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RESEARCH

Mechanism of the delayed coal–gas outburst caused by creep instability of the ''barrier layer and tectonic coal'' combination

Lehua Xu · Haina Jiang · Hao Zhang

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Abstract A delayed coal–gas outburst incident often represents a more severe threat to health and safety of mine personnel than an instantaneous coal–gas outburst incident. For a better understanding of mechanism of the delayed coal–gas outburst, structure of "barrier layer and tectonic coal" combination in the delayed coal–gas outburst is firstly introduced in this paper. Based on, the delayed coal–gas outburst under different conditions of mining depth and thickness of the barrier layer are numerically simulated. Results indicate that the barrier layer enters the tertiary creep stage in a shorter time as mining depth increases and as thickness of the barrier layer decreases. Then we analyze effect of dynamic disturbance on the delayed coal–gas outburst. Our enquires reveal that 92.31% of the delayed coal–gas outburst incidents in China from 2011 to 2020 were affected by dynamic disturbance within 10 days before their occurrence. It is also proved that presence of dynamic disturbance makes coal–gas outburst occur in advance. Finally, the creep instability model of the "barrier layer and tectonic coal'' combination under dynamic disturbance is proposed, which reflects the comprehensive effect of four main factors: the ''barrier layer and tectonic coal'' combination structure, gas pressure, in-situ stress, and dynamic disturbance on the delayed coal–gas outburst, and thus can be useful for its prevention and control.

L. Xu
Key Laboratory of In-Situ Property-Improving Mining of Ministry of Education, Taiyuan University of Technology, Taiyuan 030024, China

H. Jiang (✉) · H. Zhang
College of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China
e-mail: jianghaina@tyut.edu.cn

Article highlights

- The delayed coal–gas outburst is caused by creep instability of the barrier layer followed by sudden exposure of the tectonic coal.
- Most of the delayed coal–gas outburst incidents were affected by dynamic disturbance.
- The creep instability model of the "barrier layer and tectonic coal'' combination under dynamic disturbance is used to explain the mechanism of the delayed coal–gas outburst.

Keywords Coal–gas outburst · Creep instability · Tectonic coal · Barrier layer · Dynamic disturbance

1 Introduction

Coal–gas outburst is one of the most serious disasters in underground coal mining (Wang et al. 2020). Nearly one-third of all coal–gas outburst incidents take place in China (Skoczylas 2012). Coal–gas outburst incidents also occurs in other coal-producing countries such as Australia (Black 2019), Turkey (Fisne and Esen 2014), Poland (Skoczylas et al. 2014), and Spain (Toraño et al. 2012).

The total coal–gas outburst incidents can be classified into two types. One type, namely the instantaneous coal–gas outburst, happens at the same time of blasting or coal cutting. The other type, namely the delayed coal–gas outburst, happens at the time of implementing of auxiliary operations after the blasting or coal cutting, including drilling, pneumatic picking or hand picking, roof supporting, coal shoveling. The delay time mostly ranges from a few seconds to several minutes (Lama and Bodziony 1998). It may be even longer, as an example of 6 h and 57 min in the delayed coal–gas outburst of Wenjiaba #2 mine, Guizhou province, China. This outburst incident occurred at 21:21 of March 7, 2017 when the mine personnel were shoveling coal at the coal face which was formed by blasting at 14:24 of March 7, 2017.

The delayed coal–gas outburst often represents a more severe threat to health and safety of the mine personnel than the instantaneous coal–gas outburst. When an instantaneous outburst incident occurs, the mine personnel may not be injured because most of them are implementing blasting or waiting for implementing the auxiliary operations at one place far away from the coal face and even under some special safety precautions. But in a delayed coal–gas outburst incident, usually there are heavy casualties at the outburst site because when it happens the mine personnel are probably conducting roof support, drilling borehole, or shoveling coal or rock near the coal face, and thus don't have enough time to escape.

For better prevention and control of the delayed coal–gas outburst, many researchers dedicated to the study of its occurrence mechanism. Jiang and Guo (1999) investigated mechanism of the delayed coal–gas outburst based on "spherical shell losing stability" hypothesis and physically conducted two delayed coal–gas outburst experiments with delay times of 1.5 s and 4.6 s by pouring a 12 mm thick concrete outside of a briquette coal in laboratory. Yin et al. (2010) carried out nine delayed coal–gas outburst experiments with delay times ranging from 28.4 to 62.0 s by encasing a briquette coal with a composite made of coal powder, gypsum, and water in a certain proportion. Lu and Zhao (2016) analyzed effect of creep properties of coal and the adjacent mudstone on occurrence of the delayed coal–gas outburst. Xu and Jiang (2020) proposed a new combination model for the delayed coal–gas outburst phenomenon and adopt it to investigate the delayed coal–gas outburst incidents which occurred in China from 2006 to 2016. Cao et al. (2020) suggested that occurrence of the delayed coal–gas outburst, especially after sudden exposure of a coal seam or after blasting disturbance, might be related to gas desorption behavior.

