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Research on the escape mechanism and influencing factors of harmful gas induced by blasting excavation in deep rock tunnel

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Abstract: The escape of toxic and harmful gases is a common disaster effect in tunnel engineering. Frequent drilling and blasting excavation disturbances under high in-situ stress environment will inevitably lead to cumulative damage effect on surrounding rock, which will increase the risk of toxic and harmful gas escape, and seriously endanger construction safety. In this paper, based on real-time monitoring data of harmful gases during blasting and excavation of Yuelongmen Tunnel on Chengdu-Lanzhou Railway, this study summarized laws and distribution characteristics of harmful gas escape intensified by the blasting excavation, and the effectiveness of shotcreting and grouting for water blocking to inhibit gas escape is verified. Then, taking water-containing and gas-containing voids as carriers, considering the influence of different in-situ stress, explosion load and void parameters (including void pressure, void diameter and distance between void and tunnel), to carry out research on the escape mechanism of water-soluble (H₂S) and insoluble (CH₄) toxic and harmful gases under the coupling effect of stress-seepage-damage. The relationship between the amount of harmful gas escaped and the damage degree of the surrounding rock of the tunnel is analyzed, and the functional relationship between it and the in-situ stress, explosion load and cave parameters is established. The results further demonstrate that the amount of escaped harmful gases, such as methane and H₂S is closely related to lithology of surrounding rock, occurrence conditions of the deep rock mass, development degree of structural fractures and void parameters. The damage of surrounding rock caused by dynamic disturbance during blasting excavation is the main reason of aggravating harmful gas escape. The research results can provide a theoretical reference for preventing harmful gas from escaping in the similar engineering construction.

Keywords: Tunnel blasting excavation; Multi-field coupling effect; Toxic and harmful gas;

39 Escape mechanism; Surrounding rock damage

40 **Introduction**

41 With the continuous laying of the railway network in China to the southwest, tunnels have
42 become key projects in the railway network in the southwest region due to restrictions of
43 geographical conditions, such as mountains and hills in the region. Drilling and blasting method is
44 the main method for the construction of tunnels in deep rock mass because of its simple
45 construction process, high efficiency and economic efficiency (Hong et al., 2017; Zhang et al.,
46 2020b; Huang et al., 2019). However, while breaking rock mass, this method produces strong
47 dynamic disturbance to retaining rock mass, so that joints and fractures in surrounding rock
48 propagate and coalesce, which aggravates damages to, and raises permeability coefficient of,
49 surrounding rock. In addition, the influences that cumulative damage effects of dynamic
50 disturbance caused by frequent blasting excavation on surrounding rock of tunnels accelerate
51 harmful gas escape also cannot be ignored. After blasting for many times, a lot of toxic and
52 harmful gases, such as methane and H₂S are often contained in the air of tunnels, and they are
53 likely to accumulate in the unsupported parts, causing major safety accidents and harming
54 operators and environment to different degrees (Abdollahisharif et al., 2016; Paoia et al., 2020;
55 Marcia et al., 2007; Yan et al., 2020a). In tunnel construction, it is particularly important to
56 prevent outburst of harmful gases, like methane and H₂S, and a lot of related accidents have been
57 reported all over the world (Gao et al., 2020; Wang et al., 2018a; Zhang et al., 2018c). Therefore,
58 from the perspectives of ensuring safety of construction personnel and protecting the environment,
59 ensuring air quality in cavities has become a prerequisite for environmental-friendly and safe
60 tunnel construction.

61 In recent years, researchers at home and abroad mainly focus on the occurrence and
62 migration mechanism of toxic and harmful gases in deep rock mass. Among them, Creedy et al.
63 (1988) and Pan et al. (2014) have shown that the occurrence and migration mechanism of gas and
64 other harmful gases is significantly related to the geological structure; Naveen et al. (2018) found
65 that the heterogeneity of the pore surface and the irregularity of the pore matrix in the gas
66 reservoir have a greater impact on the gas adsorption capacity and migration. Shepherd et al.
67 (1981) confirmed that mining disturbance during tunnel construction will further aggravate the
68 escape of harmful gases. Therefore, the diffusion law of harmful gases after blasting in deep
69 tunnel engineering has also become the focus of research (Chang et al., 2020; Kurnia et al., 2015;
70 Cong et al., 2021). Numerous studies have shown that measures such as optimization of
71 ventilation duct arrangement (Yan et al. 2020; Luginet al. 2019; Yanget al. 2020), nitrate or alkali
72 dilution (Olga et al. 2015) and air-tight concrete plugging (Wang et al. 2013; Kang et al. 2008) can
73 effectively reduce the concentration of harmful gas in the tunnel and prevent its accumulation.
74 Similarly, some scholars have also carried out research on advanced prevention methods of
75 harmful gas, and proposed that pre-splitting blasting control (Xue et al. 2017) and drilling
76 pre-discharge (Xu et al. 2017; Lin et al. 2015; Zhang et al. 2013) can effectively reduce the risk of

