Study on the distribution of sulfur-bearing formations in the Sichuan Basin and its damage to tunnel engineering

Peidong SU1, Yi ZHAO1, Zhengxuan XU2, Yuben DU2, Peng QIU1, Dong WANG2 and Yougui LI1

1 College of Earth Sciences and Technology, Southwest Petroleum University, Chengdu 610500, China.
2 China Railway Second Academy Engineering Group Co., Ltd, Chengdu 610000, China.

E-mail: spdong@126.com

Abstract. The sulfur-bearing formations in the Sichuan Basin are widely distributed, whose harmful gases have caused serious threat to tunnel engineering. Based on the existing data collected, the research shows that the main sulfur-bearing formations in the Sichuan Basin include the Triassic Leikoupo Formation, Jialingjiang Formation, and Feixianguan Formation, the Permian Longtan Formation, the Carboniferous Huanglong Formation, the Silurian, the Cambrian and the Sinian. Sulfur-containing gas is closely related to the active degree of tectonic movement in the area where it is located, and is mainly manifested in three aspects: the generation, migration and storage of sulfur-containing gas. According to the tectonic distribution, depth and concentration of the Sichuan basin, the hazard grade of the sulfur-bearing strata in the basin was classified. The Permian Longtan Formation and the Carboniferous Huanglong Formation can be divided into Level IV sulfur-containing strata. The Triassic Leikoupo Formation, Jialingjiang Formation, Feixianguan Formation, and the Silurian strata can be divided into Level III sulfur-containing strata, meanwhile the Cambrian and Sinian strata can be divided into Grade II. The result of sulfur-bearing strata hazard classification was applied to the Yuelongmen Tunnel of Chenglan Railway, and the on-site inspection results were consistent with the application analysis results.

1. Foreword
The Sichuan Basin is the region with the most concentrated distribution of high-sulfur natural gas in China, where sulfur-bearing strata are widely distributed. Sulfur-containing gas will cause great harm to the human body. It will cause casualties when reaching a certain concentration, and it will cause explosion when the concentration is higher. In addition, the metal equipment is easy to be corroded if it is in a hydrogen sulfide (H2S) gas environment for a long time. Hydrogen sulfide forms a weak acid easily when it meets water, which causes electrochemical corrosion, hydrogen embrittlement and stress corrosion damage to metal equipment [1].

About the Author: Peidong Su, male, (1973–), doctor, professor, Meishan, Sichuan, mainly engaged in scientific research and teaching in geological engineering and the hazards of toxic and harmful gases to engineering construction. Email: spdong@126.com
There are many cases harmed by hydrogen sulfide gas in foreign underground engineering. For example, during the construction process of Iran’s Zagros tunnel, a sudden rush of groundwater accompanied by a rotten egg-like odor intruded the tunnel, complained from eye and respiratory tract irritation. The presence of hydrogen sulfide (H₂S) gas as high as 200 ppm was soon tested positive by gas detectors [2,3]; Nosoud Tunnel was tested before construction in Iran, groundwater sampling indicated that about 1 L of H₂S is released per 100 L of the water inflow into the Nosoud tunnel under normal conditions [4]; H₂S gas with concentrations of more than 100 ppm, released from water and dry rock, have been encountered in Alborz Service Tunnel, the longest tunnel (6.4 km) along Tehran Shomal Freeway [5]; The main components of the harmful gases in the construction of the Tecolot Tunnel in the United States were CH₄ and H₂S, which caused two explosions in the tunnel. The tunnel gushing water also contained a large amount of H₂S [6,7,8]; The Los Angeles subway tunnel in the United States also encountered a large amount of H₂S and CH₄ during the construction, which seriously affected design and construction [6,7,8]; H₂S in high concentrations (up to 200 mg/l) has been encountered in the groundwater of Kuwait City and its suburbs at relatively shallow depths [9].