Although researches on mechanism of the delayed coal–gas outburst are being updated, they are very limited until now. Most of current studies focus on the instantaneous coal–gas outburst, but mechanism of the delayed type is not very well explained (Chen 2011; Ding and Yue 2022; Guan et al. 2009; Guo et al. 2018; Ma et al. 2020; Pan et al. 2020; Xu and Jiang 2017; Zheng et al. 2022). Moreover, proportion of the more dangerous delayed type to the total is increasing in recent years. Chen et al. (2018) pointed out that from 2005 to 2014, 18.04% of the total outburst incidents of No. B-1 coal seam, Henan province, China, were the delayed type associated with roof supporting, coal shoveling and other auxiliary operations. Xu and Jiang (2020) found that probability of occurrence for the delayed coal–gas outburst was 17.8% from 2006 to 2016 in China. Therefore, further study on mechanism of the delayed coal–gas outburst is needed.

In this paper, structure of "barrier layer and tectonic coal" combination in the delayed coal–gas outburst is firstly introduced. Then, law of occurrence of the delayed coal–gas outburst under different conditions of mining depth and thickness of the barrier layer is numerically studied, and effect of dynamic disturbance on the delayed coal–gas outburst is discussed. Finally, mechanism of the delayed coal–gas outburst is explained by proposing creep instability model of the ''barrier layer and tectonic coal'' combination under dynamic disturbance.

2 Structure of ''barrier layer and tectonic coal'' combination in the delayed coal–gas outburst

Based on previous studies (Cheng and Pan 2020; Tu et al. 2019; Zhang et al. 2020), it is known that tectonic coal plays a crucial role in coal–gas outburst. Occurrence of the delayed coal–gas outburst attributes to delayed exposure of the tectonic coal, and its underlying cause is creep failure of the barrier layer between the tectonic coal and the mining space. In other words, the delayed coal–gas outburst is caused by creep instability of the barrier layer followed by sudden exposure of the tectonic coal. A schematic for the structure of ''barrier layer and tectonic coal'' combination in the delayed coal–gas outburst is shown in Fig. 1, in which a working face is advancing from right to left, "A" is position of the working face before one advancing footage, "B" is the position after this footage, and "C" is the interface between the tectonic coal and the barrier layer.

Thus, to distinguish between an instantaneous coal–gas outburst incident and a delayed coal–gas outburst incident is possible. That is, if the barrier layer from A to C as shown in Fig. 1 is removed completely and instantly by blasting or coal cutting in one advancing footage, which leads to sudden exposure of the tectonic coal, an instantaneous coal–gas outburst incident will happen. If the barrier layer is not completely removed in one advancing footage, in other words, only part of the barrier layer from position A to B as shown in Fig. 1 is removed by blasting or coal cutting, and failure of remaining of the barrier layer from position B to C is time-dependent and followed by exposure of the tectonic coal, a delayed type coal–gas outburst incident is oncoming. Accordingly,

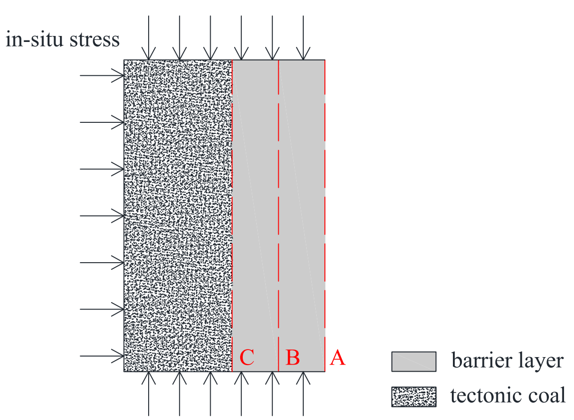

Fig. 1 A schematic for the structure of "barrier layer and tectonic coal" combination in the delayed coal–gas outburst

52 delayed coal–gas outburst incidents have been identified in all the 101 coal–gas outburst incidents from 2011 to 2020 in China. The probability of the delayed coal–gas outburst incidents is more than half, which is a significant increase compared with the statistical data given by Chen et al. (2018) and Xu and Jiang (2020). To gain a deeper understanding of mechanism of the delayed coal–gas outburst, this paper further numerically studies law of occurrence of the delayed coal–gas outburst under different conditions of mining depth and thickness of the barrier layer, and analyzes the effect of dynamic disturbance on the delayed coal–gas outburst.

3 Solid–gas coupling

3.1 Solid deformation

COMSOL Multiphysics software is adopted to numerically simulate process of the delayed coal–gas outburst in this study. The constitutive equation for solid deformation can be derived as (Zhang et al. 2008; Zhi and Elsworth 2016)

$$Gu_{i,kk} + \frac{G}{1-2v}u_{k,ki} - \alpha p_{,i} - K\varepsilon_{s,i} + f_i = 0 \tag{1}$$

where the sorption-induced strain ε_s is defined as $\varepsilon_s = \varepsilon_L p/(P_L + p)$, and ε_L is Langmuir strain constant, p is gas pressure, P_L is Langmuir pressure constant, G is shear modulus of the solid, u_i is displacement component, v is Poisson's ratio, α is Biot-Willis coefficient, K is bulk modulus of the solid, f_i is body force component, and a comma followed by an index in the subscript means partial differentiation with respect to spatial coordinate in that direction.

Creep behavior of the solid is modeled by using a nonlinear viscous-elastic–plastic rheological body as shown in Fig. 2, in which E_1 and E_2 are elastic moduli, η_1, η_2 and η_3 are viscosity coefficients, σ is in-situ stress, and σ_s is yield stress.