harmful gas emissions during the construction process. In addition, since deep rock tunnels are significantly affected by high in-situ stress, high osmotic pressure, high temperature, etc., when studying the impact of blasting excavation on surrounding rock damage, the coupling effect of stress field and seepage field is more obvious (Zhu et al. 2019). Elsworth et al. (1986) studied the relationship between the permeability and strain of rock specimens during the deformation process in 1986, and proposed introducing damage to study the permeability problem. Based on numerical simulation and experimental research, Shao et al. (2000) and Tang et al. (2002) verified that the progressive process of material deterioration and fracture can be quantitatively analyzed by considering multi-field coupling effects such as damage and seepage. However, there are few studies on the escape mechanism of harmful gases under the coupling action of stress field, damage field and seepage field, and the damage characteristics of surrounding rock under the coupling action of multiple fields need to be further studied.

By combining with real-time monitoring data in the field of actual projects, this research summarized escape laws and distribution characteristics of harmful gas aggravated by blasting excavation. By taking water-containing voids and gas-containing voids as carriers, this study discussed influence laws of factors, such as blasting load, properties of surrounding rock and parameters of the water-containing void and gas-containing void on harmful gas escape through numerical simulation. Furthermore, the comprehensive analysis revealed mechanisms of harmful gas escape aggravated by blasting excavation of a tunnel in deep rock mass. The research results can provide a theoretical reference for preventing harmful gas from escaping in the similar engineering construction.

Engineering background

Engineering characteristics of Yuelongmen Tunnel

Yuelongmen Tunnel on Chengdu-Lanzhou Railway, located in the famous Longmenshan tectonic belt, passes through Longmen Mountains and has high construction risks. Double tracks are separately constructed along the whole line. The total lengths of the left and right tracks are 19,981 m and 20,042 m and the parallel adit is 9,679.033 m in length. The whole section is generally buried deeply and the maximum buried depth is about 1,450 m. The section with buried depth larger than 500 m accounts for 77.34% of the total length of the whole line, and that with the buried depth larger than 800 m occupies 13.17%. Surrounding rock of the whole tunnel line is dominated by carbonaceous rock and surrounding rock in grades V and IV accounts for 91% in the total length of the tunnel. Affected by the Wenchuan earthquake on May 12, 2008, the surrounding rock of the whole line had been softened. The scheme with three transverse galleries, two inclined shafts and one parallel adit was adopted in the auxiliary tunnel, as shown in Fig. 1.

Fig. 1. Construction section of Yuelongmen Tunnel.

The working area of the tunnel is rich in groundwater, mainly composed of pore phreatic water in soil layers, fracture water in bedrock and water in fault zones, so water gushing and mud bursting accidents tend to occur. The carbonaceous rock of the whole tunnel is of thin-plate structures with developed joints and fractures. During the construction, harmful gases, such as H_2S and high-content methane escaped successively, resulting in superposition of multiple extremely high safety risks. To clarify escape laws and distribution characteristics of harmful gases including H_2S and methane during blasting excavation, the concentration of harmful gas in the working area of the tunnel was monitored in real time. This was based on layout principle of the automatic monitoring system for harmful gas shown in Fig. 2. In addition, Fig. 3 demonstrates blasting excavation of the working area of the tunnel and actual situations of a tunnel face.

(a) 3# transverse gallery monitoring system.

(b) 2# inclined shaft monitoring system.

Fig. 2. Automatic monitoring system for harmful gas in tunnel working area.

Fig. 3. Tunnel face of HD3K0+148 section.