Domestically, especially in the Sichuan Basin, there are many cases about the hazards of sulfur-containing gas. For example, during the excavation of the Huayingshan Tunnel on the Guangyu Expressway, H₂S and oil and gas were encountered, and the construction had to be suspended [10,11]; When the Chongqing Yufengshan Tunnel was excavated to K13+235, H₂S overflowed, and the gushing volume of the tunnel suddenly increased with a strong pungent smell of rotten eggs, the water quality was turbid, construction of the tunnel site was stopped immediately [12]; When the Micangshan extra-long tunnel of the Bashan Expressway was constructed to the left of the main tunnel to ZK40+695 and the right to K40+821, it encountered a high concentration of H₂S [13]; H₂S concentration was detected up to 19.4 ppm and SO₂ concentration was up to 17.6 ppm in the No.1 construction branch tunnel of the Shawan Hydropower Station diversion tunnel of the Muli River [14].

With the rapid development of the Sichuan Basin and the advancement of high-speed traffic, more and more tunnels are being constructed, and the number of tunnels affected by sulfur-containing gases has gradually increased. Therefore, the research on the harm of sulfur-containing gas to tunnel engineering has attracted great attention from the engineering community.

Most of the domestic and foreign experts' research on sulfur-containing gas is more focused on the description of the phenomenon of sulfur-containing gas encountered during the construction of a single tunnel project. There are very few studies about sulfur-bearing formations and the sulfur-containing gases produced by them regionally on engineering impacts and hazard levels. Based on data from gas fields, this paper studies the sulfur-bearing formations, lithologies, and distributions that can produce sulfur-bearing gases in the Sichuan Basin. Based on the structural distribution, depth and concentration, the sulfur-bearing formations in the Sichuan Basin were classified according to their hazard levels in order to make up for deficiencies of the sulfur-bearing formations' research in the Sichuan Basin. By studying the distribution of sulfur-bearing formations in the Sichuan Basin and the classification of their hazard levels, the economic loss caused by the unclear understanding of sulfur-bearing formations in the project is avoided, and the study has important theoretical guidance and practical value for formulating a reasonable tunnel survey, design and construction plan.

2. Descriptions and distributions of sulfur-bearing strata in Sichuan Basin

2.1. Overview

The sulfur-containing gases that can be produced in sulfur-bearing strata are mainly hydrogen sulfide (H₂S) and sulfur dioxide (SO₂) gas. The sulfur dioxide (SO₂) gas is easily oxidized in the formation, so it usually does not exist alone. It is accompanied by other harmful gases such as mash gas. Sichuan Basin is the most widely distributed hydrocarbon-bearing gas basin containing hydrogen sulfide in China, with content ranging from 0% to 18.83% [15].

Hydrogen sulfide (H₂S) is colorless, slightly sweet, and has a strong smell of rotten eggs. It can be smelled when the concentration in the air reaches 0.0001%, but when the concentration is high, it
cannot be smelled because of paralysis of olfactory nerve poisoning. The relative density of hydrogen sulfide is 1.19, and it is easily soluble in water. At a normal temperature and pressure, one volume of water can dissolve 2.5 volumes of hydrogen sulfide. Hydrogen sulfide can burn, and there is danger of explosion when the concentration of hydrogen sulfide in the air is 4.3% ~ 45.5% [16].

2.2. Sulfur-bearing strata

Summarizing the data of gas reservoirs, the main hydrogen sulfide gas reservoirs in the Sichuan Basin are mainly distributed in northeast and south. Sulfur-bearing strata in Sichuan Basin are arranged by stratigraphic age: Triassic Leikoupo Formation, Jialingjiang Formation, and Feixianguan Formation, Permian Longtan Formation, Carboniferous Huanglong Formation, Silurian, Cambrian, and Sinian. According to the research, the lithology of each stratum is shown in Table 1.

