

Low-index Catastrophe Model of Deep Gas-bearing Coal Seams

Tie Li (✉ litie@ustb.edu.cn)

Xiyu Pi

University of science and technology Beijing

Research

Keywords: Coal and gas outburst, Rock burst, Mining earthquake, Stress dike, Three-zone of gas, Low-index Catastrophe

Posted Date: July 1st, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-38979/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Coal and gas outburst always occur as some parameters reach its threshold in the mining process of gas-bearing coal seams. However, low-index catastrophes may happen in the deep mining although the parameters do not exceed its threshold values. This phenomenon has become a challenge for our traditional cognitions. In this paper, the mechanism of low-index catastrophes of high-stress area in the deep gas-bearing seams was investigated by the following methods including literature reviewing, on-site investigation, case analysis, physical experiments and theoretical analysis. The results indicate that there were not only primary state fissures but also many secondary fissures are formed after taking outburst eliminating measures, which is beneficial for improving the desorption performance of methane. A “three-zone” theory of gas migration in Coal Seams is given, coal seam in the front of coal mining face can be divided into three zones: the gas emission zone, the gas channel compaction zone, and disturbance gas desorption zone before reaching ultimate equilibrium, corresponding to coal and gas ejection zone, gas migration zone and gas launching zone after surpassing the limits. Importantly, the stress dike is redefined, and a new concept is proposed that the low-index catastrophe of gas bearing seams is caused by avalanche instability of the stress dikes, meanwhile its three modes are given by over static-load stress dike avalanche caused by hanging arch overlength, stress dike avalanche under roof breakage impact, and stress dike avalanche under floor breakage impact. In deep stress area, stress dike avalanche caused by dynamic-static loading could lead to low-index catastrophes of gas bearing seams. The insufficient residual gas energy could cause unusual gas emission. On the other hand, the sufficient gas energy may lead to coal and gas outbursts.

1. Introduction

Coal and gas outburst is one of the main engineering disasters in coal mining. Many efforts have been put on to explore the occurrence mechanism since the coal and gas outburst occurred in Issac coal mine, Luarelli coalfield, France in 1834. By now, the general mechanisms of coal and gas outburst is summed up in the following four manners: the gas leading role hypothesis, the geostress leading role hypothesis, the chemical effect hypothesis, and combination hypothesis which considered that the outburst is the result of combined effect of stress, gas and coal (An et al., 2019; Gao et al., 2019; Jin et al., 2018; Wang et al., 2018). A variety of techniques and measures were taken to forecast and prevent coal and gas outburst. Consensus technology and experience have been worked as national technical regulations and administrative rules, including Regulations of Coal Mine Gas Drainage in China, Temporary Regulation of Coal Mine Gas Extraction, Prevention and Control of Coal and Gas Outburst, and The Coal Mine Safety Rules, etc. These works have played a huge role in the safe mining of coal mines.

Generally, the coal and gas outburst only occurs when the threshold values of gas pressure, degree of metamorphism, coal hardness, and initial emission rate of methane from coal are reached. The outburst prevention measurements must be done before driving and mining the seams at the risk of outbursts. Constructions should not be allowed until the safety standard is satisfied, local outburst prevention measurements should also be continuously carried out in the process of construction. However, some

coal and gas outburst in the coal seams often occurred confusing even though the threshold values of gas pressure and content have met the requirements by taking related prevention treatments. The preonements are hereby defined as the low-index catastrophe of gas-bearing coal seams. Анершцп (1959) reported that unusual gas emission when rock bursts occurred in Rhine-westphal coal field, Germany. Although ventilation was promoted, the content of gas was still beyond 4% in the eye of wind for the first time at the day before the rock burst happened in mining at 760 m of Hausk coal mine in Bavaria. $4 \times 10^4 \text{ m}^3$ of methane gas released in 20 hours after a rock burst in mining at 950 m deep of Ruhr mining area as is reported by Bräuner (1985). He also raised the question about whether the coal was thrown out with the gas releasing or not.

Additionally, taking state-owned large coal mine with better safety and managements in China as examples, Zhang et al. (2005) reported in Beipiao earthquake disaster investigation report that unusual gas emission happened 6 times with the occurrence of 17 times rock bursts and strong mining-induced earthquakes in 1994 ~ 1995, indicating that 35.3% of associated gas events happened in this process. Zhang et al. reported that many strong mining-induced earthquakes ($M_L \geq 3.0$) occurred with unusual gas emission in deep mining of Hegang coalfield. As reported by (Li et al., 2005; Li et al., 2007) that high concentration methane gas instantaneously flowed out and explosion occurred resulting from the collision sparks, followed by the rock burst ($M_L=0.4$) at sealing fault in Longfeng coal mine of Fushun coalfield, and many coal and gas outburst caused by rock burst and strong mining-induced earthquake happened in Laohutai coal mine, the deeper the depth of mining depth, the higher frequency of the accident. China's state administration of work safety reported that in February 14, 2005, 14 minutes after a mining earthquake ($M_L=2.7$) in Sunjiawan coal mine in Fuxin, an extra serious gas explosion happened. This accident was attributed to unusual gas emission at outside of 3316 air flue caused by rock burst while methane gas accumulated and explosion limit was reached at driving face due to the lack of ventilation. Meng et al(2007) reported that coal and gas outbursts occurred twice times during mining process at JI₇₃ horizontal return airflow dip with the depth of 890-1100m in No. 12 coal mine of China pingmei shenma Group in 2007. Lin et al(2009) reported in March 19, 2006, a coal and gas dynamical disaster induced by a rock burst happened in JI₁₅-17310 transportation roadway driving in No. 1 coal mine of China pingmei shenma Group, and the similar phenomenon also occurred at 1100 m of the three-level return airflow dip. Zhang et al (2009) reported in November 12, 2007, a coal and gas outburst induced by a rock burst occurred at JI₁₅₋₁₆-24110 coal face of No. 10 coal mine of China pingmei shenma Group. Li et al(2011) reported that many unusual gas emissions caused by vibration shocks occurred at 620 m of 11011 and 12011 driving face of Xinyi coal mine of Henan Energy and Chemical Industry Group, and a coal and gas outburst induced by a rock burst occurred in August 10, 2009. Lu et al(2014) reported that gas outbursts at Junde coal mine in Hegang, China were induced by shock waves associated with rock bursts. As reported by Si et al(2015) a direct correlation can be built between microseisms and gas emission, and the methane emission rate tends to reach the maximum values as dramatically increased of microseism energy according to the field observation on Velenje coal mine in Slovenia.