Gas escape and distribution characteristics

Monitoring data of gas concentration obtained from 3# transverse gallery at HD3K0+120 and 2# inclined shaft at XJ2K0+080 were analyzed and time-history curves thereof were drawn, as shown in Figs. 4. Geological reports point out that surrounding rock of the 3# transverse gallery is dominated by carbonaceous slates, while carbonaceous phyllite is mainly found in the 2# inclined shaft. Monitoring data illustrate that detected gas concentration is found exceeding standard or tends to increase after excavation at the tunnel face and the return airway. Because gas escape is closely related to distribution of carbonaceous slates and development degree of structural fractures, gas concentration would increase suddenly and be distributed extremely non-uniformly when a gas-containing void in structural fractures was opened by explosives. In the meanwhile, the time-history curves of gas concentration at each mileage for monitoring show characteristics, such as wave crest, slope and platform, further indicating that gas emission has a close correlation with geological conditions of surrounding rock and excavation process.

(a) 3# transverse gallery HD3K0+120 mileage.

(b) 2# inclined shaft XJ2K0+200 mileage.

Fig. 4. Time-history curve of gas concentration.

Data in Fig. 4(a) show that the maximum and minimum gas emissions separately are 3.84 and 0.42 m³/min, with an average of about 1.65 m³/min and the duration during which the concentration exceeds 1 m³/min in a single day is longer than 12 h. Data in Fig. 4(b) illustrate that the maximum and minimum gas emissions separately reach 3.28 and 0.52 m³/min, with an average of about 1.42 m³/min. The duration during which the concentration exceeds 1 m³/min in a single day is longer than 10 h. This suggests that blasting excavation significantly affects the amount of gas escaped, mainly evinced by the gas concentration rising significantly after blasting, and the concentration increases by as much as 300~400% after a single blasting and reaches the peak after 10~30 min, lasting for about 65~195 min. The gas concentration decreases for a long time, and that on some platforms is around 1.5 m³/min. It is speculated that gas emits in the process of mucking, and the amount of methane overflowing from the tunnel face and released by slag blocks decreases with the amount of

residual slag in the process of mucking and then reduces to the lowest after shotcreting as primary supports.

Escape and distribution characteristics of water-soluble H_2S

H_2S concentrations in the working areas of the 3# transverse gallery and 2# inclined shaft were monitored in real time. Fig. 5(a) shows the H_2S concentration in a single day at different mileages of the 3# transverse gallery, which is generally 1~6 ppm. The H_2S concentration from HD3K0+140 to HD3K0+260 is obviously high, where the humidity in the tunnel is about 70~76%. Field inspection shows that there is a centralized water outlet at HD3K0+148, with water discharge of about 615 m³/h, as displayed in Fig. 6. Fig. 5(b) demonstrates that the H_2S concentration in a single day at different mileages of the 2# inclined shaft is generally 1~8 ppm. Although there is no obvious water outlet from XJ2K0+50 to XJ2K0+250, the humidity in this interval is about 51~64% and the H_2S concentration is obviously higher than those at the other mileages.

(a) 3# transverse gallery.

(b) 2# inclined shaft.

Fig. 5. H_2S concentration monitoring value in a single day.

To further study changes of H_2S concentration around the centralized water outlet at HD3K0+148 of the 3# transverse gallery, field measurement illustrates that the H_2S concentration at the water outlet is up to 91.4 ppm. A group of data was read every 10 cm around and in front of the water outlet, as shown in Fig. 6. The data in the figure demonstrate that the H_2S concentration extremely obviously reduces with the increasing distance from the water outlet. To be specific, at 10cm away from the water outlet, H_2S concentration in front and below the outlet reaches about 28ppm, it decreases to 13 ppm at location 30 cm from the water outlet and 7.3 ppm at position 50 cm from the water outlet. This indicates that H_2S is controlled by geological structures and associated with groundwater, namely a positive correlation with groundwater. Excavation disturbance further aggravates the escape of H_2S from carbonaceous phyllite and groundwater.

Fig. 6. Diffusion curve of H_2S concentration near the concentrated water outlet.

It needs to further study distribution characteristics of H_2S concentration from HD3K0+068 to HD3K0+178 of the 3# transverse gallery under conditions, such as shotcreting as primary supports, grouting sealing and general ventilation. For this purpose, starting from HD3K0+178 in the excavating face, a group of H_2S concentrations was read along the left and right side walls of the tunnel at an interval of 30 m and a curve was drawn in Fig. 7. Data in the figure demonstrate that the H_2S concentration outwards the transverse gallery gradually rises, indicating that cumulative damage effects of dynamic disturbance induced by frequent blasting excavation on surrounding rock of the tunnel can aggravate harmful gas escape, such as H_2S . A centralized water outlet is observed at location about 30 m from the tunnel face, where the H_2S concentration increases significantly, but it is much smaller than that without shotcreting as primary supports and grouting for water sealing. This implies that shotcreting as primary supports and grouting sealing can effectively reduce the amount of H_2S escaped.