2.3. Distribution of sulfur-bearing strata

Hydrogen sulfide fields in the Sichuan Basin are shown in Figure 1. Its characteristics can be summarized as "high in the northeast and low in the southwest", the high-sulfide hydrogen fields such as Puguang, Maoba, Tieshanpo, Dukouhe, Qilibei, Luojiashai gas fields are mainly distributed in the northeastern Sichuan Basin; generally low-sulfide hydrogen fields such as Moxi and Weiyuan gas fields are distributed in the southern Sichuan Basin. The Longquan Mountain and Huaying Mountain extend northward from 25 to 30° in the Sichuan Basin, and Sichuan Basin is divided by them into the western plain, the central hills and the parallel ridge valleys in the east. The northeastern Sichuan area mainly includes Dazhou, Kaixiang, Xuanhan and other areas; the main area of southern Sichuan is Yibin, Neijiang, Luzhou, Leshan and other areas.
Combining the distribution of hydrogen sulfide gas fields in Sichuan Basin with the characteristics of the stratigraphic distribution of the Sichuan Basin, the study found that the distribution characteristics of sulfur-bearing strata in the Sichuan Basin are mainly the same as those of hydrogen sulfide gas fields. Sulfur-bearing strata are mainly distributed in the northeastern Sichuan Basin. The main sulfur-bearing formations are the Triassic Leikoupo Formation, Jialingjiang Formation and Feixianguan Formation, the location distribution map of Triassic sulfur-bearing strata and tunnel projects in the Sichuan Basin is shown in Figure 2.

Figure 1. Distribution of hydrogen sulfide fields in the Sichuan Basin.

Figure 2. Location distribution map of Triassic sulfur-bearing strata and tunnel engineering cases in Sichuan Basin.
3. Hazards of sulfur-bearing strata to tunnel engineering

3.1. Cases study of impact of sulfur-bearing strata on tunnel engineering

Existing examples of the influence of sulfur-containing gases on tunnel engineering are shown in Table 2 [10-13,17,18].

| Name of tunnel | Owned line | Geological conditions | Sulfur-bearing strata affecting the tunnel | Situation of hydrogen sulfide | Damage situation |
|----------------|------------|-----------------------|------------------------------------------|---------------------------------|-----------------|
| Huayingshan tunnel | Guanyu Expressway | The crossing strata from Dongkou to Dongshen are mudstone and shale with sandstone of middle and lower Jurassic Ziliujing formation and shenzhuchong formation respectively; Sandstone and mudstone with coal seam in Xujiahe formation of Upper Triassic; A Limestone and dolomite of Leikoupo Formation and Jialingjiang formation of middle and lower Triassic - with Salt solution breccia and gypsum layer. | Leikoupo Formation of Middle Triassic and Jialingjiang formation of Lower Triassic. | The maximum pressure is 1.87mpa, the maximum mash gas concentration is 8.73%, and the maximum hydrogen sulfide concentration is 50.7ppm. | The working stuff feel dizzy and nauseous, and combustion phenomenon was found. |
| Baiyun Tunnel | Wuorgan-Shujiang section of Chongqing to Changsha Expressway | The exposed strata in the area include Leikoupo Formation of Middle Triassic, Jialingjiang formation of lower series, Feixianguan Formation, Changxing Formation of Upper Permian, Wujiaoping formation of middle series, Maokou Formation and Qixia Formation of lower series, and there are mainly limestone, dolomitic limestone, argillaceous limestone, salt soluble breccia, mudstone, shale, siltstone and so on beneath the upper strata. | Leikoupo Formation of Middle Triassic, Jialingjiang formation of Lower Triassic, Feixianguan Formation of Lower Triassic, Huanglong Formation of Carboniferous and Silurian. | The concentration of H₂S in the tunnel is 19.6-64.7ppm. | H₂S concentration is 13 times higher than the national safety standard, which is harmful to construction personnel. |
| Yulongmen tunnel | Chenglan Railway | The strata passing through the tunnel body are mainly Devonian dolomite limestone, Cambrian siltstone, phosphorite, Silurian phylite, carbonaceous phylite with limestone, Jinning diabase, Sinian siliceous rock, shale, carbonaceous shale with limestone, dolomite, etc. | Cambrian, Silurian and Sinian. | H₂S gas appears in many places, the highest value is 97.3ppm, and the concentration in water outlet is 120-378ppm. The maximum concentration of H₂S is 81ppm, and it will give off strong and pungent smell when dissolved in water and the water quality is turbid. The eyes and respiratory tract of construction workers are obviously irritated, accompanied by dizziness and nausea, the rotten egg-like smell can be found. There is a strong pungent smell of rotten eggs in the gushing water, and the water quality is turbid, and the tunnel builders' eyes became swollen to varying degrees, with tear, unclear vision and other adverse reactions. | The eyes and respiratory tract of construction workers are obviously irritated, accompanied by dizziness and nausea, the rotten egg-like smell can be found. |
| Yufengshan tunnel | Chongqing outer ring expressway | The tunnel passes through limestone karst valley of Jialingjiang formation of Lower Triassic system and Leikoupo Formation of middle series. The main crossing strata are mudstone, sandstone and limestone. The limestone is developed in karst with large scale. | Leikoupo Formation of Middle Triassic and Jialingjiang formation of Lower Triassic. | The highest concentration of H₂S is 279ppm. | On site workers have adverse reactions such as eye redness, chest tightness, etc. during construction. |
| Micangshan tunnel | BuShan expressway | The exposed strata in the tunnel site are mainly quaternary Holocene loose layer of Cenozoic, lower Ordovician, Middle Cambrian and lower Shilongdong formation of Paleozoic, lower Shipai formation and upper Dengying Formation of Sinian system of Proterozoic, upper two formations of Lower Proterozoic, dongfanggou formation and Jinning magmatic rock. | Cambrian and Sinian. | The highest concentration of H₂S is 279ppm. | On site workers have adverse reactions such as eye redness, chest tightness, etc. during construction. |