For the low-index catastrophe of gas-bearing coal seams, some experts raised questions like whether these accidents were caused by the lack of outburst eliminating measurements and management, or deliberate conceal phenomenon. All these became our driving force to explore this problem in Fushun, Pingdingshan, Xinan, and Haizi coal mine. The conclusion is that low-index catastrophe of gas-bearing coal seams really exists under certain conditions.

It is strictly forbidden by laws to coal mine that the parameters of coal and methane gas can within the threshold values in Table 1. Outburst elimination measures must be carried out to make them meet the safety requirements. So academic meaning of studies on high-index catastrophe of gas bearing seams is just in regulating level. However, the low-index catastrophe should be paid with much more attention. In this essay, mechanical processes and mechanisms of low-index catastrophe of gas-bearing coal seams were investigated by fluid-solid coupling physical test experiments taking gas-containing coal as raw material. The model and mechanism of low-index catastrophe of gas bearing seams and evolution path of stress-strain-seepage field studied and concluded by following methods: gas monitoring, microtremor observation, site investigation, and theoretical analysis.

2. Fluid-solid Coupling Physical Experiments For Gas Bearing Big Coal Samples

2.1. Experimental Preparation

The JI₁₅₋₁₆ coal seam of No. 10 coal mine of Pingdingshan is subordinate to outburst gas belt. As shown in Fig. 1, Raw coal from harder layer at 1002 m was collected to study the low-index catastrophe. The raw coal was cut into cubes with a size of 150 mm × 150 mm × 150 mm by the following processes includes sawing, drilling, and grinding were used in this work, in order to meet the requirement of conventional rock mechanics experiment. Direct method techniques for gas content and pressure measurement are used in this work. The air pressure was set to be 0.4 MPa, the parameters of coal seams and experimental samples can be seen in Table 1.

Table 1
Parameters of coal seams and experimental samples

Index	The most unfavorable value of sampled seams	Risk threshold	Discrimination criteria		Inflation under constant pressure(experimental samples)
Gas content $W(m^3/t)$	25.0	≥ 8.0	/	Regional outburst risk prediction indexes(any index reached)	/
Gas pressure $P(MPa)$	2.0	≥ 0.74	outburst indexes (all indexes reached)		0.4
Initial speed of gas diffusion Δp	23.11	≥ 10	/		17.04
Firmness coefficient f	0.167	≤ 0.5	/		0.65
Destructive type of coal	□	□□□	/		□
Tensile Strength (MPa)	/	/	/	/	0.48
Natural apparent density (kg.m ⁻³)	/	/	/	/	1308

2.2. Experiment principle and instruments

The experiment targets are to study the evolution of stress, strain, acoustic emission, and seepage field, as well as the mechanism of low-index catastrophe of nitrogen bearing coal samples under loading with the gas pressure was under the threshold values decided by simulating field-condition in the driving face and middle section of mining face.

A rock mechanics servo tester (RMT-15B), an acoustic emission detection and analyzer (CDAE-1), a big coal sample bidirectional loading permeability test device developed by Henan Polytechnic University, a gas mass flow meter (DM07-11CM), a high precision pressure sensor (CY-60), and a static resistance strain indicator (YJW-8/16) were used to measure the properties of the samples. Inert N₂ instead of CH₄ was used without regard to the adsorption and desorption of coal seams.

As shown in Fig. 2, an axial stress was applied to the top of the sealed coal samples. Rigid constraints were put on three normal sides and bottom of the sealed sample. The other normal side was free of stress. N₂ was introduced into the opposite side of sample under 0.4 MPa pressure. In order to avoid coal samples from moving free at the beginning, the gas control valve was opened when the axial stress reached to 10% of the maximum value. All of data were recorded until the samples were completely destroyed. Leaking test must be done before each test.

2.3. Experimental results and conclusion

(1) First stage- Compaction of nonlinear

In the beginning non-linear stage (stage 1), the axial stress curve of the samples is concave upward. The coal samples were in fracture compaction state with a bit of slight energy acoustic emission. A nitrogen pressure of 0.4 MPa was introduced to the samples after the stress reached to 1.1 MPa, then the flow rate returned to normal after a peak. A stress drop of 0.5 MPa appeared at 1.3 MPa at feature point A, and a first maximum peak of number and energy of acoustic emission appeared along with a reduced gas flow rate. It is found that the coal sample have no changes at the open side, indicating cracks in coal samples under load closed quickly. Then the stress curve becomes the linear stage, as shown in Fig. 3.