Fig. 7. H₂S concentration distribution curve after preliminary spraying concrete support.

Analysis of harmful gas escape mechanism and influencing factors

Multi-field coupling numerical model and its validity verification

(1) Coupling numerical model of stress, seepage and damage fields

COMSOL Multiphysics is a finite element numerical simulation software for multi-physics coupling based on the method of solving partial differential equations or equations. Based on COMSOL Multiphysics, mechanisms of harmful gas escape in the process of blasting excavation of the tunnel were simulated and analyzed. The following assumptions are made: the process of gas migration is isothermal and only single-phase gas is present in rock mass. The gas permeability is isotropic and gas whose viscosity coefficient is a constant is contained in rock mass. By simplifying the tunnel and cavity into circles, a three-dimensional model with dimensions of 100 m × 100 m × 100 m was built in Fig. 8. The diameters of the cavity and tunnel are 5 m and 5 m, respectively and the net distance from the cavity to the tunnel is 15 m.

Fig. 8. Three-dimensional numerical model.

In-situ stress boundary conditions are applied at the top, front and left boundaries of the model, and roller support constraints are applied on the right, rear and bottom boundaries. At

present, trigonometric function and double exponential function are mainly used for time history relation of load change in borehole. However, the determination of coefficient of double exponential function depends on field test data very much, which has great limitation and randomness in practical application (Lu et al. 2012). In this paper, Based on Hoek–Brown strength criterion, the function curve of triangle blasting load in Fig. 9 was selected for calculating blasting. The total duration of action is 17 ms, including an ascending phase of 2.3 ms and a descending phase of 14.7 ms, and the peak stress under blasting load is 50 MPa (Lu et al. 2012).

Fig. 9. Time-history curve of equivalent blast loading.

A laboratory test was carried out by sampling in the field. Based on this, the initial physical and mechanical parameters of surrounding rock mass of the tunnel with a gas-containing void and water-containing void were obtained, as listed in Table 1.

Table 1 Initial physical and mechanical parameters of cavity rock mass.

	Young's modulus (GPa)	Poisson's ratio	Density of rock (km/m ³)	Porosity
Gas-containing void	50	0.21	2700	0.05
	Hydraulic conductivity (m/s)	Fluid density (km/m ³)	Compressibility of fluid	Dynamic viscosity
	4.2e-11	0.77	1e-5	1.84e-5
	Young's modulus (GPa)	Poisson's ratio	Density of rock (km/m ³)	Porosity
Water-containing void	50	0.21	2700	0.05
	Hydraulic conductivity (m/s)	Fluid density (km/m ³)	Compressibility of fluid	Dynamic viscosity
	1e-9	1000	4.7e-10	1e-3

In analysis of the multi-field coupling model, the governing equation for the deformation field of rock mass is a mechanical equilibrium equation considering pore pressure, which is solved based on the built-in application mode of static plane strain of COMSOL Multiphysics. In analysis of the multi-field coupling model, the governing equation for the deformation field of rock mass is a mechanical equilibrium equation considering pore

pressure, which is solved based on the built-in application mode of static plane strain of COMSOL Multiphysics. The governing equation for the seepage field is a highly nonlinear equation, which is solved by the partial differential equation (PDE) (Qu et al. 2020). The module of Darcy's law is selected as seepage conditions and there are no flow boundaries around it. An appropriate cavity pressure is selected according to the occurrence state. When simulating the influence of the excavation of a gas-containing void, the seepage conditions are removed, and only the stress field and damage field are analyzed.

(2) Validation of numerical model

Under *in-situ* stress of 50 MPa, Fig. 10 shows the distribution of Darcy velocity of surrounding rock around the tunnel face and the water-containing void in the tunnel under the combined action of *in-situ* stress and blasting load. It can be observed from the figure that Darcy velocity is larger in the area with a close distance between the tunnel and the water-containing void and is distributed symmetrically along the connecting line between centers of circles of the tunnel and the water-containing void. Darcy velocity is redistributed under dynamic disturbance.