3.2. Harm of hydrogen sulfide to construction workers

The impact of hydrogen sulfide on construction workers is shown in Table 3 [19,20].
Table 3. Harm of hydrogen sulfide to construction workers.

| Concentration of hydrogen sulfide in air (ppm) | Impact on construction personnel |
|-----------------------------------------------|----------------------------------|
| 0.13~4.6                                      | It can be smelled that there is an obviously unpleasant smell, which is very obvious when it reaches 4.6 ppm. As the concentration increases, olfactory fatigue occurs, and the gas can no longer be distinguished by smell. |
| 10                                            | Average 15 min short-term exposure range recommended by the American Association of governmental industrial health experts. |
| 15                                            | After exposure for 1 hour or longer, the eyes have burning sensation and the respiratory tract is stimulated. The smell will be lost after exposure for 15 minutes or more. Headache, dizziness and/or shaking may result if the time is more than 1 h. More than 50 ppm will lead to pulmonary edema and serious irritation or injury to human eyes. |
| 20                                            | Within 3-15 minutes, it will damage the olfactory nerve and the eyes of bad people; After 20 minutes, the heart and pulse speed up. After 1 h, it will stimulate the throat and damage the eyes. People will be in danger of losing life if don't leave the dangerous area. |
| 50                                            | It has obvious conjunctivitis and respiratory tract irritation, which is harmful to life or health immediately. |
| 100                                           | Short term exposure will cause unconsciousness. If not handled quickly, people will stop breathing, lose sense of reason and balance. If the rescue measures are not taken in time, the poisoned person may die. |
| 300                                           | Consciousness will be lost soon and breathing stops, if not immediately take rescue measures, it will lead to the death of the poisoned person. |
| 500                                           | Consciousness will be lost immediately, permanent brain injury or brain death will occur as a result. Rescue must be operated quickly, or the poisoned person will die. |

3.3. Effect of hydrogen sulfide on reinforced concrete structure of tunnel

The harm of hydrogen sulfide to reinforced concrete can be divided into the following three points [19]:

- Hydrogen sulfide can cause hydrogen embrittlement damage of steel materials.
- Hydrogen sulfide can cause concrete corrosion.
- Hydrogen sulfide will cause the rubber to swell and lose its elasticity, which will affect the waterproof quality of the tunnel in a certain degree.

4. Hazardous level of sulfur-bearing strata

4.1. Division of construction environmental hazard areas

See Table 4 for restrictions on hydrogen sulfide in Chinese engineering construction environment.

Table 4. Hydrogen sulfide limits in Chinese engineering construction environment

| Limit value (ppm) | Treatment measures for over limit |
|-------------------|----------------------------------|
| Breathing height of operators 6.6 | Alarm, ventilation, spray mist dilution. |
| Breathing height of operators 13.2 | Construction personnel shall wear protective equipment and strengthen ventilation. |
| Breathing height of operators 33.0 | Personnel are not allowed to enter, strengthen ventilation. |
With reference to Tables 3 and 4, according to the hazards of the hydrogen sulfide concentration to the construction personnel, the construction environment can be divided into low-risk areas, medium-risk areas, high-risk areas and extremely dangerous areas.