3.2 Gas flow

The governing equation for gas flowing through the solid can be derived as (Zhang et al. 2008; Zhi and Elsworth 2016)

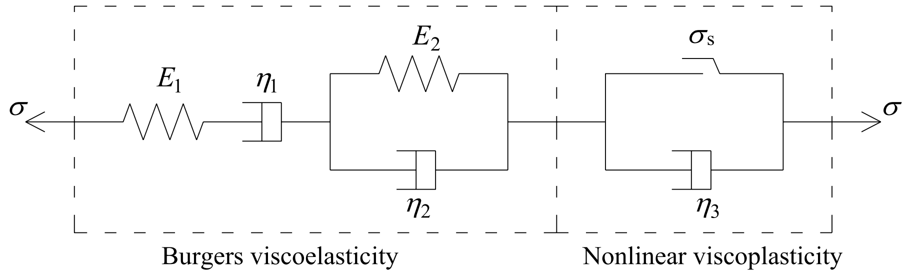

Fig. 2 Nonlinear viscous-elastic–plastic rheological body

$$\left(\phi + \frac{\rho p_a V_L P_L}{\left(p+P_L\right)^2} + \frac{p(\alpha-\phi)}{(1+S)}\left(\frac{1}{K_s} - \frac{\varepsilon_L P_L}{\left(p+P_L\right)^2}\right)\right)\frac{\partial p}{\partial t} - \nabla\cdot\left(\frac{k}{\mu}p\nabla p\right) = -\frac{(\alpha-\phi)pM_g}{(1+S)RT}\frac{\partial \varepsilon_v}{\partial t} \tag{2}$$

where

$$\begin{cases} S = \varepsilon_v + \dfrac{p}{K_s} - \varepsilon_s \\ k = k_0\left(\dfrac{\phi}{\phi_0}\right)^3 \\ \phi = \phi_0\left(1 + \dfrac{\alpha}{\phi_0}\left(\varepsilon_v + \dfrac{p-p_0}{K_s} + \dfrac{\varepsilon_L P_L\left(p_0-p\right)}{\left(p_0+P_L\right)\left(p+P_L\right)}\right)\right) \end{cases} \tag{3}$$

and ϕ is porosity, ρ is gas density, p_a is atmospheric pressure (0.101325 MPa), V_L is Langmuir volumetric constant, K_s is bulk modulus of the solid skeleton, t is time, k is permeability, μ is dynamic viscosity of the gas (1.84×10^{-5} Pa·s for methane), M_g is molar mass of the gas (0.016 kg/mol for methane), R is universal gas constant (8.314 $\mathrm{J\cdot mol^{-1}\cdot K^{-1}}$), T is absolute temperature (293.15 K), ε_v is volumetric strain, and the subscript "0" for a variable indicates its initial value. Parameters for gas flow simulation are listed in Table 1, in which h represents mining depth.

It should be noted that the volumetric strain in compressive process of the solid is negative in the numerical calculation, which means that negative porosity and permeability will be obtained by Eq. (3) when the absolute of the volumetric strain goes up to a certain value. But it is impossible in actual. Thus, porosity and permeability of the solid are presumed to keep unchanged after the porosity drops to 1/10 of its initial value and the corresponding permeability drops to 1/1000 of its initial value. But both suddenly gain big increases as the tertiary creep stage is initiated (Zhou et al. 2019).

4 Results and discussion

4.1 Law of occurrence of the delayed coal–gas outburst under different mining depths

Coal mining depth in China has reached 1500 m, as an example of 1501 m at Suncun coal mine, Xintai city, Shandong province, and the average mining

Table 1 Parameters for gas flow simulation

Parameters	Tectonic coal	Barrier layer
Initial gas pressure, p_0 (MPa)	0.6 (h=400 m) 1.0 (h=600 m) 1.4 (h=800 m)	0.101325
Initial porosity,ϕ_0	0.08	0.02
initial permeability, k_0 ($\mathrm{m^2}$)	2×10^{-16}	2×10^{-17}
Biot-Willis coefficient,α	0.9	0.8
Langmuir strain constant,ε_L	0.03	0
Langmuir volumetric constant, V_L ($\mathrm{ml\cdot g^{-1}}$)	20	0
Langmuir pressure constant, P_L (MPa)	1.0	0

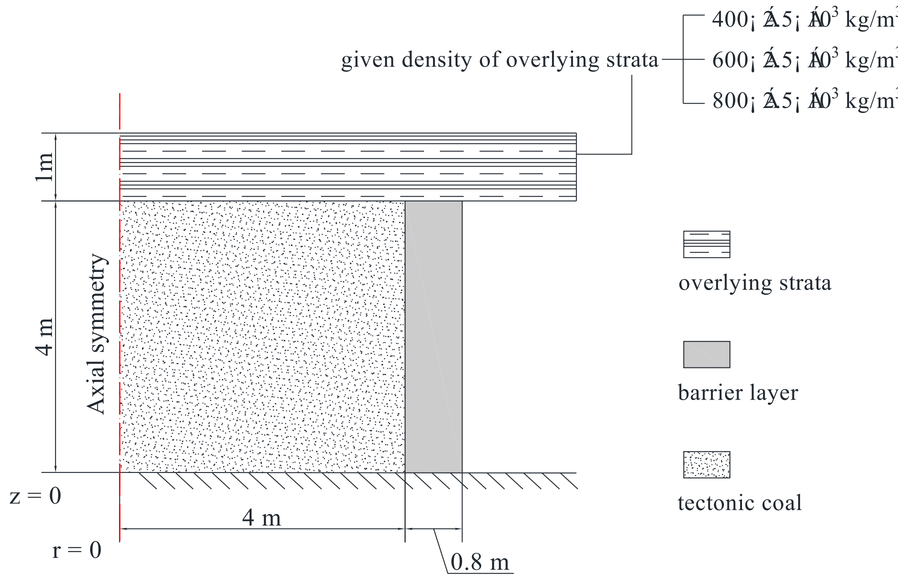

Fig. 3 The geometry diagram for the delayed coal-gas outburst under different mining depths

