Geotech Geol Eng (2018) 36:1525–1543
https://doi.org/10.1007/s10706-017-0406-6

ORIGINAL PAPER

Study on the Development Laws of Bed-Separation Under the Hard-Thick Magmatic Rock and its Fracture Disaster-Causing Mechanism

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Received: 30 November 2016 / Accepted: 6 November 2017 / Published online: 14 November 2017

Abstract Based on the analysis of dynamic phenomena under the condition of high-located hard-thick (HLHT) stratum of one coal mine, along with the similar material simulation and theoretical analysis, the characteristics of bed separation development and cracks distribution under the HLHT stratum are studied. This paper proposes a discriminating method for overlying strata Three Zones considering the influence of HLHT stratum. The development laws of cracks and disaster-causing mechanism of hard-thick magmatic rock in different strata are respectively analyzed. The studies show that in line with the working face advancing direction, the height of bed separation under the magmatic rock increases in the trend of "Increase–Stability–Decrease", and the width of bed separation increases linearly. The width of bed separation reaches the maximum before the first breaking of magmatic rock, the bed separation completely closes after the breaking. There are no obvious bed separations during the period migration of magmatic rock. Along the direction of the height of roof, the development of bed separation is characterized by bottom-up jump based on the key strata. The analyzed results of "Three zone" height obtained by the discriminate method of overlying strata Three Zones which is based on the key strata theory and the S–R instability theory are in line with the actual facts. When the hard-thick magmatic rock is in the fractured zone, large amounts of gas and water are easy to accumulate in the bed separation space and "O" ring space around the gob. The first breaking of magmatic rock may induce bed separation gas outburst and water inrush. When the hard-thick magmatic rock is in the sagging zone, the long-term stability of magmatic rock will not cause serious disasters. But with the adjacent working face mining, bed separation gas and water often become a safety hazard.

Keywords Hard-thick magmatic rock · Bed separation · Three zones height · Rock breaking · Disaster-causing mechanism

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1 Introduction

In China, hard and thick strata are commonly found in coal bearing strata (Xuan et al. 2012). The lithology of the hard and thick strata is mainly dominated by sedimentary rock and magmatic rock, such as the giant thick conglomerate in Yima mining area, giant thick conglomerate in Huafeng coal mine, giant thick conglomerate of Jiao Ping coal mine, thick layer of red sandstone in Baodian coal mine, giant thick magmatic rocks in Huaibei mining area, giant thick magmatic rocks in Jining mining area, etc.

For the hard and thick sedimentary conditions, a few scholars, through the field measurement and theoretical research means, studied the influence of hard thick sedimentary rocks of overlying rock and disaster-causing mechanism, and thought that hard thick sedimentary rocks can lead to rock burst (Li et al. 2014), water inrush (Zhu et al. 2009), shock bump (Lu et al. 2010), surface subsidence and crack (Guo et al. 2009; Wang and Zhang 2009) and other disasters. For the hard and thick magmatic rock, the hydrocarbon production of coal seam increases influence by thermal metamorphism of magmatic rocks. Meanwhile, the low permeability of magmatic rocks has a good sealing effect on the gas generated by the adjacent coal seams (Wang et al. 2014). With the high strength, hard thick magmatic rock can keep stable for a long time, and a large number of gas are easy to accumulate under the lower bed separation space. When the retreating distance reaches the maximum stability span of magmatic rock, magmatic rock breaking easily cause rock burst, shock bump, surface subsidence and other disasters, and is also easy to cause the gas outburst, mine water disasters and other serious disasters. Therefore, there is a need for systematic study of the development laws of bed separation under the magmatic rock and the disaster-causing mechanism of magmatic rock breaking and put forward effective prevention and control method.

In the study of hard thick magmatic rock, Wang (2010), combined with specific examples, studied the coupling rules between mining fracture field and gas flow field under the giant thick magmatic rock; Xuan (2011, 2012), through numerical simulation, studied the reasons of coal outburst and gas inrush under the giant thick magmatic rock and put forward the technical scheme of dynamic disasters in the control of giant thick magmatic rock by grouting in gob area. The literatures mentioned above only analyzed the gas flow field and coal and gas outburst under the hard thick magmatic rock, while the systematic researches related to the development of bed separation and breaking disaster-causing mechanism of magmatic rock are quite few.

Taking gas inrush of surface gas drainage borehole, working face water inrush accidents and surface subsidence of a coal mine as the research background, along with the similar material simulation and theoretical analysis, the bed separation and breaking disaster-causing mechanism of magmatic rock are studied. This paper proposes a discriminating method for overlying strata Three Zones considering the influence of HLHT stratum. It provides a theoretical basis for the control of disasters under the hard and thick strata.

2 Mining Conditions Under Hard and Thick Magmatic Rock and Bed Separation Dynamic Disasters

2.1 Geological Mining Conditions of Working Face

10414 working face is the first working face of 104 mining district of Yangliu coal mine, surrounded by solid coal. The length along strike is 1080 m and the width along incline is 180 m. At present, the coal seam mined is 10# coal seam, thickness of coal seam is 3 m, dip angle is 5°, and average buried depth of working face is 608 m. There are two layers of magmatic bedrock in the overlying strata of the working face, and the composition of magmatic rock is mainly dominated by neutral diorite, and comprehensive strength ranges from 80 to160 MPa, which belongs to a typical hard rock. The occurrence featuring with coal and rock strata and magmatic rock are revealed by 10414-1 borehole (Table 1). According to the **key strata theory** (Qian et al. 2003), the key strata of the 10414 working face were identified, and the 2# magmatic rock layer were determined as the main key stratum.

The definition of **key strata** (Cheng and Song 2011; Pan et al. 2012; Zhang and Huang 2012; Han and Meng 2013) is as follows: There are strata with different thickness and strength above the immediate roof, among them, one or several strata play a major role in controlling overlying strata movement. The strata, which play a major role in controlling overlying strata movement, are called the **key strata**. The sub-key stratum is the key strata which control the local motion of overlying strata. The main key stratum is the

Table 1 Columnar section of 10414-1 borehole

Number of strata	Thickness/m	Buried depth/m	Lithology
32	25.86	351.26	1# Magmatic rock
31	31.37	377.12	Mudstone
30	10.2	408.49	Fine sandstone
29	4.83	418.69	Sandy mudstone
28	4.45	423.52	Fine sandstone
27	9.27	427.97	Mudstone
26	8.64	437.24	Siltstone
25	4.2	445.88	Mudstone
24	47.01	450.08	2# Magmatic rock
23	2.85	497.09	Mudstone
22	4.39	499.94	Fine sandstone
21	4.52	504.33	Mudstone
20	12.45	508.85	Fine sandstone
19	4.3	521.3	Sandy mudstone
18	4.18	525.6	Siltstone
17	2.15	529.78	Coal
16	1.5	531.93	Mudstone
15	1.7	533.43	Coal
14	4.32	535.13	Mudstone
13	5.53	539.45	Fine sandstone
12	2.16	544.98	Mudstone
11	3.79	547.14	Siltstone
10	6.48	550.93	Mudstone
9	5.86	557.41	Siltstone
8	2.4	563.27	Mudstone
7	3.24	565.67	Mudstone
6	11.05	568.91	Siltstone
5	5.4	579.96	Mudstone
4	7.02	585.36	Siltstone
3	4.23	592.38	Piebald mudstone
2	2.54	596.61	Siltstone
1	7.3	599.15	Fine sandstone
	3.01	606.45	10# Coal seam

key stratum which controls the movement of all the strata to the surface.