(2) Second stage- Gas-tightness of elastic compression

During the linear stage, the number and energy of acoustic emission was lower and stable. The nitrogen flow rate was stable in the former 40% linear stage (stage 2 – 1), and largely reduced in the latter 60% linear stage (stage 2–2). It was still no changes at the open side of coal samples, indicating that the primary fissures were further compacted, and gas channels tends to be closed. Feature point A is elastic load lower limit, as shown in Fig. 3.

(3) Third stage- Gas-overflow of plastic expansion

A stress drop of 1.85 MPa appeared at feature point B when load to 7.0 MPa, and a second maximum peak of number and energy of acoustic emission appeared, which was higher than the first one. Then the nitrogen flow rate increased fast, indicating internal failures were produced quickly, and gas channels were open. Then number and energy of acoustic emission stayed at higher level, many macroscopic cracking were found at the open side of coal samples. The nitrogen flow rate increased greatly and flowed out of the open side. The results indicated gas channels were unimpeded, and a great number of internal failures were produced. The samples were in plastic yielding and expansion state (stage 3). In the whole stage 2 and 3, the gas pressure was in stable, a bit loss of pressure might occur. Feature point B is elastic load upper limit or yield point, as shown in Fig. 3.

(4) Fourth stage- ejection of broken instability

As shown in Fig. 3, Coal sample appeared a lot of macroscopic cracking at the open side when the pressure reaching to unidirectional compression ultimate load of 8.7 MPa at feature point C, then the

stress reduced rapidly. It is found that the number and energy of acoustic emission reached a maximum peak, some debris fell off and nitrogen gas ejected out with coal particle erupted, the test was finished. Feature point C was marked as the limited load followed by stage 4. As can be seen in Fig. 4, the damage to coal was mainly in breeding way at ventilate side and splintering at the open side. If the nitrogen pressure getting increased, more gas and coal would be ejected.

(5) Regular recognition

- a. In each stage, the gas seepage stage is different resulting from the strain function from the effective stress (the difference between axial pressure and gas pressure). At the initial non-linear stage (stage 1), the expansion fissures generated by unloading are gradually compacted, the gas flow is relatively large and unstable, and the seepage is attenuated along the expansion fissures. At the initial period of elastic stage (stage 2 - 1), the coal sample is basically compacted and primary fracture is produced. The gas is relatively stable and display seepage situation along the primary fissure. At the late period of elastic stage(stage 2 - 1), the primary fracture compacted and the gas display seepage situation along the compacted primary fissure until a new equilibrium state is reached; At plastic expansion stage (stage 3), plastic expansion fissure is generated, air flow along the expansion of fissures to accelerate seepage; At the ultimate load and the post-peak broken stage (stage 4), a large number of macroscopic fissures are generated, and the gas flow is emitted at high velocity.
- b. As reported by Geng et al(2017) that the porosity and permeability of coal decreased exponentially with the increase of effective stress. Ju et al(2017) showed that the change of stress load under different excavation paths caused the complex evolution of coal fissure network, which significantly changed the methane permeability of fissured coal. Jiang et al (2017) showed that the absolute recovery rate of permeability increased first and then increased with the stratified cycle loading and unloading, and the relative recovery rate of permeability increased gradually. (Kong et al., 2017; Xie et al., 2015) showed that stress and porosity are closely related to gas pressure evolution. Changes in stress can cause changes in porosity, affecting gas pressure, and methane desorption and coal stress, all of which form a coupling relationship. Although the test methods and gas pressures used in the above studies differed from this paper, similar results were obtained from this paper.
- c. As gas pressure reached 0.4 Mpa, it also could produce gas/solid mixture catastrophe when the compaction zone of stress concentration was destroyed.

3. The Empirical Analysis Of Low-index Catastrophe Of Coal And Gas Outburst

In the past 15 years, the low-index catastrophe of coal and gas outburst in coal mine including Fushun, Pingdingshan, Xin'an and Haizi in China were continuously tracked and analyzed. Three catastrophe models were concluded based on the reliable and complete data from these coalfields.

3.1. Unusual gas emission or outburst of roof weighing

Laohutai coal mine is a rock burst and coal and gas outburst coal mine. After regional and local outburst's elimination, the pressure of residual gas in coal seams on 63001 mining face at 710 m was about 0.5 MPa, and other parameters were within the limits. At 17:45 on December 13, 2002, roof weighting on mining faces increased, the content of gas increased to 3.25%, without vibration sense.

As shown in Fig. 5, the process including the following steps: in the initial 4 days (stage 1), it is the gas-fightness of elastic compression form stress wall, then the gas-overflow of plastic expansion process last one day (stage 2). Finally, the coal wall burst rapidly and unusual gas emission (stage 3). During this stage, the coal wall was instability, the pressure supporting zone is forwarded, resulting in the simultaneous movement of roof. 8 minutes later (17:52:55), far-field roofs fractured, resulting in a mine earthquake (ML2.0) that can be detected on the mining face. Quick instability of the stress wall was caused by periodic roof weighting. Based on this phenomena, it can be concluded that the only unusual gas emission would happen due to low residual gas pressure and content in coal seams, while rock gust would happen if hardness of coal seams was appropriate, accompany with that coal and gas out bursting would happen if the pressure and contents of residue gas are both higher, these two cases have occurred in the Laohutai coal mine.