Table 2 Mechanical parameters for simulations

Parameters	Tectonic coal	Barrier layer	Overlying strata
Density, ρ (kg·m^{-3})	1.3×10^3	2.5×10^3	$400\times2.5\times10^3$ $600\times2.5\times10^3$ $800\times2.5\times10^3$
Young's modulus, E (GPa)	0.12	6	600
Poisson's ratio,v	0.30	0.25	0.25
Cohesion, c (MPa)	0.4	4	400
Angle of internal friction, (°)	30	35	35

depth increases at a rate of 10–25 m/year (Chen et al. 2019; Ranjith et al. 2017; Xie et al. 2019, 2021, 2022; Zhai et al. 2016). As coal mining depth increases, the coal–gas outburst disaster is becoming more serious (Kong et al. 2022; Kursunoglu and Onder 2019). The geometry diagram for the delayed coal–gas outburst under different mining depths is shown in Fig. 3.

The geometry diagram is composed of "overlying strata", "barrier layer", and "tectonic coal". Fixed constraint is used for the lower horizontal boundary. Only the right boundary is permeable. Thicknesses of the barrier layer and the tectonic coal are set to be 0.8 m and 4 m, respectively. Height of the overlying strata is set to be 1 m and density is set to be $400\times2.5\times10^3$ kg/m^3 ($600\times2.5\times10^3$ kg/m^3 or $800\times2.5\times10^3$ kg/m^3) which is 400 (600 or 800) times the general rock density of 2.5×10^3 kg/m^3. Thus, there are three simulations with mining depths of 400 m, 600 m and 800 m. Deflection of the overlying strata is ignored, and thus Young's modulus and cohesion of the overlying strata are set to be very big, which are 100 times those of the barrier layer. Mechanical parameters for simulations are listed in Table 2.

Time history of the radial strain (ε) at the observation point of ($r=4.8$ m, $z=2$ m) under different mining depths (h) is shown in Fig. 4. It can be observed in Fig. 4 that under mining depths of 400 m, 600 m and 800 m, the curves successively pass through primary, secondary, and tertiary creep stages, but the creep rates are very different. After 60 min, the radial strains are 0.0404, 0.0850 and 0.1315, respectively; while after 120 min, the radial strains are 0.0644, 0.1300 and 0.1940, respectively. If the critical failure radial strain of the barrier layer is 0.06, failure occurs after 107 min under mining depth of 400 m, and failure occurs in the primary creep stage under mining depth of 600 m or 800 m. It can be concluded that