Fig. 10. Darcy velocity of the surrounding rock.

Under *in-situ* stress of 50 MPa, damage distribution on three sections of surrounding rock of the tunnel under the combined action of *in-situ* stress and blasting load is shown in Fig. 11. It can be seen from the figure that under the coupled action of *in-situ* stress, seepage and blasting load, the damage degree and extent of surrounding rock on the left side of the tunnel are the largest, followed by the right side, while those at the top are the smallest.

Fig. 11. Damage distribution of surrounding rock in tunnel.

Based on numerical simulation and field measurement, the average damage depth of rock mass is obtained, as demonstrated in Fig. 12 and damage extents on vault, floor and both side walls are different. Due to cumulative damage effects of multiple repeated blasting on surrounding rock in practical engineering, the damage extent in the field test is larger than that in numerical calculation. Excluding this difference, the field measurement results are in good agreement with the numerical calculation results, which further verifies the correctness of the model calculation.

Fig. 12. Comparison of on-site measurement and simulation results.

Escape mechanism of harmful gas under blasting load

(1) Effect of the blasting load on the seepage and damage field in surrounding rock of the tunnel with the water-containing void

Fig. 13. Darcy velocity distribution of tunnel under different blast loads

Under the combined action of blasting load and *in-situ* stress, Fig. 13 shows changes of Darcy velocity around the tunnel and the water-containing void with the blasting load. When the blasting load is 0 MPa, peak Darcy velocity is the minimum, which is concentrated near

the water-containing void, and points to the void. With the increase of the blasting load, the peak Darcy velocity around the tunnel and the water-containing void rises. Furthermore, Darcy velocity around the water-containing void increases more obviously and it points to the tunnel.

Figure 14 illustrates distribution of damages of different blasting loads to surrounding rock under *in-situ* stress. As the blasting load is 0 MPa, the damage degree changes slightly and the damage zone is concentrated in the vicinity of the connecting line between centers of circles of the void and the tunnel. With the rise of the blasting load, the damage zone is concentrated in the zone outside of the connecting line, showing obvious changes in location. The damage degree of surrounding rock of the tunnel is positively correlated with the blasting load and changes the permeability coefficient of surrounding rock, thus affecting the water inflow into the tunnel.

Fig. 14. Damage distribution of tunnel surrounding rock under different blast loads.

Figure 15 illustrates the water inflow into the tunnel under different blasting loads under *in-situ* stress. By fitting, the curve for the relationship between the water inflow into the tunnel and the blasting load was obtained. It can be observed from the figure that when *in-situ* stress and parameters of the water-containing void remain unchanged, with the increase of the blasting load, the water inflow exponentially rises, while the increase rate gradually reduces. When the blasting load increases from 0 to 100 MPa, the water inflow rises by about $3.8 \text{ m}^3/\text{d}$. After the blasting load exceeds 25 MPa, the water inflow is almost no longer affected by the blasting load. The reason why water is able to dissolve gas is that there are cavities between water molecules in water phases. When gas enters the cavities, it will release the heat of dissolution. When the kinetic energy of gas molecules dissolved in the cavities in water phases is enough to overcome van der Waals potential energy, gas will turn back to the gas phase. Relevant studies reveal that the solubility of H_2S in water is related to factors, like temperature and pressure (Roberto et al. 2008; Vorholz et al. 2008). In the meanwhile, sulfide in water is mainly produced

by decomposition of sulfur-containing organic matters and reduction of sulfate by bacteria in the presence of ozone, and the latter plays the dominated role. Finally, H₂S gas escapes from water and is dispersed in the air.

Fig. 15. Influence of blast loading on water inflow in tunnel.

(2) Effect of the blasting load on the damage field in surrounding rock of the tunnel with the gas-containing void

Figure 16 displays distribution of damages of different blasting loads to surrounding rock of the tunnel under *in-situ* stress. When the blasting load is 0 MPa, the damage degree changes slightly and a damage zone is concentrated near the connecting line between centers of circles of the gas-containing void and the tunnel. With the increase of the blasting load, the damage zone is concentrated in the zone outside this connecting line, showing an obvious change in location. The damage degree of the tunnel is positively correlated with the blasting load and changes the permeability coefficient of surrounding rock around the tunnel, thus influencing the gas inflow into the tunnel.

Fig. 16. Damage distribution of tunnel surrounding rock under different blast loads.