2.2 Dynamic Hazard Analysis of Hard Thick Magmatic Rock

In July 17, 2011, when the 10414 working face retreating 525 m, the total amount of gas emission from the surface borehole suddenly increased (Fig. 1a). A large mount of gas erupted from the 2# surface gas drainage borehole are located 12 m behind the working face, lasting 33 h and 16 min, and the total amount of gas emitted from the surface borehole during the eruption is 166383 m^3 (Fig. 1b). Meanwhile water inflow in working face increased suddenly: water inflow per shift in July 17 was 304 m^3, and the water inflow per shift had been maintained at more than 304 m^3 until July 21. Then water inflow per shift gradually reduced with the retreating of working face, the total water inflow of 87# hydraulic support(2# Borehole) was 7845.6 m^3 (Fig. 2). The gas

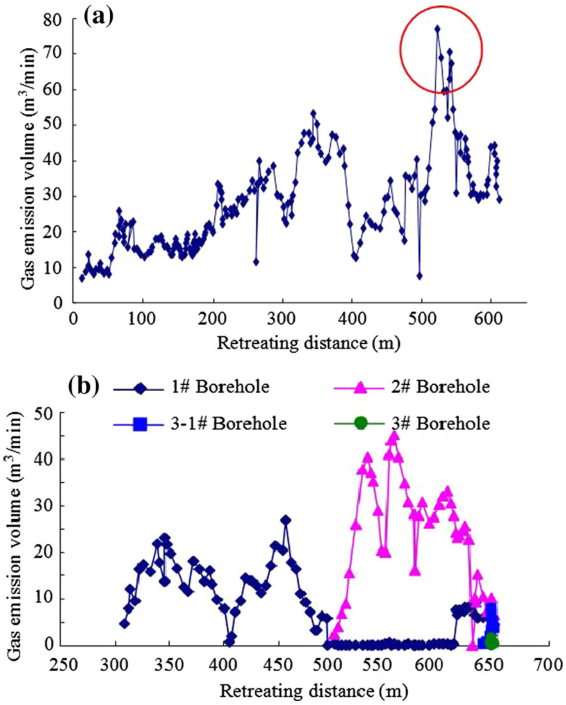

Fig. 1 The relationship between gas drainage-emission volume and retreating distance. **a** The relationship between the total gas emission volume and retreating distance; **b** The relationship between gas emission volume of each surface gas drainage borehole and retreating distance

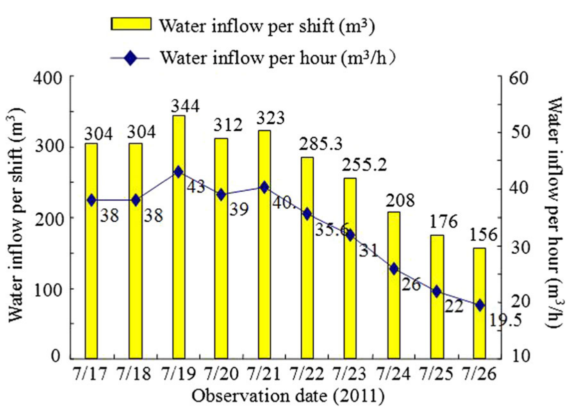

Fig. 2 10414 Working face water inflow statistics

emission and water gushing position are shown in Fig. 3.

A surface subsidence observation line was assigned along 10414 working face strike, and the arrangement of measuring points is shown in Fig. 4, and the number is from 1 to 9.

The measured surface subsidence curve is shown in Fig. 5. In the early stage of working face mining, the displacement of each measurement point is very small, the maximum subsidence position is 2# borehole, and the maximum subsidence is 453 mm. When the working face retreating distance is 684 m, 2# borehole subsidence suddenly increased from 700 to 1543 mm, all the measurement points in the mining influence area appeared obviously subsiding. The sudden subsiding of the surface measured points also confirmed that the magmatic rocks were broken in the mining process of the working face. Note that the retreating distance when gas emission and water inrush occurred is 525 m, but the retreating distance of surface sudden subsiding is 684 m, the distance between the two distances is 159 m, implying that there is obvious lag effect from the magmatic rock breaking to causing surface subsiding. The lag effect of surface subsidence can be verified by the subsiding values of the 7# measurement point 654.3 m from the open-off cut: When the working face retreated to 684 m, no surface subsidence of the 7# measurement point 654.3 m from the open-off cut was measured, but the surface subsidence of 6# measurement point 514.9 m from the open-off cut only slightly changed; the measuring point is located at the rear of the working face 169 m.

From the above analysis, we know the magmatic rock breaking is the trigger that induces the surface borehole gas emission and working face water inflow and surface subsidence, and these field measured data can provide a reliable basis for further study of the disasters caused by hard thick magmatic rocks.

3 The Development Laws of Bed Separation and Distribution Characteristics of Fractures Under the Hard Thick Magmatic Rock

From the previous analysis, we already know the magmatic rock breaking is the trigger that induces the surface borehole gas emission and working face water inflow and surface subsidence, and the formation of bed separation under the hard thick magmatic rock is the main disaster source of gas and water accumulation. Therefore, to study hard the thick magmatic rock breaking disaster-causing mechanism, we need first to find out the development laws of bed separation and distribution characteristics of fractures.