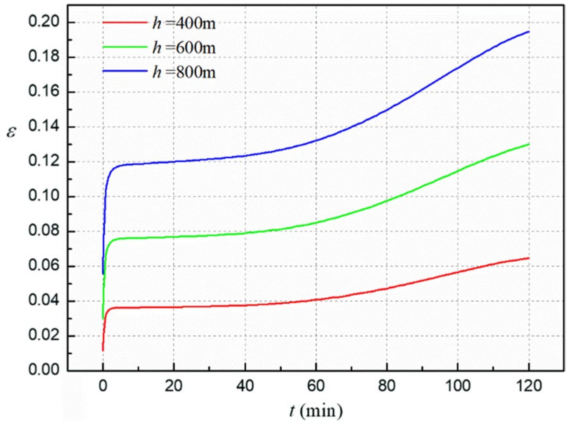

Fig. 4 Time history of the radial strain under different mining depths

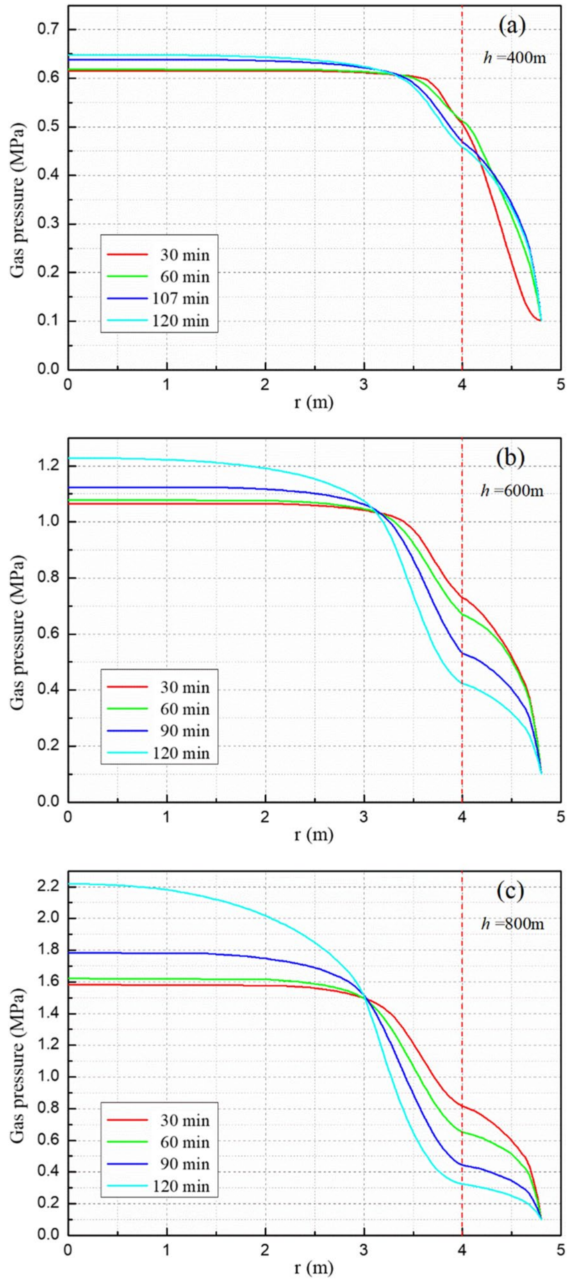

Fig. 5 Gas pressure distribution under different mining depths

the time required for the barrier layer to be destroyed is shortened as the mining depth increases. Therefore, in order to prevent occurrence of a delayed coal–gas outburst incident, roof support should be implemented at the fastest speed under large mining depth to reduce stress before the barrier layer enter the tertiary creep stage.

When the barrier layer enters the tertiary creep stage, it will be destroyed almost immediately, and consequently the tectonic coal will be revealed. At this time, an important factor determining whether a coal–gas outburst incident will happen or not is the gas pressure of coal body at the exposed coal surface (the interface between the tectonic coal and the barrier layer, $r=4$ m). Based on the numerical calculation results under mining depths of 400 m, 600 m and 800 m and barrier layer thickness of 0.8 m, gas pressure distribution of the ‘‘barrier layer and tectonic coal’’ combination at different times can be obtained. For observation convenience, gas pressure data at 30 min, 60 min, 90 min and 120 min are selected for analysis as shown in Fig. 5, in which “90 min” is replaced with “107 min” under mining depth of 400 m, in order to analyze gas pressure distribution at the time of barrier layer’s failure.

It can be observed in Fig. 5 that gas pressure of the ‘‘barrier layer and tectonic coal’’ combination decreases with the increase of r value at the same time. However, there is no uniform changing law of gas pressure of the tectonic coal at the same location as time increases. When mining depth is 400 m, gas pressure of the tectonic coal basically does not change as time increases, except for a certain decline near the interface between the tectonic coal and the barrier layer ($r=4$ m). When the mining depth is 600 m, the tectonic coal is compressed remarkably. Gas pressure of the tectonic coal in the range of $r=0$–3.2 m has a big increase, while in the range of $r=3.2$–4 m gas pressure decreases with time because most of the gas in this range penetrates the mining space through the barrier layer. Gas pressure distribution of the tectonic coal is similar when the mining depth is 800 m.

Gas pressure distribution of the barrier layer depends on the difference in volume of gas between the gas from the tectonic coal and the gas entering the mining space. When the mining depth is 400 m, gas pressure curves of the barrier layer at the selected times of 60 min, 107 min and 120 min are similar, and have a little difference with the curve at the time of 30 min. When the mining depth is 600 m or 800 m, gas pressure at the same location of the barrier layer decreases with time because permeability of the barrier layer increases rapidly when the mining depth is large and a large amount of gas penetrates the mining space through the barrier layer. That is the main reason of a sudden increase of gas concentration at the working face within a short time before occurrence of a delayed coal–gas outburst incident (Wang et al. 2022).

In addition, we can analyze gas pressure data at the time of 107 min when considering the failure of the barrier layer under mining depth of 400 m, as shown by the blue curve in Fig. 5a. In this case, gas pressure at the interface between the tectonic coal and the barrier layer ($r = 4$ m) drops to 0.469 MPa, which is smaller than the critical outburst pressure of 0.740 MPa stated in Detailed Rules for Preventing Coal and Gas Outburst (State Administration of Coal Mine Safety 2019). But gas pressure at the location of $r = 3.5$ m rises to 0.593 MPa, becoming close to the critical outburst pressure, thus this situation still has a certain outburst risk if the tectonic coal is soft enough.

4.2 Law of occurrence of the delayed coal–gas outburst under different thicknesses of barrier layer

Thickness of the barrier layer decreases gradually during the working face's advancing. To study mechanism of the delayed coal–gas outburst during this process, we establish a geometry diagram for the delayed coal–gas outburst under different thicknesses of barrier layer as shown in Fig. 6, in which (a), (b) and (c) represent simulations under barrier layer