Figure 17 demonstrates the gas inflow into the tunnel under different blasting loads under *in-situ* stress. Through fitting, the curve for the relationship between the gas inflow into the tunnel from the gas-containing void and the blasting load was obtained. It can be seen from the figure that when the *in-situ* stress and parameters of the gas-containing void are constant, the gas inflow into the tunnel from the gas-containing void exponentially increases with the blasting load and the increase rate gradually decreases. As the blasting load rises from 0 to 100 MPa, the gas inflow increases by 7.02 m³/d, at the increase rate of 21.6%.

Fig. 17. Influence of blast loading on gas inflow in tunnel.

Analysis of influencing factors of water-soluble gas escape

(1) Impact of properties of surrounding rock on the water inflow into the tunnel

Under two working conditions, namely the action of *in-situ* stress alone and combined action of *in-situ* stress and blasting load, effects of changes of factors, such as horizontal *in-situ* stress, coefficient of lateral pressure and net distance between the water-containing void and the tunnel on the water inflow were analyzed. By fitting numerical calculation results, the curves for the water inflow into the tunnel under different factors were obtained, as displayed in Fig. 18.

(a) Horizontal in-situ stress variation.

(b) Lateral pressure coefficient variation.

(c) Distance variation between water-containing void and tunnel.

Fig. 18. Influence of surrounding rock characteristics on water inflow in tunnel.

As shown in Fig. 18(a), when the *in-situ* stress acts alone, with the increase of the horizontal *in-situ* stress, the water inflow into the tunnel firstly reduces and then rises. The reason for such a phenomenon is that when the *in-situ* stress is small, the *in-situ* stress is partially offset by the pressure in the void, so the water inflow into the tunnel firstly decreases. Under the combined action of blasting load and *in-situ* stress, the water inflow into the tunnel gradually rises with the increase of the horizontal *in-situ* stress, with a small increase rate in the early stage. As demonstrated in Fig. 18(b), the water inflow into the tunnel exponentially decreases with the coefficient of lateral pressure under both of the two working conditions and the decrease rate also gradually reduces. Relatively speaking, the coefficient of lateral pressure has a small influence on the water inflow into the tunnel. As displayed in Fig. 18(c), with the increase of the net distance between the water-containing void and the tunnel, the gas inflow exponentially reduces. After the net distance rises to 15 m, the water inflow basically keeps unchanged.

(2) Effect of parameters of the water-containing void on the water inflow into the tunnel

Under the two working conditions, namely the action of *in-situ* stress alone and combined action of *in-situ* stress and blasting load, the effects of the diameter of the water-containing void and the pressure in the void on the water inflow into the tunnel were analyzed. On this basis, the curves of the water inflow into the tunnel under different factors were obtained, as shown in Fig.19.

As shown in Fig. 19(a), under the two different working conditions, the diameter of the gas-containing void exerts the basically consistent influence laws on the water inflow into the tunnel. With the increase of the diameter of the gas-containing void, gas inflow exponentially rises and the increase rate also gradually rises. It can be seen from Fig. 19(b) that under the *in-situ* stress alone, as the pressure in the void increases, the water inflow into the tunnel decreases. When the pressure in the void rises to 12 MPa, the water inflow into the tunnel reduces to the lowest and then gradually rises with the pressure in the void. Under the combined action of blasting load and *in-situ* stress, with the increase of the pressure in the

void, the water inflow into the tunnel decreases. When the pressure in the void rises to 15 MPa, the water inflow into the tunnel decreases to the lowest and then gradually increases with the pressure.

Fig. 19. Influence of water source cave parameters on tunnel water inflow.

Analysis of influencing factors of insoluble gas escape

(1) Impact of properties of surrounding rock on the gas inflow into the tunnel

By considering two different working conditions, namely the action of *in-situ* stress alone and the combined action of *in-situ* stress and blasting load, the effects of changes of factors, such as horizontal *in-situ* stress, coefficient of lateral pressure and net distance between the gas-containing void and the tunnel on the gas inflow into the tunnel were analyzed. By fitting numerical calculation results, the curves of the gas inflow into the tunnel under different factors were obtained, as shown in Fig. 20.

