prone to happening.

3 Countermeasures of construction

To sum up the preceding analyses, the most important objects that can cause disasters include coal gas, karst flaws and mining goafs. Safety precaution has to be adopted in view of the different nature of possible disasters. They could be narrated from three aspects.

3.1 Countermeasures to coal gas

3.1.1 Gas explosion and its influential factors

Under high temperature, the intensive and complicated oxidation reaction happens between a certain concentration of gas and oxygen, producing water and CO_2, meanwhile

releasing large amount of heat, which in return expands vapor and CO_2 and generates air with high pressure and temperature [6]. The whole course is called gas explosion, which own powerful energy to damage equipments and human bodies.

Gas explosion needs three necessary factors: (1) the gas concentration reaches 5%−16%; (2) ignition source with temperature ranging from 650 °C to 750 °C; (3) oxygen concentration is no less than 12% [7].

The main factors to influence gas explosion include followings [8–13].

3.1.1.1 Mixing of combustible gas

When the mixture of gas and air mixed with combustible gas such as hydrogen, hydrogen sulfide, ethane, carbon monoxide and so on, as the explosion ability of their own, on one hand the total concentration of explosion gas is increased, on the other hand the explosion limits of gas would be lowered. In other word, the gas explosion limits would be expanded.

3.1.1.2 The initial temperature of the mixture (i.e., the temperature of the mixture gas before the explosion)

The experimental results show that the higher the initial temperature, the greater the gas explosion extent is. When the initial temperature is 20 °C, the gas explosion extent is 6%−13.4%; but when the initial temperature is 700 °C, the explosion extent would expand to 3.25%−18.75%. So in case of fire, the high temperature will cause gas explode under its original lower limit of explosion.

3.1.1.3 Pressure of the mixed gas

The greater the pressure, the lower the temperature required for ignition. When the mixed gas is compressed to 1/20 of its original volume, the heat generated by compression is able to cause explosion. High pressure caused by blasting operation in tunnel face would greatly reduce the ignition temperature.

3.1.1.4 Gas explosion induction period

Under normal conditions, the bigger the surface area of ignition resource, the longer the combustion, the more easily happen the gas explosion. On the contrary, even if the fire temperature were very high, the gas wouldn't explode on condition that the combustion time is very short. This phenomenon is called ignition delay. The delayed period is called induction period of gas explosion.

The induction period of gas explosion is very short, but it is very important to guide the safety production of gas tunnel. Based on this knowledge, the gas explosion could be get rid of by limit the combustion time of such high temperature ignition source as tunnel face blast under the induction period. In fact the millisecond detonators and safe explosives are developed on this principle. Meanwhile some high temperature fire such as flame, electric fire that can last long should be forbidden seriously in case gas explosion would happen once the combustion time exceed the induction period.

3.1.2 Countermeasures to prevent gas explosion

Since three necessary factors of gas explosion are necessary, this suggests without one of them, the explosion wouldn't happen. All countermeasures are based on this principle. In view of the concrete conditions of Huaying mount, the follow measures were adopted.

3.1.2.1 Geology prediction

Huaying mount tunnel is about 5 km long, and not everywhere exists coal. Without coal, there would be no gas, so three kinds of prediction methods were adopted to detect coal layer [14–17]. The geology analyses, geophysics exploration (TSP, Radar, Infrared detector, see Fig. 3) and horizontal drills were used synthetically to investigate position, thickness, tilt angle and azimuth, nature (gas content, pressure and so on) exactly. Based on the results, the right measures maybe designed.

Fig. 3 Tunnel seismic prediction (TSP)

3.1.2.2 Gas monitoring and checking in tunnel [18,19]

A set of automatic wireless realtime gas monitoring system was arranged in tunnel to scout gas content in every doubtful position, see Fig. 4. Once gas content exceeded the threshold, the system would give an alarm with sound and light flash. As an automatic power-off equipment and gas locker equipment had been installed, the power supply system would be turned off on alarming condition.