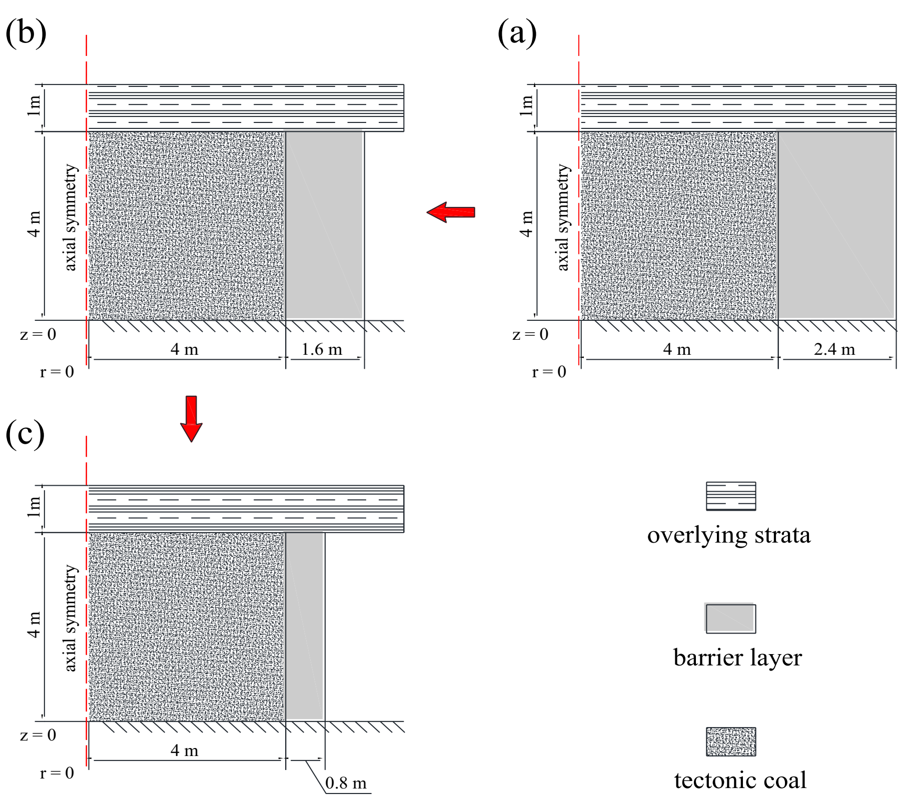

Fig. 6 Geometry diagram for the delayed coal–gas outburst under different thicknesses of barrier layer (**a**: $d = 2.4$ m; **b**: $d = 1.6$ m; **c**: $d = 0.8$ m.)

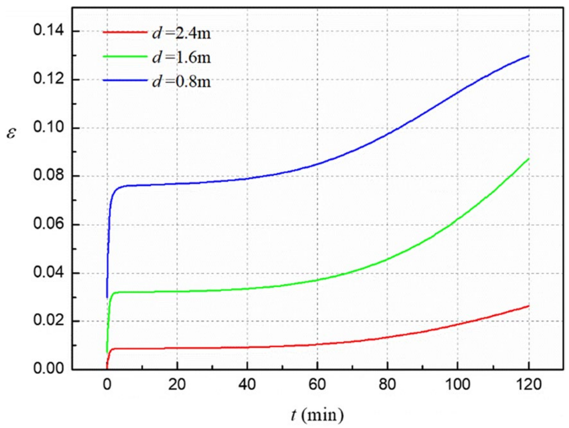

Fig. 7 Time history of the radial strain under different thicknesses of barrier layer

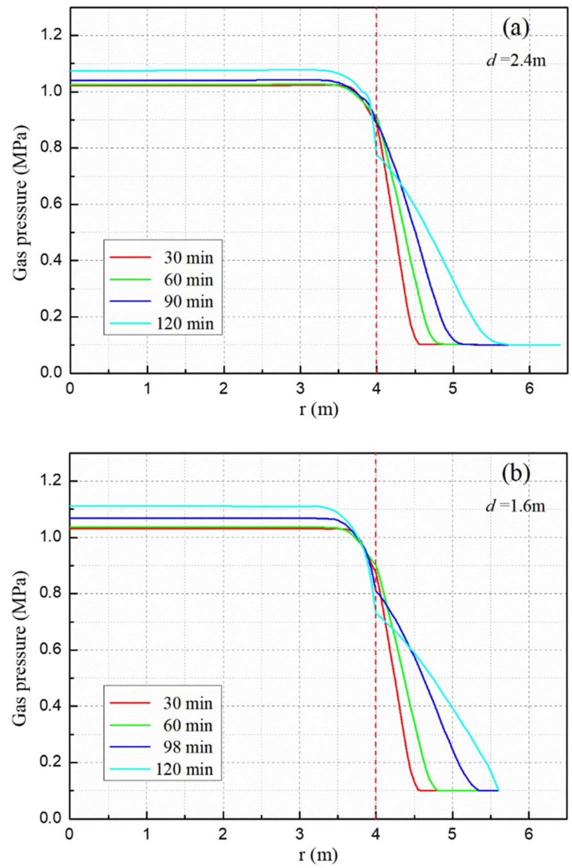

Fig. 8 Gas pressure distribution under different thicknesses of barrier layer

thicknesses of 2.4 m, 1.6 m and 0.8 m, respectively. Thickness of the overlying strata is set to be 1 m and its density is set to be $600\times2.5\times10^3$ kg/m^3, which is 600 times the general rock density of 2.5×10^3 kg/m^3. That is, the mining depth is 600 m.