It can be observed from Fig. 20 that the action of *in-situ* stress alone and combined action of *in-situ* stress and blasting load do not change the shape of the curves for the relationship between the amount of escaped gas and various factors. However, more significant influence laws are shown under the combined action. Fig. 20(a) demonstrates that the gas emission from the gas-containing void linearly rises with the horizontal *in-situ* stress at the same increase rate under the two working conditions. Fig. 20(b) illustrates that the gas emission from the gas-containing void exponentially decreases with the coefficient of lateral pressure under the two working conditions and the exponential coefficient of the function does not change. As shown in Fig. 20(c), with the increase of the net distance between the gas-containing void and the tunnel, the gas emission from the gas-containing void exponentially reduces under the two working conditions. After the net distance reaches 15 m, the gas emission basically remains unchanged.

(a) Horizontal crustal stress variation.

(b) Lateral pressure coefficient variation.

(c) Distance variation between gas-containing void and tunnel.

Fig. 20. Influence of surrounding rock characteristics on gas inflow in tunnel.

(2) Effect of parameters of the gas-containing void on the gas inflow into the tunnel

Influences of the diameter of the gas-containing void and pressure in the void on the amount of gas escaped from the void were analyzed under the action of *in-situ* stress alone and combined action of *in-situ* stress and blasting load. On this basis, the curves for the gas inflow into the tunnel under different factors were obtained, as displayed in Fig. 21.

(a) Gas-containing void diameter variation.

(b) Gas-containing void pressure variation.

Fig. 21. Influence of gas-containing void parameters on tunnel gas inflow.

As displayed in Fig. 21(a), under the two working conditions, the diameter of the gas-containing void has the consistent influence laws on the amount of escaped gas, namely the amount of escaped gas exponentially rises with the diameter, and the increase rate gradually rises. The reason for such a phenomenon is that with the increase of the diameter of the void, its edge is closer to the position of blasting excavation of the tunnel, while the explosion-induced stress wave attenuates very significantly in the early stage, so the influence is greater. It can be observed from Fig. 21(b) that with the increase of the pressure in the gas-containing void, the gas inflow linearly changes with a small amplitude. However, under the two working conditions, the influence trends are contrary. Under the action of *in-situ* stress alone, the gas inflow into the tunnel decreases with the increase of the pressure in the gas-containing void; on the contrary, the gas inflow into the tunnel rises with the increase of the pressure in the void under the combined action of blasting load and *in-situ* stress.

Conclusions

In this paper, based on real-time monitoring data of harmful gases during blasting and excavation of Yuelongmen Tunnel on Chengdu-Lanzhou Railway, this study summarized laws and distribution characteristics of harmful gas escape intensified by the blasting excavation. By taking the water-containing void and gas-containing void as carriers, considering the influence of different *in-situ* stress, explosion load and void parameters, to carry out research on the escape mechanism of water-soluble (H_2S) and insoluble (CH_4) toxic and harmful gases under the coupling effect of stress-seepage-damage. The conclusions are made as follows:

(1) The amount of escaped harmful gases, such as methane and H_2S is closely correlated with lithology of surrounding rock, occurrence conditions of the deep rock mass, development degree of structural fractures and void parameters. The damage of surrounding rock caused by dynamic disturbance during blasting excavation is the main reason of aggravating harmful gas and groundwater escape. H_2S dissolved in water can turn back to the gas phase and be dispersed in the air when the atmospheric pressure changes. Methods such as fine blasting to control surrounding rock damage and to drain the gas-liquid mixture in the cave in advance can effectively reduce the risk of harmful gases during tunnel construction.

(2) The water inflow and gas inflow into the tunnel both exponentially increase with the blasting load. The gas inflow into the tunnel from the gas-containing void constantly, slowly rises with the increase of the blasting load. Owing to the tunnel with the water-containing void in the surrounding rock is subjected to the multi-field coupled action of stress, seepage and damage fields, the change trend is different. After the blasting load exceeds 25 MPa, the water inflow in the tunnel with the water-containing void in the surrounding rock is basically not affected by the increase of the blasting load.

(3) When the diameters of the water-containing void and gas-containing void increase, the gas inflow and water inflow into the tunnel both exponentially rise. The net distance of 15

m from the water-containing void and gas-containing void to the tunnel is considered as the critical distance of influence. The coefficient of lateral pressure has basically same influence laws on the water inflow and gas inflow into the tunnel. The gas inflow into the tunnel linearly changes with the pressure in the gas-containing void, but the overall change is slight. With the increasing pressure in the water-containing void, the water inflow into the tunnel firstly reduces and then rises.

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