Sensors of CH_4, CO, H_2S, SO_2 were hung on tunnel

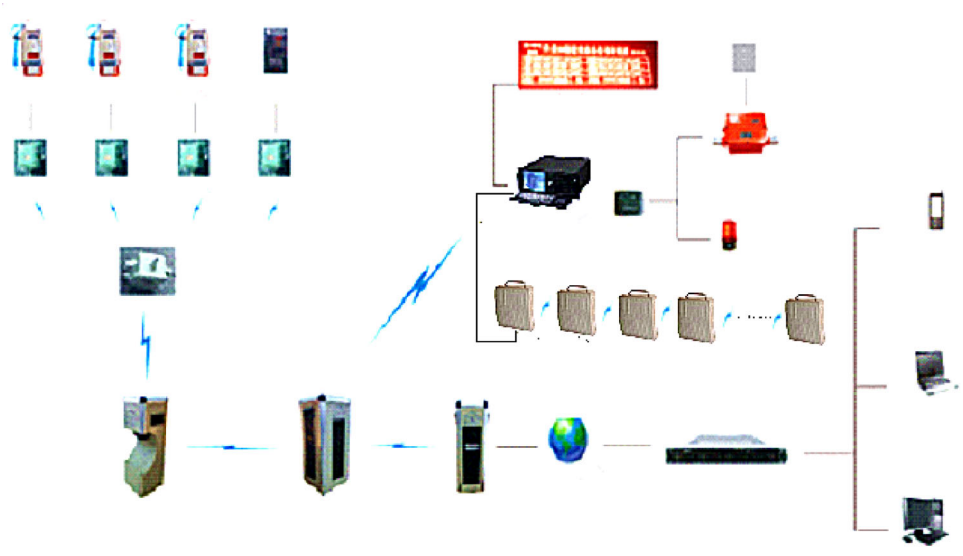

Fig. 4 Automatic wireless realtime gas monitoring system

face, lining platform, transverse gallery. Wind speed sensors were equipped on tunnel face and entrance to monitor speed of ventilation. Once the speed lowered than threshold, the alarm would be given and the power would be turned off since the ventilation speed didn't reach the requirement.

Moreover some common functions such as video monitor, staff location were included in the system.

In view of the high risk of Huaying mount tunnel, the double monitoring was planned. Except for the automatic monitoring system, the special manual gas detectors were arranged to scout gas content where the automatic method fail to carry out.

3.1.2.3 Ventilation

Ventilation is the most effective method to deliquate gas in tunnel. In Huaying mount tunnel, the around clock ventilation was required. Ventilators have function of explosive proof. The ventilation pipe is made of antistatic and flame retardant material, whose air leakage rate every 100 m should be no less than 2%. The distance from the tunnel face to the wind pipe outlet is not more than 5 m. Two power supply systems were fixed to guarantee the ventilators to work continuously.

In order to prevent gas accumulation, an axial flow fan with a soft wind pipe was installed on a flat trolley to ventilate somewhere necessary.

3.1.2.4 Blast operation of tunneling

According to Technical Code for Railway Tunnel With Gas (TB10120-2002) [20], in high gas or gas outburst tunnel only coal mine permissible explosive and detonators delaying 130 milliseconds or less could be used. But in the big section tunnel and hard rock mass, it is almost impossible because of its low explosive power. In order to solve this contradiction, No. 2 rock emulsion explosive was used and specially made rubber bags filled with water were adopted to seal the explosion hole to cease the flame [21]. See Fig. 5.

Fig. 5 Specially made rubber bags

During blasting the "triple inspection with one explosion" (three times of gas inspection were carried out before filling explosive, immediately before blasting and after explosion respectively) regulation and "three man chain blast" (only when the preparation had been established to be OK by the blaster, the gas inspector and the team leader commonly, could be started the blasting) regulation were seriously implemented [22].

3.1.2.5 Sealing of gas

Gas can not only cause explosion or combustion during tunneling, but it can also give rise to serious accidents during tunnel operation period. So for the sake of security the rock mass surface has to be sealed.

To prevent possible gas explosion or combustion caused by welding of arch frame, sprayed concrete has to be immediately operated to seal gas after digging.

Air tight concrete is adopted in both the cast concrete lining and the shotcrete lining. the permeability coefficients of shotcrete and cast concrete are no more than 10^{-10} cm/s and 10^{-11} cm/s respectively.

In gas engineering area, buried type rubber sealing belt, water swellable rubber sealing stripe, concrete interface agent and lining surface waterproof coating were used in sealing radial and longitudinal construction joints of cast lining.

In between the sprayed concrete lining and cast in place lining the gas isolation layer and closed cell foam cushion were used to pack all over the tunnel to segregate gas completely (see Fig. 6).

3.1.2.6 Electricity management

To prevent sparks and cable to be too heat, all electric equipments and lights are explosion proof type. The double power line is used in the tunnel, and the electric source line is not connected with any load outside the tunnel. The neutral points of distribution transformers are strictly prohibited to connect the ground directly.

3.1.2.7 Modification of machinery

To prevent sparks from machinery working, necessary modifications were implemented in trucks, excavators, and loaders [23].

The methane power off device is fixed on machineries to ensure that the engine power would be cut off once the gas concentration was too high.

The flame arrestor and exhaust spark arrester were installed in the intake and exhaust system of diesel engines to prevent sparks ignite gas.