As reported by Lv and He (1999) that the stress dike located in the vicinity of the peak of the stress concentration is key zone to load maximum face stress and heavy damage but not a concentration zone. It has a certain width, and with the shape of the wall between the relief pressure belt and the stable pressure zone. In this paper, the stress dike was further defined as an elastic supercharging zone produced by influence of mining in front of coal seams in the mining faces. In the second half of elastic bearing, pores and fissures of coal seams were compacted and air current channels were closed, which produced this stress-concentration wall to prevent gas seepage.

Many similar cases happened in Laohutai coal mine and Haizi coal mine.

3.2. Low-index unusual gas emission or outburst under breakage impact loading of roof

The pressure of residual gas in coal seams on 68002 mining face at 760 m was about 0.5 MPa, and other parameters were within the limits. At 17:15 on December 13 to 16:00 on December 14, 2002, roof weighting was applied to mining faces, and front part of hydraulic support was rib spalling. The gas content was within the limits by sensor. A mine earthquake (ML0.5) occurred at 08:39:54 on December 14. The gas content reached 3.92% (time difference 6 s) at 08:40. Another mine earthquake (ML2.6) occurred at 00:32:54 on December 16, front part of hydraulic support was rib spalling, support deformation in air return way. At 00:35–40, gas content reached 7.94% (time difference 126 s), which was beyond the limit.

As shown in Fig. 6, this process was caused by twice of roof weighting. Stage 1 was elastic consolidation stage. Stage 2 was overlord by roof weighting. During this stage 2, the stress dikes get instable by plastic expansion, then unusual gas emission happened under breakage impact loading of roof. The elastic

consolidation for next period is stage 3, and stage 4 marked as the plastic expansion stage was short, followed by the stage 5. During this last stage 5, unusual gas emission could happen resulting from high-energy roof breakage and stress dike was unstable, and coal and gas outbursting could happen if gas pressure and contents were higher. There were many similar cases in Laohutai coal mine.

3.3. Low-index unusual gas emission or outbursts under impact loading of floor

12011 driving face at 620 m was gas outburst working face in Xinyi coal mine of Xin'an coal field. After regional outburst elimination, residual gas pressure was below 0.6 MPa. At 14:00 on August 10, 2009, coal and rock burst sounds happened more than 10 times continually in the head of the belt roadway driving face. At 14:09, unusual gas emission leading to gas online monitoring system automatic power off. It was found that floor rock bursts happened after field investigating the floor bulking breakage. Before that, the partial dangerous forecast index, maximum methane inrush initial velocity (q) of drilling was 2.4 L/min. The maximum methane desorption index (Δh_2) of drillings was 120 Pa, and the maximum amount (S) of drilling was 2.3 kg/m. All these parameters were below the Xinyi coal mine's limits ($q = 3.5$ L/min, $\Delta h_2 = 140$ Pa, $S = 4.0$ kg/m). As shown in Fig. 7, gas content in the driving face and the return airway were both below 0.3% (0.8% was the upper limit of automatic control), it was indicating that pressure, content, and emission of gas in coal seams in the driving face was normal.

Fig. 7 showed that the gas emission concentration at driving face was greatly reduced at 4:00 to 20:00 on August 9 in Stage 1, it was indicating that floor upwards was bended under high floor pressure, stress dike effect caused by the increase in coal wall pressure boost zone index, and the process in which the overflow channels of dissociative gas in coal was closed. Then, gas emission concentration raised up for 14 h at 0:00 to 14:00 on August 10 in Stage 2, it was indicating that plastic expansion of the coal was occurring in the first half of Stage 2, the elastic consolidation was also occurring in the second stage 2. Rock burst was occurring in the second and third stages of the dividing line due to the consolidation and expansion reciprocal. About 14:00 on August 10 in Stage 3, unusual gas emission leading to gas online monitoring system automatic power off. Flexure of the floor was beyond the limit of elasticity, leading to a rock burst. The stress dike became quick instable, and gas seepage channels was opened, resulting in unusual gas emission. There were many similar cases in Laohutai coal mine. Higher residual gas pressure and content could lead to coal and gas outburst. Similar accidents happened in Xinyi coal mine and No.10 coal mine of Pingdingshan Group.

4. The Model Of Low-index Catastrophe Of Gas-bearing Coal Seams

It is proved further that there are many cases and scientific evidence where low-index catastrophes occurred in gas-bearing coal seams. In this section, the catastrophe rule was studied using mechanical model.

4.1. Mining stress-strain-seepage distribution of gas-bearing coal seams

According to the classical theory of mining pressure, mining pressure can be divided into pressure relief zone, pressure boost zone, and pressure stable zone, as shown in Fig. 8. Based on practical observation of working face in coal seam roadway, the researcher in Magkeyev coal mine safety research institute in the former Soviet Union put forward that the strain of coals in front of the face could be divided into extrusion zone (pressure relief zone a_1), compress zone (pressure boost zone B), and undisturbed coal zone (pressure stable zone C). Nowadays, it is generally recognized that the pressure relief zone a_1 of coals in front of the face has gone through plastic strain expansion, and compression fractures growth. Pressure boost zone is composed of two parts. Outside is plastic-strain pressure boost zone b_1 , where coals expansion, shear-tension fissures grow, and dissociative gas can emission as in pressure relief zone. The inside is elastic-strain pressure boost zone b_2 , where fractures is compacted and closed, gas is in an adsorbed state, and gas seepage channels become smaller. In pressure stable zone C, the mining effect is below 5%, which can be regard as stress state of the original rock. The pores and fractures are in a state of nature, and gas is in an adsorbed state.