Low-risk areas: When the concentration range of H$_2$S is between 0 and 6.6ppm, When the concentration is lower than 6.6ppm, H$_2$S will not cause discomfort to the human body, tunnel engineering Construction can be proceeded normally.

Medium-risk areas: When the concentration of H$_2$S is 6.6~198ppm, the construction staff may feel the discomfort such as burning sensation in the eyes or cause severe symptoms such as pulmonary edema, if they are exposed to H$_2$S for a long time.

High-risk areas: When the concentration of H$_2$S is 198~502ppm, it can cause severe lung diseases such as pulmonary edema, bronchitis and pneumonia, which are mainly manifested as headache, dizziness, nausea and vomiting.

Extremely dangerous area: When the concentration of H$_2$S is greater than 502ppm, it will cause irreparable harm to the construction workers, and if they do not evacuate the danger area immediately, they will be in the danger of lives.

4.2. Hazardous grades of sulfur-bearing strata in Sichuan Basin on tunnel engineering

On the basis of making full use of the existing geological survey data and referring to domestic and foreign sulfur-containing gas related cases, especially which occurred near the sulfur-bearing strata in Sichuan Basin, research on the distribution of sulfur-bearing strata and the hazards of tunnel engineering based on the following three aspects:

- **Analysis of Geological structure**
  
  Geological tectonic activities have a certain effect on the generation, migration, storage and sealing of harmful gases, and the influence of fault activities is more obvious. The influence of geological structure on sulfur-containing gas is mainly manifested in three aspects: generation, migration, and storage. First of all, the sulfate (magnesium) fluid in the dolomite in the sulfur-bearing formation may originate from the deep fluid that migrates upward under the condition of regional fault tectonic activity; secondly, when the region is affected by fault tectonic activity, through the drainage of faults, sulfur-containing gas can migrate upwards into the reservoir; finally, the carbonate rock is affected by regional fault tectonic activity and hydrothermal dolomitization occurs. The pores are more developed, thus forming high-quality dolomite reservoirs.

  If the sulfur-bearing stratum is located in an area with active tectonic movements in the Sichuan Basin, tectonic movements such as folds or faults will cause some strata to be missing or the cap of the sulfur-bearing stratum to be unstable. At this time, the sulfur-bearing gas produced by the sulfur-bearing stratum will have a greater impact on the tunnel engineering.

- **The Depth Analysis**
  
  Based on the approximate burial depth of the sulfur-bearing stratum, the possible digging depth of the tunnel project, and the height of the hydrogen sulfide gas that can be generated by the sulfur-bearing stratum, judging whether the sulfur-containing gas generated by the sulfur-containing formation will affect the tunnel project.

- **The Concentration Analysis**
  
  According to the concentration of hydrogen sulfide that can be generated in sulfur-containing strata rising to the tunnel, the harm that its concentration will cause to construction personnel is analyzed.

  Based on the above three factors, the classification standard of the hazards of the hydrogen sulfide concentration to the construction workers and the existing cases in the Sichuan Basin, the sulfur-bearing strata in the Sichuan Basin can be divided into four grades, I (extremely dangerous) and II (High-risk), III (medium-risk), IV (low-risk), the classification basis and the corresponding grade of sulfur-bearing strata are shown in Table 5.
Table 5. Hazardous Division of Sulfur-bearing Strata