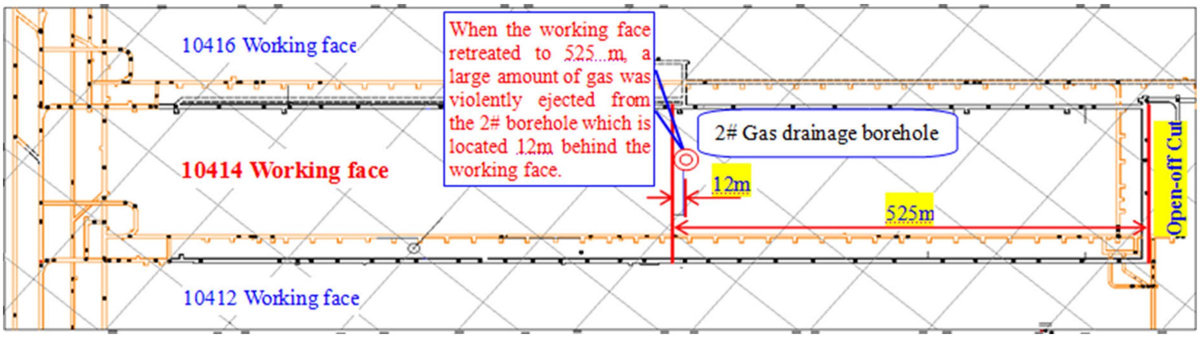

Fig. 3 10414 working face gas emission and water inflow position

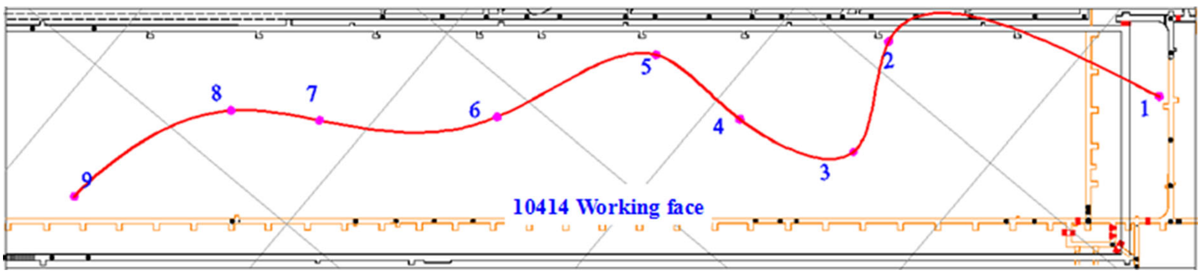

Fig. 4 10414 working surface subsidence measurement points layout

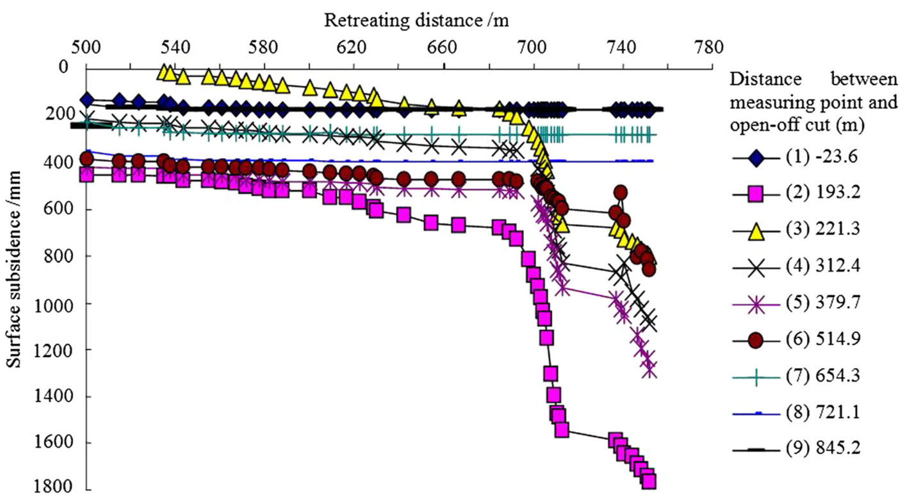

Fig. 5 Dynamic subsidence curve of 10414 working face surface subsidence measurement point along strike

The research methods in the field of mining engineering include field measurement, theoretical analysis, numerical simulation and physical simulation of similar materials (Wang et al. 2015). Based on the borehole imaging technology, field measurement can prove the existence of bed separation and fractures, but can not reveal the development laws of bed separation and distribution characteristics of fractures (Wang et al. 2016). The theoretical analysis and field measurement are often based on the experimental results, so it is difficult to analyze the development and distribution of bed separation and fractures systematically (Zhou et al. 2015). Numerical simulation technology is one of the most widely used research techniques, but it also has some shortcomings, for example, difficult to achieve real reduction in the simulation of the process of the overlying strata movement. Similar material simulation experiment can simulate the process of the overlying rock caving movement, formation and development of bed separation and fractures, which is very similar to the real situation (Peng et al. 2013). Therefore, in this paper, similar material simulation experiment was adopted to study the effect of magmatic rock breaking on the bed separation development and fractures distribution characteristics.

Similar simulation experiment model is designed based on the geological conditions and rock mechanics parameters of Yangliu Coal Mine 104 district. In 104 district, the vertical distance between the low magmatic rock and 10# coal seams is 78.2–130 m, the thickness of magmatic rock is 22–65 m, and the thickness of the 10# coal seam is 0–7.97 m. By the aforementioned key layer discriminated results, the low magmatic rock layer is the main key stratum, and the high magmatic rock layer is the sub-key stratum. The high magmatic rock breaks with the breaking of low magmatic rock main key stratum in the process of the overlying strata movement. It only plays the role of load and has little effect on the underlying strata bed separation and fracture distribution. Therefore, in the model design, omitting the high magmatic rock will have no influence on simulation results.

Based on the above considerations, the basic dimension parameters of the similar simulation experiment model are determined: the thickness of the mining coal seam is 8 m, the thickness of the overlying hard thick magmatic rock is 60 m, and the distance between the coal seam and the coal seam is 80 m. The geometric dimension (length × width × height) is 3000 mm × 400 mm × 1800 mm. The model takes river sand as aggregate, gypsum and calcium carbonate as cementing materials. It was determined that the similarity ratio of the model (Huang et al. 2011) is: the geometric similarity ratio $C_L = 1:200$; the bulk density similarity ratio $Cr = 1:1.5$ and the stress similarity ratio $C_\sigma = C_L \times C_r = 300$. Considering the edge effect of the model, the cutoff site was chosen to be 250 mm from the left model edge and the same distance was chosen to the takeoff site from the right edge. The mining length is 2500 mm, corresponding to the actual size of 500 m (Fig. 6). The material ratio and main parameters of the similar model are shown in Table 2.

Coal seam mining will cause the mining field overlying strata to move and break, resulting in the formation of mining fractures in the overlying strata. Overlying rock fissure can be divided into vertical fractures and bed separation fractures (Su 2001). The key layer has played an important role in the formation and development of bed separation and fractures, and spatial and temporal distribution process, which gives rise to the bed separation fractures under the key layer. According to the different process and characteristics of bed separation development along the retreating direction and vertical direction, the research of bed separation development is divided into two parts.

3.1 The Development Characteristics of Bed Separation Along the Retreating Direction

Before the breaking of magmatic rock, the bed separation volume increases with the working face retreating, and the bed separation volume above the central of gob is the maximum. After the magmatic rock is broken, the bed separation above the central of gob disappears under extrusion of caving rock mass, only bed separation surrounding gob still remains, resulting in the formation of a special "O-shaped" ring of mining fractures. The development and closing process of bed separation in the retreating direction is shown in Fig. 7.