It should be noted that regional outburst elimination measures must be done for outburst seams before mining. Therefore, pressure stable zone was influenced by outburst elimination measures, natural pores and fractures turned into secondary pores and fractures and the adsorbed gases started to undergo desorption, which was less than plastic expansion zone ($a_1 + b_1$). In this case, we divided the strain field of the coal seams in front of mining zones into plastic expansion zone D, elastic compaction zone E, and disturbance fractured zone F. The corresponding seepage field were strong gas desorption zone, gas migration barrier zone, and weak gas desorption dissociate agglomeration zone, separately.

The elastic compaction zone E was the stress dike which prevented gases from unusual emission. Generally, the low gas pressure could not break through the constraint of stress dikes without applied stress. The model of low-index catastrophe of gas-bearing coal seams was decided by the reason that the stress dikes failed.

4.2. Avalanche model of stress dikes under impact super loading of roof static pressure

It was similar to the case in Sect. 3.1, improper control of the roof and too long hanging roof resulted in mining stress concentration factor to suddenly increased to k_1 , which was exceed than the ultimate equilibrium mining stress concentration factor k_0 , then avalanche breakage of stress dikes rapid rupture instability and instantaneously produced a stress drop $\Delta\sigma$, resulting in changes in the three-area distribution of mining stress, as shown in Fig. 9. It was marked as pressure relief zone that absolute seam pressure relief zone a_1 became wider. The coals would produce compression and shear-tension fractures, and became coal and gas outburst zone D'. It was named as relative pressure relief zone B' that forward lead of pressure boost zone caused rapid stress drop and decrease of mining stress concentration factor.

In this process, a lot of tensile fractures were produced. (Tan et al.,1997; Zhang et al., 2019) found that when the strength of the unloading stress suddenly applied on the coal samples was larger than the plus of tensile strength and air pressure, breakage occurred and approached to the deep in the form of fractioned wave. The primary stress dikes failed, and became a gas migration zone E', resulting in unusual emission of dissociative gas in the stress dikes. It became a source F' of coal and gas outbursts. Dissociative gas with sufficient pressure and content can bring out crushed coals in absolute pressure relief zone which leads to the catastrophe marked as coal and gas outburst. Otherwise, when gas pressure and content was insufficient, the catastrophe was only unusual gas emission. If hardness of the coal seams was appropriate, stress avalanche could become a coal seam rock burst, and further induced outburst. If gas pressure and content became larger in pressure stable zone C', the catastrophe would develop inward.

Loading condition for stress dike avalanche under impact super loading of roof static pressure was a short-time difference (minute or second scale):

$$\sigma_{k1} = k_1rh > k_0rh \quad (1)$$

4.3. Avalanche model of stress dikes under roof breakage impact

It was similar to the case in Sect. 3.2 that roof breakage impact generated an acceleration a_1 , and the equivalent static load ($F_1 = m_1.a_1$) on unit coal area gets accumulated with the vertical mining stress, which was over the ultimate stress equilibrium, resulting in a quick breakage instability like stress avalanche. This caused a rapid stress drop $\Delta\sigma$, leading to changes of mining stress in the three-area distribution, as shown in Fig. 10. Absolute pressure relief zone a_1 of coal seam was not enough time to be wider. The compact energy could also take them off, and induced coal and gas outburst D'. Pressure boost zone might not enough time to move forwards. However, relative pressure relief zone B' would be produced because of the decrease in mining stress concentration coefficient caused by stress dike breakage instability and rapid stress drop. Catastrophes similar to the cases in Sect. 4.2 would occur, because of the failure of preventing effect of primary stress dikes on gas.

Loading condition for stress dike avalanche under roof breakage impact was a short time difference (minute or second scale):

$$F_1 + krh > k_0rh \quad (2)$$

4.4. Avalanche model of stress dikes under floor breakage impact

It was similar to the case in Sect. 3.3 that the vertical mining stress applied to floor active region OPQ pushed passive region (or a_2), and generated horizontal force, leading to an upwards convex elastic deflection of the floor. When over the elastic limit, an acceleration a_2 was produced by floor breakage impact suddenly, and the equivalent static load ($F_2 = m_2 \cdot a_2$) on unit coal area gets accumulated with the vertical mining stress, which was over the ultimate stress equilibrium, resulting in quick breakage instability of the stress dike. The catastrophe was similar to the case in Sect. 4.3, as shown in Fig. 11.

Loading condition for stress dike avalanche under floor breakage impact was a short-time difference (minute or second scale):

$$F_2 + krh > k_0rh \quad (3)$$

5. Conclusions

(1) The primary cracks are not the initial states, and a large number of secondary cracks are generated in the stable pressure zone due to the fact that outburst elimination measures are taken. The three coal seam strain zones are divided into a plastic expansion zone, an elastic compaction zone and a disturbance fractured zone in front of the mining face before the limited loading pressure of mining coal seam reached balance state. The corresponding gas occurrence states are the strong gas desorption zone, gas migration barrier zone, and weak gas desorption dissociate agglomeration zone, separately.