| Hazard grade | Classification basis | Sulphur formation | Typical Case |
|--------------|-----------------------|-------------------|-------------|
| I (extremely dangerous) | The sulfur bearing formation is located in the active section of tectonic activity, the buried depth of the formation is shallow, and the concentration of hydrogen sulfide gas produced can reach above 502ppm. if the concentration of any toxic, corrosive or asphyxiating gas in the atmosphere reaches this level, it will immediately cause a threat to life, or an irreversible or delayed adverse effect on health, or affect the ability of personnel to evacuate from the dangerous environment. | - | - |
| II (High-risk) | The sulfur bearing stratum is located in the active tectonic activity section or the buried depth of the stratum is shallow, which can produce the concentration of hydrogen sulfide in the range of 198-502ppm, which will seriously affect the health of construction personnel, the place where concentration of hydrogen sulfide is relatively high may cause death. At the same time, when hydrogen sulfide dissolves in water, it will cause corrosion to concrete and steel. | Cambrian and Sinian. | Yuelongmen Tunnel, Micangshan Tunnel. |
| III (medium-risk) | When the sulfur-containing formation is near the active tectonic activity area or the depth of the formation is deep, the concentration of hydrogen sulfide is in the range of 6.6-198ppm, which will have an irreversible or delayed impact on life and health. | Leikoupo Formation of Triassic, Jialingjiang Formation, Feixianguan Formation, Longtan Formation of Permian, Silurian. | Huayingshan Tunnel, Yuelongmen Tunnel, Baiyun Tunnel, Yufengshan Tunnel. |
| IV (low-risk) | When the sulfur-containing formation is not located near the fault zone, the depth of the formation is deep, and the cover is good, the concentration of hydrogen sulfide is in the range of 0-6.6ppm, so the risk of the formation is low. | Huanglong Formation of Carboniferous. | Baiyun Tunnel. |

5. Engineering applications

5.1. Tunnel engineering geological conditions

- Project overview
  The Yuelongmen Tunnel on the Chenglan Railway is connected to Gaochuan Station in front, and Yangjigou Bridge at the back. The double-track sub-repair is adopted, with a maximum line spacing of 60m and a minimum spacing of 30m. The starting and ending mileage of the left line of the tunnel is D2K91+020~D2K110+994.3, the total length is 19974.3m; the starting and ending mileage of the right line is YD2K91+002~YD2K111+046, the total length is 20044.0m. The tunnel is uphill on one side with a maximum buried depth of about 1445.5m. The tunnel is pre-installed with 3 horizontal tunnels, 2 inclined shafts, and 1 horizontal guide.

- Formation lithology
  The exposed strata in the tunnel site area are mainly the Cenozoic Quaternary Holocene, and the underlying strata are the Lower Permian, the Lower Carboniferous Zongchanggou Group, and the Upper Devonian Tang Wangzhai Group, Middle Guanwushan Formation, Upper Silurian Maoxian Group First Subgroup, Lower Longmaxi Group, Ordovician Middle Baota Formation, Lower Cambrian Qingping Formation, Lower Sinian Qiujiahe Formation, fault breccia, crushed rock. Jinning period intrusive rocks are distributed in the area, dominated by diabase. The stratigraphic lithology is mainly limestone, dolomite, dolomitic limestone, phyllite, carbonaceous phyllite intercalated with limestone, carbonaceous slate, and siliceous rock.

- Geological structure
  The Yuelongmen Tunnel is located in the famous Longmenshan structural belt in my country. The Longmenshan structural belt is a large-scale and complex-structured giant nappe structural belt. The overall direction is 45°NE, leaning to the northwest, extending 500km, and with a width of 25~50km. The Longmen Mountain Central Fault Zone which the Yuelongmen Tunnel crosses is one of the backbone faults of the structural belt, has a total length of 500km. The overall fault strikes N40~60°E, inclines NW, and dips 60°~80°.
5.2. Sulfur-containing gas impact analysis

- Sulfur-bearing formation lithology

According to Table 1 and Table 5, it can be seen that the sulfur-bearing strata crossed by the Yuelongmen Tunnel are Silurian, Cambrian, and Sinian, of which the Cambrian and Sinian are grade II sulfur-bearing strata, and the Silurian is III. The lithology of the sulfur-bearing formation is shown in Table 6.

Table 6. The lithology of sulfur-bearing strata in the Yuelongmen tunnel.