Figure 7 captures several typical state of the development of bed separation along the horizontal direction, showing bed separation first develops to the bottom of magmatic rock (Fig. 7a), bed separation extends along the horizontal direction (Fig. 7b, c), and then closed separation (Fig. 7d). The development situation of bed separation height and width in the experiment process is shown in Fig. 8.

We can see from Fig. 8, when the working face retreated to 160 m, the bed separation for the first time developed to the bottom of magmatic rock in the vertical direction. With the continuous excavation of the working face, the height of bed separation under magmatic rock changed in the trend of "Increasing–Stability–Reducing"; Bed separation width increased linearly with retreating distance, and the bed separation width reached the maximum before the first breaking of magmatic rock (retreated 340 m), and before the bed separation completely closed after the

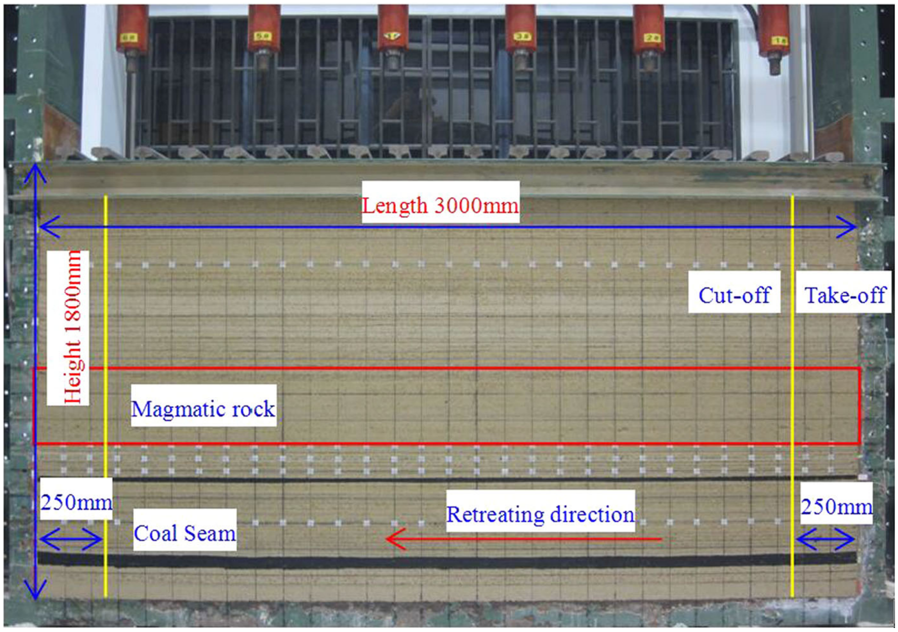

Fig. 6 Similar material simulation experiment model

magmatic rock breaking. The lower strata near the magmatic rock is mudstone. Lithology is weak so that the mudstone is not easy to break. In the process of sinking, the mudstone can be kept intact. Vertical fracture basically is not developed, which can effectively prevent water from losing. Mudstone and other weak rock are prone to disintegrate when the mudstone is exposed to water (Liu and Lu 2000). The disintegrate mudstone is filled to the developed micro cracks, which making water resistance capacity further improved. Finally a large number of water will accumulate in the bed separation space.

Figure 9 shows the development situation of bed separation under the magmatic rock in the process from the initial breaking to the first periodic breaking, during which no new bed separation occur under the magmatic rock since the first breaking.

Therefore,the lower bed separation volume reaches the maximum before the initial breaking of magmatic rock, and the bed separation closes after the initial breaking. With the retreating of working face, the periodic breaking of magmatic rock does not cause the development and closure of bed separation again. The disappearance of bed separation space and the formation of longitudinal cracks stop the gas and water from accumulating.

3.2 The Development Characteristics of Bed Separation Along the Vertical Direction

The development layer position of bed separation above the gob suddenly changes with the breaking of key strata, from low-located layers to high-located layers in a leap type (Fig. 10).

As shown in Fig. 10, with the breaking of key strata, the upper soft rock is bent down in a integral state. Vertical fracture is mainly distributed in the key strata. The lithology of soft strata above the key strata are weak so that the soft strata are not easy to be broken, vertical fracture basically is less developed. The farther the distance from the mining coal seam is, the stronger the integrity of the overlying soft rock is.

Figure 11 shows the change regulation of bed separation layer height with the working face retreating. The curve is made of five flat stages, bed separation layer height is controlled by the magmatic rock, and each stage corresponds to a key stratum. With the retreating of working face, the “O-shaped” ring is formed with the breaking of the lower sub-key stratum; bed separation appears at the bottom of the adjacent sub-key stratum, the bed separation layer height remains unchanged until the breaking of adjacent sub-key stratum. The largest bed separation layer height will stop at the bottom of key stratum in a

Table 2 The mixture ratio of the similar materials and the dosage of each layer

Number	Lithology	Thickness/mm	Accumulated thickness(mm)	Ratio	Density/(g/cm^3)	Weight/kg				Key strata
						Sand	Calcium carbonate	Gypsum	Water	
31	Siltstone	60	1627	755	1.6	100.8	7.2	7.2	11.52	
30	Mudstone	60	1567	864	1.5	96	7.2	4.8	10.8	
29	Fine sandstone	60	1507	782	1.6	100.8	11.52	2.88	11.52	
28	Siltstone	52	1447	755	1.6	87.36	6.24	6.24	9.984	
27	Mudstone	52	1395	864	1.5	83.2	6.24	4.16	9.36	
26	Siltstone	50	1343	755	1.6	84	6	6	9.6	
25	Mudstone	120	1293	864	1.5	192	14.4	9.6	21.6	
24	Fine sandstone	70	1173	782	1.6	117.6	13.44	3.36	13.44	
23	Sandy mudstone	44	1103	864	1.5	70.4	5.28	3.52	7.92	
22	Fine sandstone	48	1059	782	1.6	80.64	9.216	2.304	9.216	
21	Mudstone	46	1011	864	1.5	73.6	5.52	3.68	8.28	
20	Siltstone	54	965	755	1.6	90.72	6.48	6.48	10.368	
19	Mudstone	36	911	864	1.5	57.6	4.32	2.88	6.48	
18	Magmatic rock	300	875	737	1.5	472.5	20.25	47.25	54	Main key stratum
17	Mudstone	15	575	864	1.5	24	1.8	1.2	2.7	
16	Fine sandstone	28	560	782	1.6	47.04	5.376	1.344	5.376	
15	Sandy mudstone	30	532	864	1.5	48	3.6	2.4	5.4	
14	Siltstone	32	502	755	1.6	53.76	3.84	3.84	6.144	Sub-key stratum 4
13	8# Coal	16	470	864	1.5	25.6	1.92	1.28	2.88	
12	Siltstone	15	454	755	1.5	23.625	1.6875	1.6875	2.7	
11	Mudstone	32	439	864	1.5	51.2	3.84	2.56	5.76	
10	Siltstone	32	407	755	1.6	53.76	3.84	3.84	6.144	Sub-key stratum 3
9	Sandy mudstone	40	375	864	1.5	64	4.8	3.2	7.2	
8	Siltstone	30	335	755	1.6	50.4	3.6	3.6	5.76	
7	Mudstone	28	305	864	1.5	44.8	3.36	2.24	5.04	
6	Siltstone	30	277	755	1.6	50.4	3.6	3.6	5.76	Sub-key stratum 2
5	Piebald mudstone	30	247	864	1.5	48	3.6	2.4	5.4	
4	Siltstone	30	217	755	1.6	50.4	3.6	3.6	5.76	Sub-key stratum 1