(2) The stress dike is composed of elastic compaction zone, a new definition of stress dike was given, and the condition of avalanche instability was decided. Three catastrophe models were proposed, including over static-load stress dike avalanche caused by hanging arch overlength, stress dike avalanche under roof breakage impact, and stress dike avalanche under floor breakage impact.

(3) It is because the avalanches instability of the stress wall become unstable that original elastic compacted zone of coal seam strain zone in the front face of mining face is transformed into a tensile zone. The gas state is transformed into coal and gas ejection zone, gas migration zone and gas launching zone. The evolution of gas occurrence "three zones" with the avalanche instability of stress dike leading to the low-index catastrophe of gas-bearing coal seams.

(4) The time of stress dike avalanche caused by dynamic-static overload was 6 s to 126 s, which means it is the minute or seconds level. The time of the stress wall avalanche caused by static overloading is currently no reliable observation data.

Declarations

Acknowledgements

This work was supported by the Natural Science Foundation of China (51674016,51534002, 51274025). The liquid/solid coupling physical experiments were done with help of Professor Chengdong Su and Doctor Baobin Gao in Henan Polytechnic University.

References

- An FH, Yuan Y , Chen XJ, Li ZQ, Li LY (2019) Expansion energy of coal gas for the initiation of coal and gas outbursts. *Fuel* 235: 551-557.
- Анерщцн СГ (1959) Rock burst. Translated from Russian into Chinese by Zhu M,Wang BY, Han JX. China Coal Industry Publishing House:259.
- Bräuner G (1985) Rock pressure and rockburst . Trans. Li YS. Beijing: Coal Industry Press:15-16.
- Gao MZ, Zhang S, Li J, Wang HY (2019) The dynamic failure mechanism of coal and gas outbursts and response mechanism of support structure. *Thermal Science* 23: 122-122.
- Geng YG, Tang DZ, Xu H, Tao S, Tang SL, Ma L, Zhu XG (2017) Experimental study on permeability stress sensitivity of reconstituted granular coal with different lithotypes. *Fuel* 202:12-22.
- Jiang CB, Duan MK, Yin GZ, Wang JG, Lu TY, Xu J, Zhang DM, Huang G (2017) Experimental study on seepage properties, AE characteristics and energy dissipation of coal under tiered cyclic loading. *Engineering Geology* 221: 114-123.
- Jin K, Cheng YP, Ren T, Zhao W, Tu QY, Dong J, Wang ZY, Hu B (2018) Experimental investigation on the formation and transport mechanism of outburst coal-gas flow: Implications for the role of gas desorption in the development stage of outburst. *International Journal of Coal Geology*194: 45-58.
- Ju Y, Zhang QG, Zheng JT, Wang JG, Chang CH, Gao F (2017) Experimental study on CH₄ permeability and its dependence on interior fracture networks of fractured coal under different excavation stress paths. *Fuel* 202:483-493.
- Kong XG, Wang EY, Liu LQ, Li ZH, Li DX, Cao ZY, Niu Y (2017) Dynamic permeability and porosity evolution of coal seam rich in CBM based on the flow-solid coupling theory. *Journal of Natural Gas Science and Engineering* 40:61-71.
- Li T, Mei TT, Li GQ, Xu SR, Yang JL, Dong H (2011) Mechanism study of coal and gas outburst induced by rockburst in "three-soft" coal seam. *Chinese Journal of Rock Mechanics and Engineering* 30(6):1283-1288.
- Li T, Cai MF, Wang JA, Li DC, Liu J (2005) Discussion on relativity between rockburst and gas in deep exploitation. *Journal of China Coal Society* 30(5):562-567.