| Sulfur-bearing strata       | Formation lithology                                                                                                                                                                                                 |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Middle and Upper Maoxian   | The green shale is composed of intercalated limestone lens, oolitic limestone and purple phyllite. The lithology is relatively simple, with a total thickness of 500–900m. The exposed area of the tunnel site is mainly phyllite. Drilling reveals that the part is carbonaceous phyllite with a limestone lens. The phyllite is gray-green, green-gray with palimpsest texture and phyllite-like struct. The joint fissures are well developed, and the joint surface is grayish brown. |
| Group First Subgroup (S2-3mx1) |                                                                                                                                                                                                                     |
| Lower Longmaxi Group (S1ln) | The interbedded carbonaceous slate and siliceous rock are in black, gray-black with plate-like structure. Affected by regional geological structure, the rock mass has developed joints and fissures with poor integrity. Siliceous rock is in the form of thin layers and flakes with a thickness of 20-40m. Parallel unconformity contact with the underlying Ordovician Pagoda Formation (O2b). |
| Qingping Formation of Lower Series | The main exposed areas in the survey area are siltstone and apatite, which are light gray, yellow gray, gray, with silty structure, argillaceous structure, medium-thick layered structure. There are broken rock mass and well-developed joints. It is in parallel unconformity contact with the underlying Sinian Qiujiahe Formation (Zbq). |
| Cambrian (Є1c)              |                                                                                                                                                                                                                     |
| Sinian (Zbq)               | The main exposed areas in the survey area silaceous rock, shale, carbonaceous shale intercalated with limestone, and dolomite. The overall appearance is gray-black, gray, and gray-white, with mainly thin-layered, plate-like, and sheet-like structures. There is a medium-thick layer in some parts, with well-developed joints and fissures. |
Geological structure influence

The geological structure mainly controls the migration of sulfur-containing gas. The geological structure that mainly controls the migration of sulfur-containing gas in the Yuelongmen Tunnel is the Dawuji inverted compound anticline, Laolinkou inverted compound syncline, half-mountain inverted compound anticline, Qianfo mountain fault, Qianfo mountain 1# fault. The following is shown in the Table 7.

Table 7. The table of related geological structures.

| Geological structure name                  | Overview                                                                 | Intersection mileage with tunnel | Intersection angle with tunnel |
|--------------------------------------------|--------------------------------------------------------------------------|----------------------------------|--------------------------------|
| Dawuji inverted compound anticline         | It developed from Yudongkou at the junction of Mianzhu and Maoxian to the vicinity of Dawuji, the axial direction was extended from east to west. The SE wing formation is reversed, and the NW wing formation is normal. The secondary folds are roughly parallel to the same oblique folds, arranged in the shape of geese. There are several layers of diabase dikes along the structural line in the core of the anticline. The dike intrusion period is earlier than that of the fold formation. | D2K99+460                        | 43°                            |
| Laolinkou inverted compound syncline       | It develops from Laolinkou to Huangshuiguou, and is discontinued near the line by the Qianfo mountain fault. The core stratum is phyllite and sandstone of the second subgroup of the Maoxian group of Silurian. There is no exposure near the tunnel body, and the wing stratum is phyllite of the first subgroup of the Maoxian group. Its axis is N60°E and leaning northwest with an inclination angle of 40°~50°. | DK108+050                        | 35°                            |
| Half-mountain inverted compound anticline  | It's adjacent to the Laolinkou inverted complex syncline, the core and wing strata are both phyllites of the first subgroup of the Silurian Maoxian Group, with an axial direction of N60°E, leaning northwest, and with a dip angle of 40°~50°. | DK108+900                        | 35°                            |
| Qianfo Mountain fault                      | The fault developed from Huangshuiguou on the south side of Tumen in Maoxian County to the south side of Qianfo Mountain, and its strike generally extended in a nearly east-west arc. The fault plane is inclined to the north with a dip angle of 60°. The north plate is the Silurian Maoxian Group (S2 mx1) phyllite strata, and the south plate is the Lower Cambrian Qingshui Formation (Є1 c) siltstone and apatite, with thrust properties and a fault distance of more than 500m. | the left line of D2K107+271~301, the right line YD2K107+289~320 | 35°                            |
| Qianfo Mountain 1# fault                   | It is a branch fault of the Qianfo mountain fault, the fault occurrence is N77°E/70°NW, with strike-slip properties, and the fault distance is more than 500m. The north west plate is the Sinian-Cambrian strata, the south east plate is the Cambrian-Silurian strata. The stratum has a broken bandwidth of 100~130m. | the left line D2K105+066~170, the right line YD2K105+127~188 | 64°                            |

Comprehensive analysis

The Yuelongmen Tunnel passes through the Cambrian, Sinian and Silurian, of which the Cambrian and Sinian are the II sulfur-bearing strata, and the Silurian is the III sulfur-bearing strata. According to the analysis of Table 5, the hydrogen sulfide concentration that can be produced under the combined action of the above three sulfur-bearing formations can reach up to 198~502ppm. At this time, it is in a highly dangerous area where the concentration of hydrogen sulfide will do harm to the construction personnel, which will have a great impact on the construction personnel and the tunnel project.