Table 2 continued

Number	Lithology	Thickness/mm	Accumulated thickness(mm)	Ratio	Density/ (g/cm^3)	Weight/kg				Key strata
						Sand	Calcium carbonate	Gypsum	Water	
3	Fine sandstone	12	187	782	1.6	20.16	2.304	0.576	2.304	
2	10# Coal	40	175	864	1.5	64	4.8	3.2	7.2	
1	Grit stone	135	135	773	1.6	226.8	22.68	9.72	25.92	

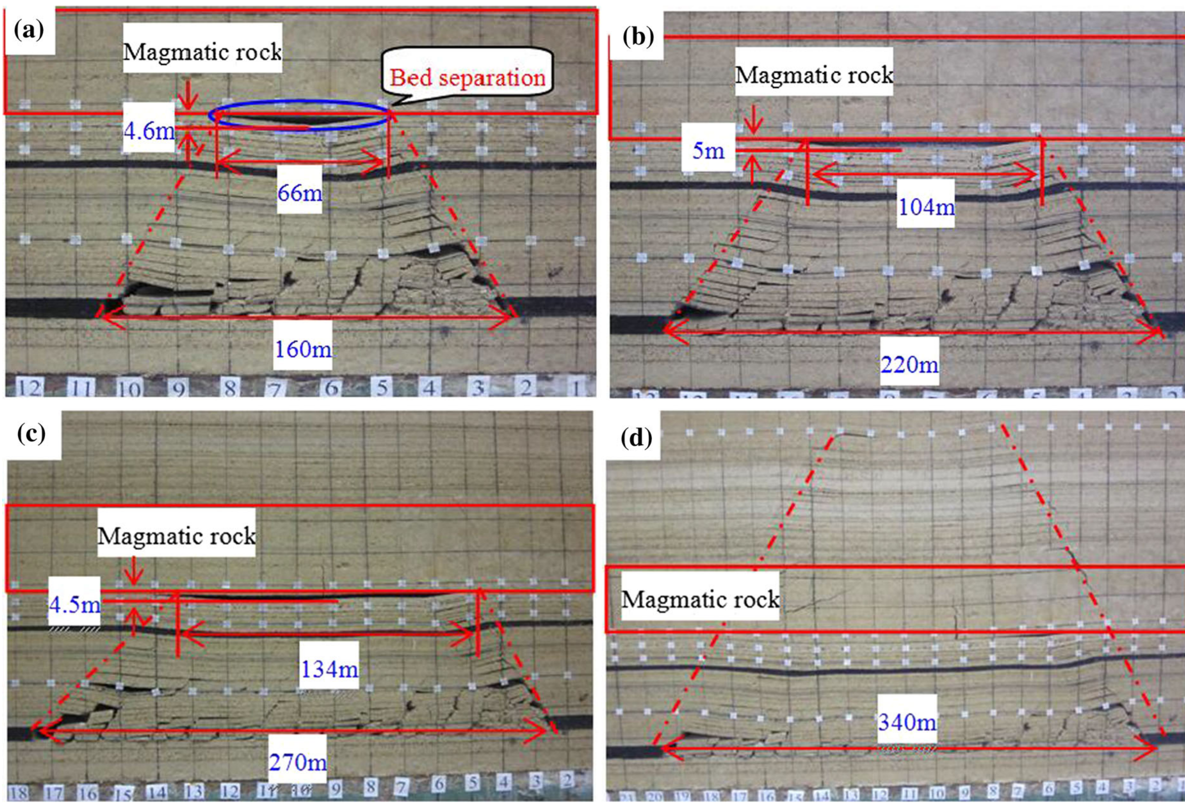

Fig. 7 The lower bed separation distribution before and after the first breaking of hard-thick magmatic rock. **a** The bed separation first develop to the bottom of magmatic rock (retreating 160 m), **b** The middle process of bed separation development 1 (retreating 220 m), **c** the middle process of bed separation development 2 (retreating 270 m), **d** The closure of bed separation with the first breaking of magmatic rock (retreating 340 m)

certain geological condition and mining area. Compact and complete hard and thick magmatic rock effectively prevents the escape of gas upward, finally a large number of gas accumulating in the bed separation space.

4 A Method for Determining the Height of "Three Zone" in the Overlying Strata of Magmatic Rock

The occurrence of dynamic disasters in 10414 working face of Yangliu coal mine is caused by the rupture of magmatic rocks, and there is a great relationship between the breaking of magmatic rocks and the formation of magmatic rocks. In order to study the mechanism of the dynamic disaster causing mechanism of the magmatic rock, which zone the hard thick magmatic rocks is in among the three zones should be determined.

Practice has proved that there is a big difference between many measurement results of coal caving mining fracture zone height and results of the estimated method with "Mining regulations Rules for pillar design under buildings, water bodies, railways and main roadway", the applicability of the empirical formula is questionable (Ni et al. 1996; Zan and Wu 2010). In order to find a more effective forecasting method, the domestic scholars have done a lot of related researches. Xu et al. (2009) found when the distance between the key strata and the mining coal seam is 7–10 times the height of mining height, the water conducted zone height should reach the nearest key stratum 10 times the height of the mining height. By comparing with the measured value of the medium thick coal seam and thick coal seam mining, it is believed that the height of the water conducted zone based on the key strata theory is closer to the measured value. Similar simulation experiment results show that the overlying height of "Three Zone" is affected by key strata (Wang et al. 2013).