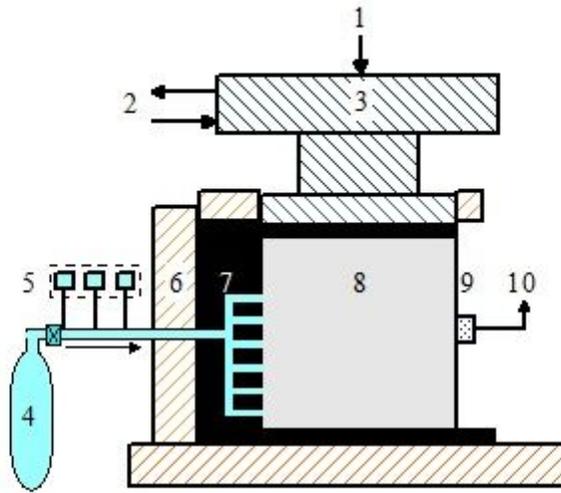
- Li T, Cai MF, Cai M (2007) Earthquake-induced Unusual Gas Emission in Coalmines – A km-scale- in-situ Experimental Investigation at Laohutai Mine. *International Journal of Coal Geology* 71(2-3): 209-224.
- Lin SL, Ma CX, Wang GJ (2009) Comprehensive prevention technology on rock burst and gas outburst in deep well driving. *Zhongzhou Coal* 163(7):83-85.
- Lu CP, Dou LM, Zhang N, Xue JH, Liu G.J (2014) Microseismic and acoustic emission effect on gas outburst hazard triggered by shock wave: a case study. *Natural Hazards* 73:1715–1731.
- Lv SL, He JS (1999) Key layer and stress dikemechanism of coal and gas outbursts. *Journal of Chongqing University (Natural Science Edition)* 06:80-84.
- Meng XZ, Wang CM, Tang B, Sun BX (2007) Prediction theory and practice of dynamic disaster occurred in coal face with outburst and rock burst. *Mining Safety & Environmental Protection* 34(3):1-4.
- Si GY, Durucan S, Jamnikar S, Lazar J, Abraham K, Korre A, Shi JQ, Zavšek S, Mutke G, Lurka A (2015) Seismic monitoring and analysis of excessive gas emissions in heterogeneous coal seams. *International Journal of Coal Geology* 149(49):41-54.
- Tan QM, Yu SB, Zhu HQ, Zheng ZM (1997) Fracture of coal containing pressurized gas by sudden relieving. *Journal of China Coal Society* 22(5):514-518.
- Wang CJ, Yang SQ, Li XW, Yang DD, Jiang CL (2018) The correlation between dynamic phenomena of boreholes for outburst prediction and outburst risks during coal roadways driving. *Fuel* 231:307-316.
- Xie HP, Xie J, Gao MZ, Zhang R, Zhou HW, Gao F, Zhang ZT (2015) Theoretical and experimental validation of mining-enhanced permeability for simultaneous exploitation of coal and gas. *Environmental Earth Sciences* 73(10):5951-5962.
- Zhang JG, Wang M, Wang YW (2019) Fracture evolution and gas transport laws of coal and rock in onekilometer deep coal mine with complicated conditions. [Thermal Science](#) 23: 126-126.
- Zhang FM, Yu ZY, Xu XY, Yang WD, Zhang SZ, Zhang JS, Liu TJ, Zhou H (2005) Research on induced earthquakes by coal mining in Hegang. *Journal of Natural Disasters* 14(1):142-146.
- Zhang FW, Li T (2009) Cognizance on compound dynamic disaster of coal and gas in deep mining. *Zhongzhou Coal* 106(4):73-76.

Figures



Figure 1

Raw coal samples



1-Compression system, 2-Data acquisition control system, 3-Compression pad, 4-Air supply system, 5-Gas data acquisition system, 6-Support system, 7-Sealing system, 8-Sample, 9-Acoustic emission sensor, 10-Acoustic emission amplification and data acquisition system