Time history of the radial strain (ε) at the observation points of ($r=6.4$ m, $z=2$ m), ($r=5.6$ m, $z=2$ m) and ($r=4.8$ m, $z=2$ m) under different thicknesses of barrier layer (d) is shown in Fig. 7. It can be observed in Fig. 7 that when thicknesses of the barrier layer are 2.4 m, 1.6 m and 0.8 m, the radial strains are 0.0104, 0.0371 and 0.0850 after 60 min, respectively, and the radial strains are 0.0263, 0.0873 and 0.1298 after 120 min, respectively. If the critical failure radial strain of the barrier layer is 0.06, the failure does not occur even after 120 min under barrier layer thickness of 2.4 m. When thickness of the barrier layer is 1.6 m, the failure occurs after 98 min. When thickness of the barrier layer is 0.8 m, the barrier layer is destroyed in the primary creep stage. It can be concluded from the above that when the barrier layer thickness decreases, the time for the barrier layer entering the tertiary creep stage is shortened. Therefore, in order to prevent a delayed coal–gas outburst incident, roof support also should be implemented as fast as possible to reduce stress before the barrier layer enters the tertiary creep stage when the length of one advancing footage (the distance from position A to B as shown in Fig. 1) is long and then the thickness of the barrier layer becomes small, which is similar to the case with a large mining depth (Yang et al. 2012).

Based on the numerical calculation results under mining depth of 600 m and barrier layer thicknesses of 2.4 m, 1.6 m and 0.8 m, gas pressure distribution of the "barrier layer and tectonic coal'' combination at different times can be obtained. For observation convenience, gas pressure data at 30 min, 60 min, 90 min and 120 min are selected for analysis, as shown in Fig. 8. But when the thickness of barrier layer is 1.6 m, "90 min" is replaced with "98 min" for a better analysis of the gas pressure distribution at failure of the barrier layer. The curve under mining depth of 600 m and barrier layer thickness of 0.8 m is shown in Fig. 5b.

It can be observed in Fig. 8 that gas pressure of the "barrier layer and tectonic coal'' combination decreases with the increase of r value at the same time. However, gas pressure of the tectonic coal has no uniform changing law as time increases. When thickness of the barrier layer is 2.4 m or 1.6 m, gas pressure of the tectonic coal has a slight increase because of small volumetric strain of the tectonic coal, and has a certain decline near the interface between the tectonic coal and the barrier layer ($r = 4$ m) because some of the gas penetrates the mining space through the barrier layer. The case when thickness of the barrier layer is 0.8 m has been analyzed in Sect. 4.1.

The variation law of gas pressure of the barrier layer is complicated. When the thickness of barrier layer is 2.4 m or 1.6 m, gas pressure of the barrier layer increases with time because gas from the tectonic coal is more than that enters the mining space. When thickness of the barrier layer is 0.8 m, gas pressure of the barrier layer decreases with time because a large amount of gas penetrates the mining space.

In addition, gas pressure data at the time of 98 min are analyzed when thickness of the barrier layer is 1.6 m, as shown by the blue curve in Fig. 8b. In this case, gas pressure at the interface between the tectonic coal and the barrier layer ($r = 4$ m) drops to 0.810 MPa, which is bigger than the critical outburst pressure of 0.740 MPa, and thus a high risk of outburst exists.

4.3 Effect of dynamic disturbance on the delayed coal–gas outburst

The load in the process of creep instability of the barrier layer generally does not often keep a fixed value (Du et al. 2016; Hu et al. 2020). This is due to the ‘‘first-time” disturbance to the barrier layer produced by blasting or coal cutting during advancing of the working face, and the ‘‘second-time’’ disturbance to the barrier layer generated by operations of drilling, pneumatic picking, or hand picking near the barrier layer after the working face’s advancing has ceased. According to the accident data investigation, 48 of the total 52 delayed coal–gas outburst incidents, which occurred in China from 2011 to 2020, associated with dynamic disturbance to the barrier layer within 10 days before their occurrence, accounting for 92.31%. That is, most of the delayed coal–gas outburst incidents were affected by dynamic disturbance. Taking uncovering coal at rock roadway as an example, a schematic drawing of the two main types of dynamic disturbance during creep instability of the barrier layer is shown in Fig. 9.

Based on previous studies (Zhu et al. 2010, 2019), it is known that presence of dynamic disturbance promotes crack nucleation and induces new damages. Therefore, it can be concluded that the role of dynamic disturbance is to reduce the critical failure strain of the barrier layer. Taking the simulation result under mining depth of 600 m and barrier layer thickness of 0.8 m as an example, the times when the radial strain of the barrier layer reaches 0.04, 0.05, 0.06 and 0.07 are 0.6 min, 61 min, 83 min and 100 min, respectively. If the critical radial strain of the barrier layer’s failure separately declines from 0.07 to 0.06, 0.05 and 0.04 at different dynamic disturbance levels, coal–gas outburst will occur up to 17 min, 39 min and 94.6 min in advance, respectively. That is, the delay

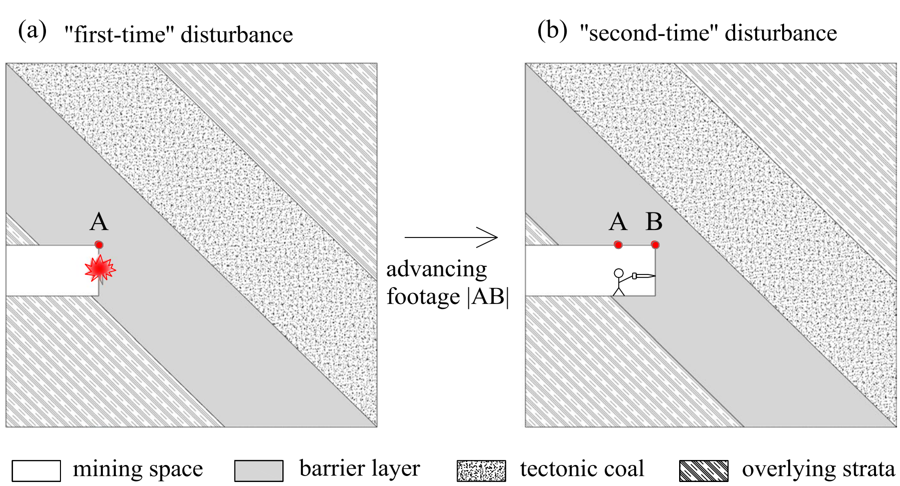

Fig. 9 Two types of dynamic disturbance during creep instability of barrier layer (taking uncovering coal at rock roadway as an example)