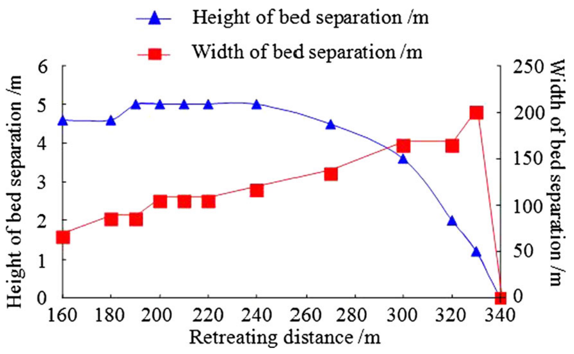

Fig. 8 The height and width of bed separation before and after the first breaking of hard-thick magmatic rock

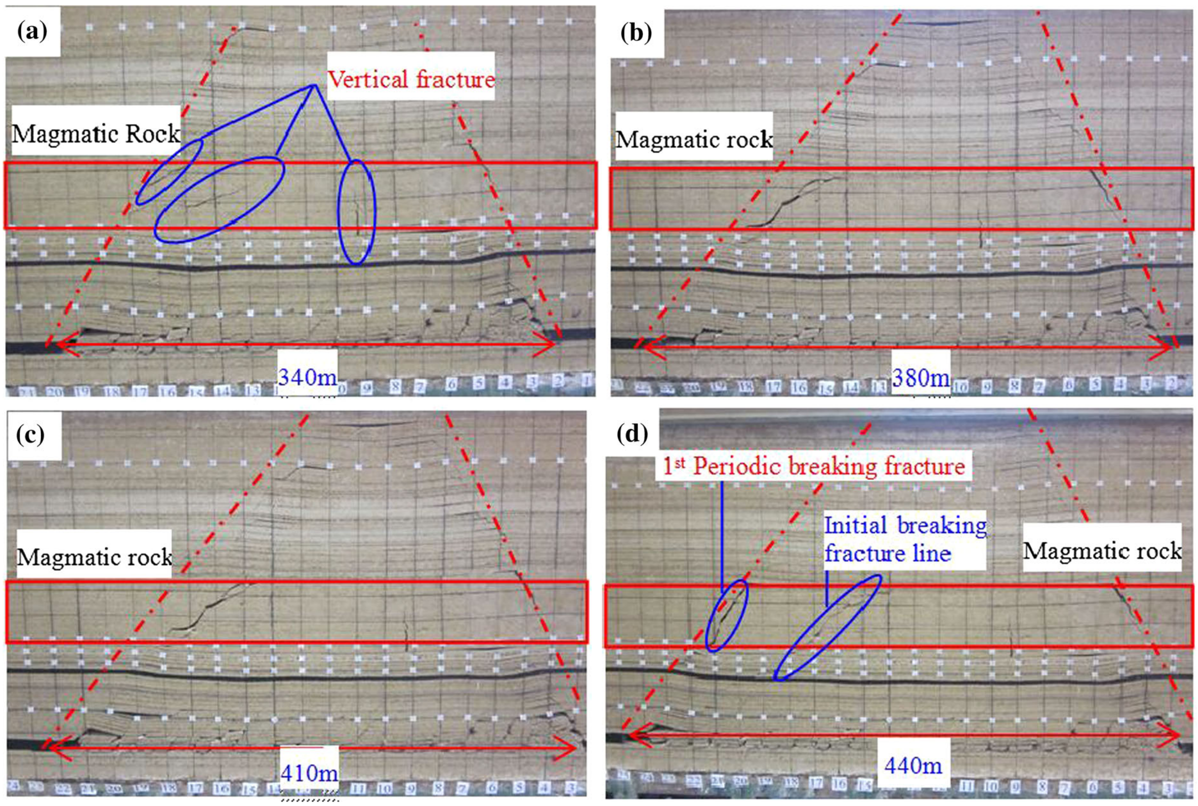

Fig. 9 The development process of the lower bed separation before and after the 1st periodic weighting of hard-thick magmatic rock. **a** Closure of bed separation after the first breaking of magmatic rock (retreating 340 m), **b** process 1 after the first breaking of magmatic rock (retreating 380 m), **c** process 2 after the first breaking of magmatic rock (retreating 410 m), **d** Periodic breaking of magmatic rock (retreating 440 m)

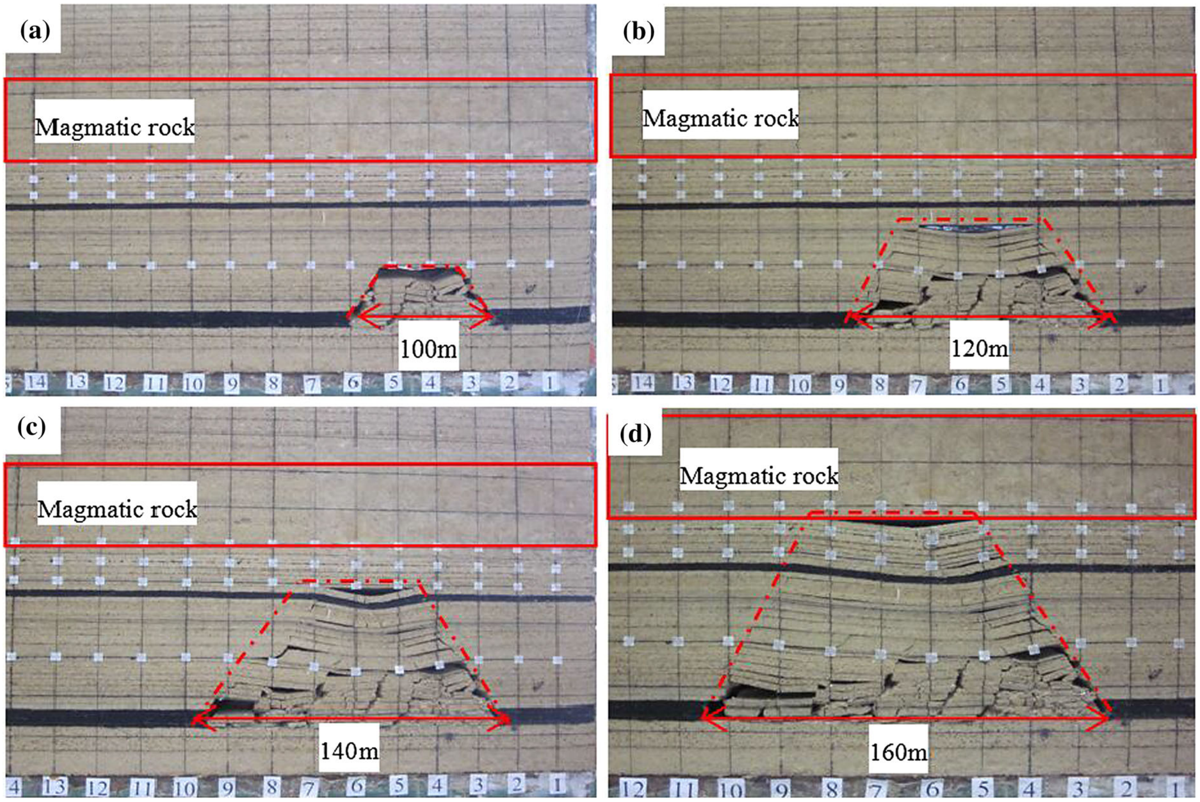

Fig. 10 The development process of bed separation in vertical direction. **a** Retreating 100 m, **b** retreating 120 m, **c** retreating 140 m, **d** retreating 160 m