Figure 2

Schematic diagram of experimental principle

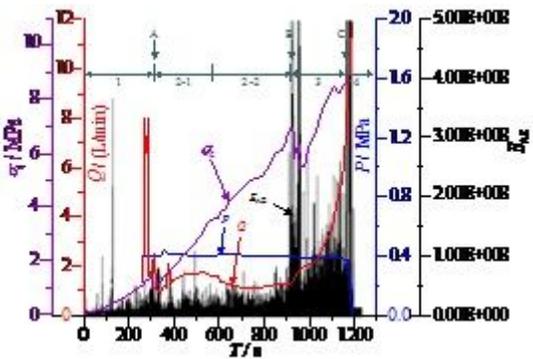


Figure 3

Physical evolution curves of the nitrogen bearing coal samples under load

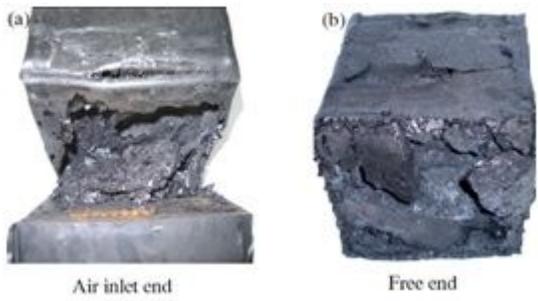


Figure 4

The state of coal samples after test

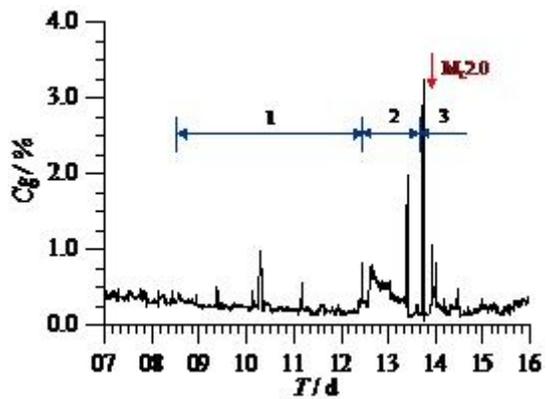


Figure 5

Gas abnormal effusing process under roof weighting

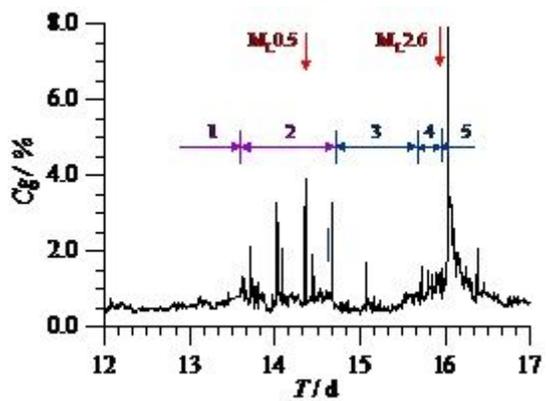


Figure 6

Gas abnormal effusing process under roof impact

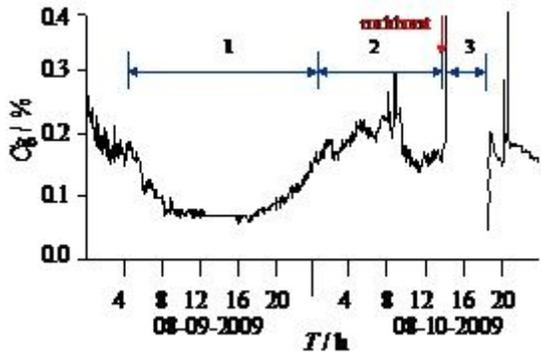
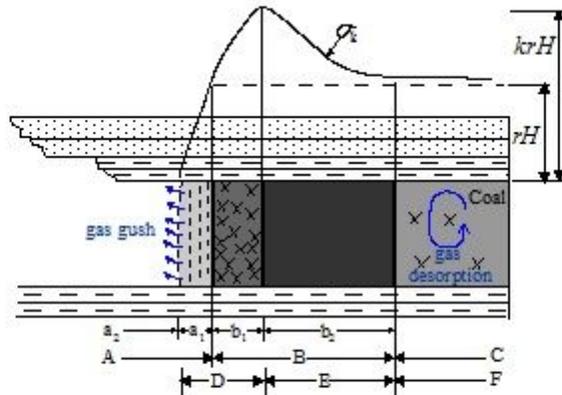


Figure 7

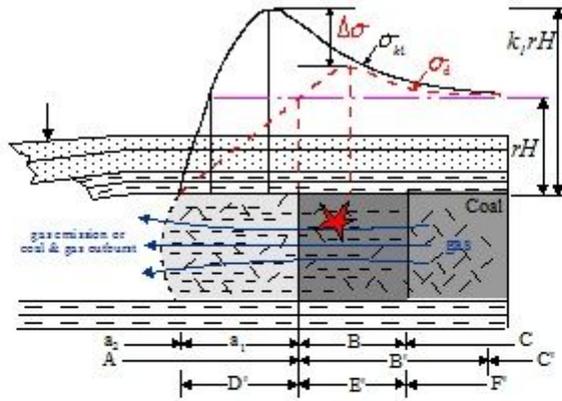
Gas abnormal effusing process under floor impact



k -Mining stress concentration factor below ultimate equilibrium, r -Cover rock volume weight, H -Cover rock thickness, σ_x -Vertical mining stress function curve

Figure 8

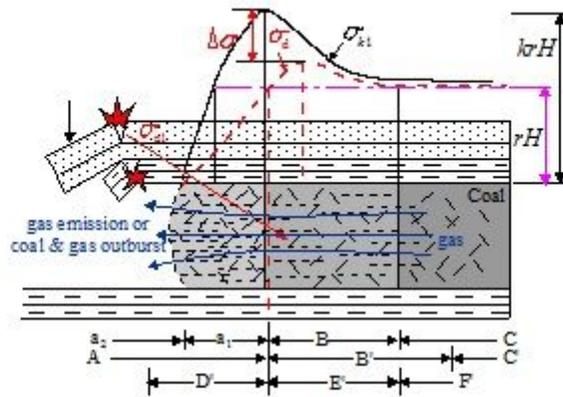
Mining stress-strain-seepage model of gas-bearing seams



k_1 -Mining stress concentration factor above ultimate equilibrium, r -Cover rock volume weight, H -Cover rock thickness, σ_{k1} -Function curve of vertical mining stress above ultimate equilibrium, σ_d -Vertical mining stress transfer function curve, $\Delta\sigma$ -Stress drop after stress dike avalanche

Figure 9

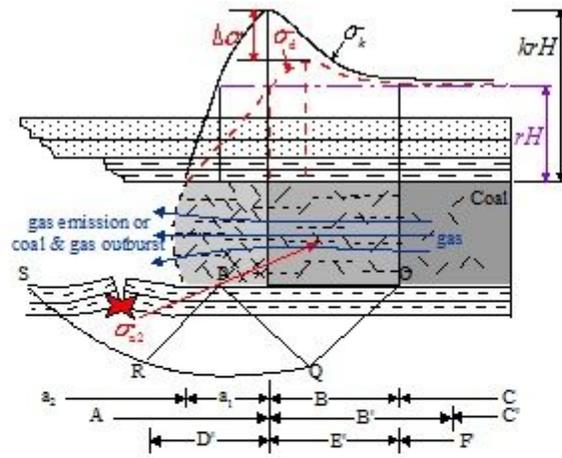
The mechanical model of coal roof super hydrostatic catastrophe



k -Mining stress concentration factor, r -Cover rock volume weight, H -Cover rock thickness, σ_k -Vertical mining stress function curve, σ_d -Vertical mining stress transfer function curve, $\Delta\sigma$ -Stress drop after stress dike avalanche, σ_{a1} -Equivalent static stress per unit area caused by the roof breakage impact.

Figure 10

The mechanical model of coal roof impact catastrophe



k -Mining stress concentration factor, γ -Cover rock volume weight, H -Cover rock thickness,
 σ_k -Vertical mining stress function curve, σ_d -Vertical mining stress transfer function curve,
 $\Delta\sigma$ -Stress drop after stress dike avalanche, σ_{a2} -Equivalent static stress per unit area caused
 by the floor breakage impact.

Figure 11

The mechanical model of coal floor impact catastrophe