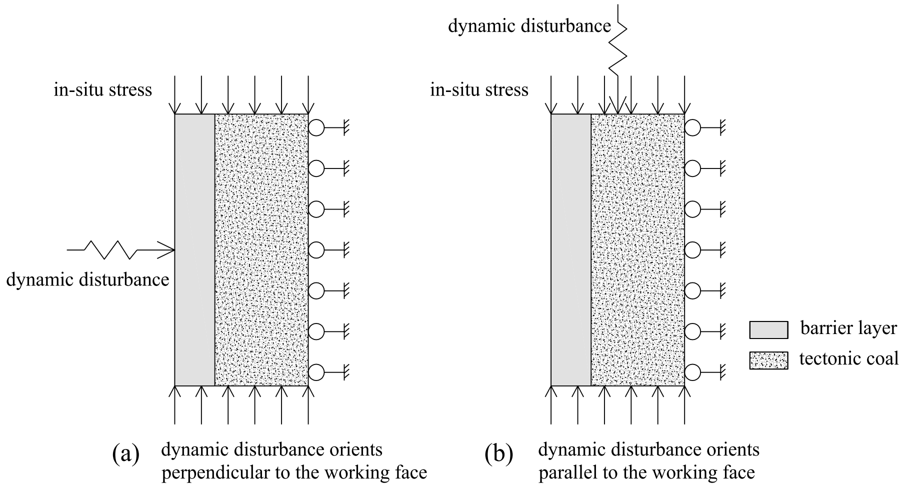

Fig. 10 The creep instability model of the ‘‘barrier layer and tectonic coal’’ combination under dynamic disturbance (the working face is advancing from left to right)

of an outburst incident is shorter at a relatively higher level of dynamic disturbance.

In summary, the delayed coal–gas outburst is caused by creep instability of the barrier layer followed by sudden exposure of the tectonic coal in the combination of ‘‘barrier layer and tectonic coal’’, and most of the delayed coal–gas outburst incidents have the effect of dynamic disturbance. From these, the creep instability model of the ‘‘barrier layer and tectonic coal’’ combination under dynamic disturbance is proposed as shown in Fig. 10, which reflects the effects of four main factors: the ‘‘barrier layer and tectonic coal’’ combination structure, gas pressure, in-situ stress, and dynamic disturbance on the delayed coal–gas outburst.

The creep instability model of the ‘‘barrier layer and tectonic coal’’ combination under dynamic disturbance is not only applicable to prevention and control of the delayed coal–gas outburst occurring in hard coal seam mining or coal roadway tunnelling with local tectonic coal developing ahead of a working face, but also applicable to prevention and control of the delayed coal–gas outburst occurring in uncovering soft coal seam at rock roadway with a rock pillar presenting ahead of the working face. Therefore, it has a broad application prospect in the field of prevention and control of the delayed coal–gas outburst, especially in the current situation of deep coal mining with increasing creep properties of coal or rock, and with various types of dynamic disturbance in underground coal mining.

5 Conclusions

This paper first introduces the ‘‘barrier layer and tectonic coal’’ combination structure in the delayed coal–gas outburst, then focuses on three aspects: variation of radial strain of the barrier layer with time under different mining depths and different thicknesses of the barrier layer, gas pressure distribution of the ‘‘barrier layer and tectonic coal’’ combination at failure of the barrier layer, and effect of dynamic disturbance on the delayed coal–gas outburst. The main conclusions are summarized as follows.

(1) If the barrier layer from A to C as shown in Fig. 1 is not removed completely in one advancing footage, in other words, only the barrier layer from position A to B as shown in Fig. 1 is removed by blasting or coal cutting, and failure of the barrier layer from position B to C is time-dependent and is followed by exposure of the tectonic coal, the oncoming outburst of coal–gas will be a delayed type.
(2) The barrier layer enters the tertiary creep stage in a shorter time as the mining depth increases and as thickness of the barrier layer decreases. The stress of the barrier layer should be reduced before the barrier layer enters the tertiary creep stage to prevent occurrence of the delayed coal–gas outburst.
(3) Delayed coal–gas outburst incidents are almost affected by dynamic disturbance. Dynamic dis-

turbance will reduce the critical failure strain of the barrier layer and result in prior exposure of the tectonic coal, and finally make coal–gas outburst occur in advance.

(4) The creep instability model of ‘‘barrier layer and tectonic coal’’ combination under dynamic disturbance reflects the comprehensive effect of the ‘‘barrier layer and tectonic coal’’ combination structure, gas pressure, in-situ stress, and dynamic disturbance on the delayed coal–gas outburst.

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Data availability The data are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Ethical approval Not applicable.

Consent to publish The authors confirms that its publication has been approved by all co-authors and its publication has been approved by the responsible authorities at the institution where the work is carried out.

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