Overheating protection devices and temperature sensor alarm devices were Installed on frictional heating components and increase cooling system.

On surface of the mechanical friction parts deposited chromium with low activity so that the possible friction sparks wouldn't ignite gas.

3.2 Countermeasures to karst flaws

Huaying mount has enough factors to develop large scale karst flaws. In order to prevent serious accidents, the most important is to ascertain the position, dimension, nature and category of karst flaws. So the geology prediction has to be carried out systemically.

Based on the exact geology exploration, the targeted scheme was designed.

To avoid large amount of water and mud outburst, the microseismic, stress and settlement monitoring technology was put into use.

Furthermore, a set of emergency measures were planned to copy with possible sudden accident.

3.3 Countermeasures to mining goafs

In Huaying mount tunnel there are eight positions influenced by mining goafs concerning three coal mines.

The general principle of countermeasures is strengthening the supporting structure based on accurate geology prediction.

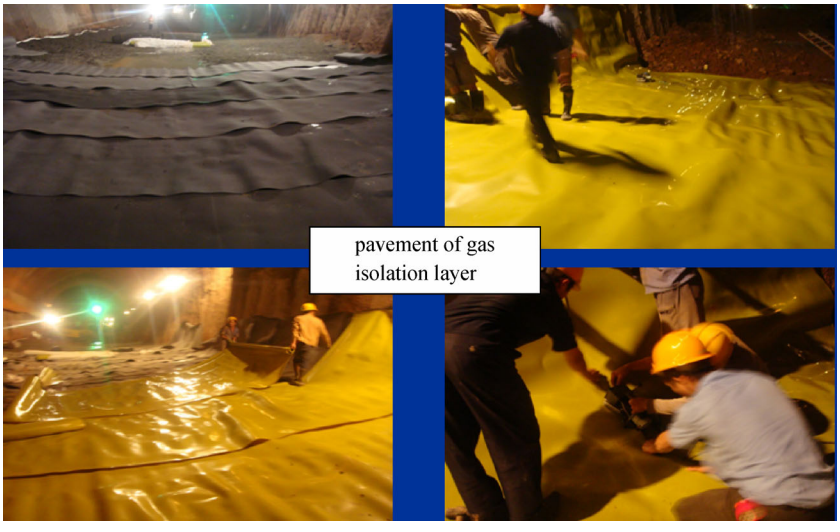

Fig. 6 Construction of gas isolation layer

In Hongguang coal mine the tunnel would go through under goafs with 10 m rock mass sandwiched. Tunneling had to focus on the possible cave-in accident. Except for the arch pipe umbrella support with steel pipes, the single digging amount must be reduced so as to degrade the interruption to rock mass.

In Liujiagou coal mine tunnel would pass from above the goaf with 195 m distance in between. Deformation joints were designed every ten meters in influential zone meanwhile the gas monitoring and inspection were implemented more seriously.

In Bailing coal mine, the tunnel would cross the goafs directly. The tunnel base was consolidated by grouting and long steel pipes of 89 mm in diameter were used to support in advance.

4 Conclusions

Particular geology structure and techtonic of Huaying mount bring about high risks of tunneling. Gas explosion or outburst, underground water inflow, outburst of mud, large scale of cave in, anyone of them would cause serious accident. In order to get rid of loss of lives and fortune, a series of countermeasures were adopt based on research on the nature of possible disasters, the main methods are as follows:

(1) Geology prediction is the most important way to get rid of hazards.

Based on analyses of regional geology and human activities such as coal mining, the basic geology conditions were grasped. Then some earth physics methods and level drilling were used to make clear the geology flaws.

(2) Security monitoring, Equipments transformation and Strengthened ventilation are three effective methods to control gas explosion.

A set of remote, wireless and real-time monitoring system were put into use to supervise gas contents, wind speed, staff positions and activities in tunnel. Once alarming, necessary measures would be carried out to cease the danger.

Necessary transformation were made in machines used to loading, transportation, ventilation and power supply system to get rid of sparks that would ignite gas.

A spare ventilator was fixed on each tunnel entrance in case of break-off of ventilation, moreover a moving fan was used to disperse gas where needed.

(3) Microseismic, stress and settlement monitoring played an important role in control hazards while tunneling through karst area and coal goafs.

(4) Management measures.

Any work is finished by people. So the excellent and effective management system must be made.

Huaying mount is famous for its high risk of geology disasters. In history the first tunnel going through Huaying mount was a railway tunnel that had been built with the cost of over 100 people's lives. But today with the development of new technology, more and more advanced methods are used in construction to cope with all kinds of disasters and reduce drastically the project risk.

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