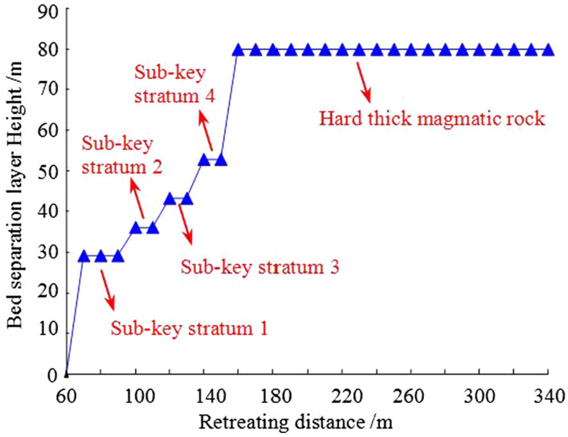

Fig. 11 The change regulation of bed separation layer height

To sum up, the traditional judgment method that depends on the height of the water conducting fractured zone is no longer applicable, while determining method based on the key strata theory is more objective and truthfulness (Shi et al. 2012). Based on the above analysis, by combing mining height, mining area, overburden rock mechanical properties and other factors, this paper puts forward the method of "Three Zone" identification method and carries on the example verification.

4.1 "Identification Steps for "Three Zone"

Step 1 According to the drilling histogram and overlying strata lithology, it is advisable to use the key strata theory (Qian et al. 2003) to determine all the key layers above the mining field. Assuming that the mining field is covered with n layers of the key strata, the mining pressure model is shown in Fig. 12, where then key stratum is the main key stratum and other key strata are the sub-key stratum.

Step 2 Calculation of ultimate stability span of key strata

Marcus engineering formula (Qian et al. 2003) proposed by Qian Ming-gao, academician of Chinese Academy of Engineering, is used to carry out the

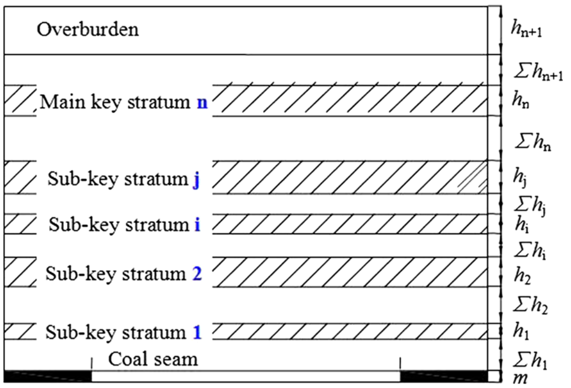

Fig. 12 Rock pressure model of working face

calculation of ultimate stability span of key strata. Calculations of ultimate stability span of key strata under different boundary conditions are as follows:

Boundary condition (1): Four clamped boundaries (surrounded by solid coal)

$$a_1 = \begin{cases} b \cdot \sqrt[4]{\dfrac{l_m^2}{b^2 - l_m^2}} (l_m < b < \sqrt{2} l_m) \\ \dfrac{b}{\sqrt{2} l_m} \cdot \sqrt{b^2 - \sqrt{b^4 - 4 l_m^4}} (b \geq \sqrt{2} l_m) \end{cases} \quad (1)$$

where a_1 is the ultimate stability span of key strata along the retreating direction; b is the ultimate stability span of key strata along the length direction of working face; l_m is the dimensionless number of ultimate stability span of slab roof with infinite length clamped in four boundaries, $l_m = \frac{h}{1-\mu^2} \cdot \sqrt{\frac{2\sigma_t}{q}}$; H is the key strata thickness; μ is the key strata Poisson's ratio; σ_t is key strata tension strength; q is the key strata weight and load.

Boundary condition (2): One boundary free (gob or faults) and three clamped boundaries

$$a_2 = \begin{cases} b \cdot \sqrt[4]{\dfrac{l_m^2}{2(b^2 - l_m^2)}} \left(l_m < b < \sqrt[4]{2} l_m \right) \\ \dfrac{b}{l_m} \cdot \sqrt{b^2 - \sqrt{b^4 - 2 l_m^4}} \left(b > \sqrt[4]{2} l_m \right) \end{cases} \quad (2)$$

Boundary condition (3): Two adjacent boundaries clamped and two adjacent boundaries simply supported

$$a_3 = \begin{cases} b \cdot \sqrt[4]{\dfrac{2 l_m^2}{3b^2 - 2 l_m^2}} \left(\sqrt{\dfrac{2}{3}} l_m < b < 2\sqrt{\dfrac{2}{3}} l_m \right) \\ \dfrac{b}{2 l_m} \cdot \sqrt{3b^2 - \sqrt{9b^4 - 16 l_m^4}} \left(b > 2\sqrt{\dfrac{2}{3}} l_m \right) \end{cases} \quad (3)$$

Boundary condition (4): Three boundaries free (gob or faults)

$$a_4 = \begin{cases} b \cdot \sqrt[4]{\dfrac{4 l_m^2}{15b^2 - 10 l_m^2}} \left(\sqrt{\dfrac{2}{3}} l_m < b < 2\sqrt[4]{\dfrac{10}{225}} l_m \right) \\ \dfrac{b}{2\sqrt{2} l_m} \cdot \sqrt{15b^2 - \sqrt{225b^4 - 160 l_m^4}} \left(b > 2\sqrt[4]{\dfrac{10}{225}} l_m \right) \end{cases} \quad (4)$$

Step 3 Based on the calculation results of step 2, combined with the mining parameters of the working face, determine the key strata layer of breaking. Judgment condition is:

1. For boundary condition (1) and boundary condition (2), $b \geq l_m$;
2. For boundary condition (3) and boundary condition (4), $b \geq \sqrt{2/3} l_m$.

When the key stratum length along the retreating direction is equal to the ultimate stability span, the ultimate length of working face $L_C = b + 2\sum H \cot\alpha$. When the retreating distance L_T is equal of greater than $a + 2\sum H \cot\alpha$, the key stratum will be broken. The corresponding geometric relations are shown in Fig. 13. Where $\sum H$ is vertical distance between key stratum and coal seam, α is the fracture angle of overlying strata, usually ranging from 65° to 70° (Ma et al. 2011).