The Yuelongmen Tunnel is located in a regional fold-faulted structural belt which is more complicated. The active structural belt affects the upward migration of sulfur-containing gas generated from the sulfur-bearing formation. The Yuelongmen Tunnel is deeply buried, with a maximum buried depth of about 1445.5m. Combined with the hydrogen sulfide concentration, geological structure and tunnel buried depth that can be produced by sulfur-bearing formations, it is comprehensively analyzed that the yuelongmen tunnel is extremely vulnerable to the harm of hydrogen sulfide gas in the construction process. Among them, after hydrogen sulfide gas drifts upward and dissolves in groundwater, the concentration of hydrogen sulfide gas may be lower in the tunnel, while the...
concentration of gas in groundwater is higher, but in general, the concentration of hydrogen sulfide can be as high as 198 ppm, which requires attention and timely treatment.

5.3. Sulfur gas detection in tunnel site area

On January 16, 2015, hydrogen sulfide gas was found in the HD3K0+217 section of No. 3 horizontal tunnel of the Yuelongmen Tunnel, with a concentration of 1~97.3 ppm, and a maximum concentration of 120~378 ppm at the water outfall. On February 3, 2015, the Construction Sifang conducted on-site verification of the hydrogen sulfide gas overflow from the inclined well 2 and the horizontal tunnel 3 of Yuelongmen, and the concentrations were 0.7~14.6 ppm and 1~91.4 ppm respectively.

The on-site test results are basically consistent with the results of sulfur-bearing formation analysis.

6. Conclusion

The sulfur-bearing strata in the Sichuan Basin are mainly the Middle Triassic Leikoupo Formation, the Lower Triassic Jialingjiang Formation and Feixianguan Formation, the Permian Longtan Formation, the Carboniferous Huanglong Formation, Silurian, Cambrian, and Sinian. Among them, the distribution of sulfur-bearing formations is characterized by "more in Northeast and less in Southwest". Geological tectonic activities have a certain effect on the generation, migration, storage and sealing of harmful gases, and the influence of fault activities is more obvious. The influence of geological structure on sulfur-containing gas is mainly manifested in three aspects: generation, migration, and storage.

Based on influence of sulfur-bearing strata distribution on tunnel damage, the sulfur-bearing strata in the Sichuan Basin can be divided into four grades: I (extremely dangerous), II (High-risk), III (medium-risk), and IV (low-risk). Among them, the Carboniferous Huanglong Formation can be divided into Grade IV sulfur-bearing formations, the Middle Triassic Leikoupo Formation, the Lower Triassic Jialingjiang Formation, the Lower Triassic Feixianguan Formation, the Permian Longtan Formation, and the Silurian Formation can be divided into Grade III sulfur-bearing formations. The Cambrian and Sinian strata can be divided into Grade II sulfur-bearing strata.

Applying the above classification results to the Yuelongmen Tunnel of the Chenglao Railway, the analysis shows that the Yuelongmen Tunnel passes through the Cambrian, Sinian and Silurian, of which the Cambrian and Sinian are the II sulfur-bearing strata, and the Silurian is the III sulfur-bearing strata. It is deeply buried and located in a regional fold-faulted structural belt which is more complicated, hydrogen sulfide generated by sulfur-bearing strata will flow upward in the structural zone, which will have a great impact on tunnel construction and construction personnel. The on-site hydrogen sulfide detection results of the Yuelongmen Tunnel are basically consistent with the application analysis results of sulfur-bearing formations.

Acknowledgements

The scientific research project is co-funded by "Study on Harmful Gases in Sichuan-Tibet Railway Plate Collision Orogenic Belt (Section 2019-097)" which organized by China Railway Second Academy Engineering Group Co., Ltd. and the Applied Basic Research Project of Sichuan Provincial Department of Science and Technology named "Toxic and Harmful Gases in Tunnels in Metamorphic Rock Areas in Western Sichuan Plateau Research on Cause Mechanism and Evaluation Model (19YYJC1060)". We thank them for sharing information and providing technical support.

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