Step 4 To determine the height of caving zone and fractured zone

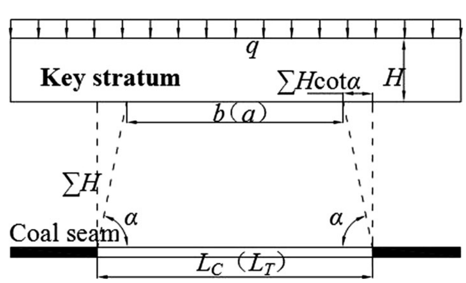

Fig. 13 Mechanical model

According to the theory of rock pressure, the main roof is the nearest key stratum to the mining field. So, firstly assume that the main roof is the key stratum 1. Then the height of bed separation space under the key stratum 1 is

$$\Delta h_1 = m - (K_z - 1) \sum h_1 \tag{5}$$

where K_z is the breaking expansion coefficient of caving rock from 1.33 to 1.5 (Frank et al. 1979).

S–R (Sliding and Rotating) instability theory (Qian et al. 2003) is used to judge the stability of the key stratum 1, judgment condition is

1. Sliding instability condition: $\frac{h}{L} \geq \frac{1}{2}\tan\varphi$
   where φ is friction angle between rock, from 38° to 45°, $\tan\varphi = 0.8 \sim 1$; h is the rock thickness; L is the rock length, $L = a/2$; a is the ultimate stability span of key strata along the retreating direction.
2. Rotating deformation instability condition: $\Delta h > \Delta$
   where Δh is the bed separation space height under the key stratum; Δ is the allowing maximum swivel height for rock to remain stable.

For Δ we have (Qian et al. 2003): $\Delta = h \cdot (1 - \sqrt{\frac{1}{3nK \cdot \overline{K}}})$. where $n = \sigma_c/\sigma_t$, σ_c is the compression strength, σ_t is tensile strength; $\overline{K} = \sigma_p/\sigma_c$; σ_p is compression strength between rock mass, $\sigma_p = \frac{2qL^2}{(h - L\sin\alpha)^2}$, $\sin\alpha = \frac{1}{\frac{L}{h} + \sqrt{\frac{\sigma_t}{6Kq}}}$; K is a constant determined by the boundary condition, from 1/2 to 1/3; q is unit area load on rock.

If the key stratum 1 can meet the S–R stability theory of the two instability conditions at the same time, the assumption that the key stratum 1 as the main roof is not established, that is the key stratum 1 belongs to the caving zone, otherwise belongs to fracture zone.

Determine the key stratum layer by layer by following the above steps.

Step 5 Through step 4 to determine the boundary layer between the caving zone and the fractured zone, assuming that the boundary layer is i (i>1), the highest located broken key stratum is j ($i \leq j \leq n$).

The bed separation space height under the highest located key stratum before its broken is

$$\Delta h_j = m - (K_z - 1)\left(\sum h_1 + h_1 + \sum h_2 + h_2 + \sum h_i\right) - (K_l - 1)\left(h_i + \sum h_j\right) \tag{6}$$

where K_l is the breaking expansion coefficient of fractured rock from 1.15 to 1.33 (Frank et al. 1979).

When $j < n$, the highest located broken key stratum is sub-key stratum, and the upper main key stratum n and the follow-up layers and the surface layer belong to the continuous deformation zone, then the mining condition is sub-critical extraction; When $j = n$, the main key stratum is broken in the mining area of the working face, and the main key stratum n and the follow-up layers belong to the fractured zone, the overlying soft rock (mainly mudstone), the loose deposition layer including the surface area belong to the continuous deformation zone, then the mining condition is full subsidence. In particular, there may not be a continuous deformation zone when the main key stratum is covered with a thin layer of soft rock and a thin layer of loose sediment.

Step 6 For a certain geological condition and mining area, the “Three Zone” height of the overlying strata is relative. Along the excavation of the adjacent working face coal seam, the three belt height of some rock strata in the overlying rock will be changed. When the gob size is larger than the ultimate stability span of key strata, the main key stratum is broken, leading to the upward development of fractured zone. If the overlying strata thickness of the main key stratum is thin, the range of the fractured zone will be spread to the surface.

4.2 Engineering Case Verification

According to the “three zones” identification method of the overlying strata, the “Three Zones” of the overlying strata are determined. 10414 is the first mining working face, with four boundaries clamped. Using the formula in step 2 to calculate the ultimate stability span of key strata, the calculation parameters and calculation results are shown in Table 3.

Through the calculation results, it is clear to know all the key strata satisfy $b > l_m$, the key strata in the retreating process will be broken. The bed separation height Δh under the sub-key stratum 1 is 0.9415 m, $\Delta = 2.53$ m. The key stratum 1 doesn’t meet the S–R

Table 3 Calculation parameter values

Number	Lithology	Thickness/m	Poisson's ratio μ	Tensile strength σ_t/MPa	Compression strength σ_c/MPa	Overlying load q/MPa	The dimensionless number of ultimate stability span l_m/m	The ultimate stability span of key strata along the length direction of working face b	The ultimate stability span of key strata along the length direction of working face a	Retreating distance L_T
4	Sub-key stratum 1	7.02	0.19	3.11	35.81	0.411	28.31	168.31	28.32	37.25
6	Sub-key stratum 2	11.05	0.19	3.11	35.81	1.502	23.31	154.36	23.32	45.1
20	Sub-key stratum 3	12.45	0.22	3.59	42.64	1.469	28.9	103.43	28.99	94
24	Main key stratum	47.01	0.18	6.3	112.25	11.252	51.412	53.59	98.81	459.93

stability theory of the two instability conditions at the same time, and then the key stratum 1 and its follow-up layers belong to the fractured zone. The lower strata under the key stratum 1 belong to the caving zone, the caving zone height is 14.07 m.

From the case analysis in the Sect. 2 of this paper, we know the key stratum magmatic rock was broken, and the hard thick magmatic rock belongs to the fractured zone.

When the hard thick magmatic rock main key stratum breaks, the corresponding working face retreating distance by the theoretical calculation is 459.93 m, which belongs to the fracture zone, so the theoretical calculation conclusion is more practical.

5 Analysis of the Fracture Development and Disaster Causing Mechanism of the Overlying Strata of the Hard Thick Rock

When hard thick magmatic rock is in different zone of "Three Zone", the bed separation and fractures height and breaking disaster-causing mechanism will be different. The hard thick magmatic rock distribution data show that the hard thick magmatic rock usually in high located layer with large thickness, generally does not belong to the caving zone (Li et al. 2015; Huang 2007; Shen and Brett 2014). Therefore, only the hard thick magmatic rock in the caving zone and the continuous deformation zone two conditions are analyzed.

5.1 Analysis of the Mechanism of the Fracture Development and Disaster Causing Mechanism by the Hard Thick Magmatic Rocks in the Fractured Zone

5.1.1 The Effect of Hard Thick Magmatic Rock on the Bed Separation Gas Outburst

The high degree of thermal metamorphism of the adjacent coal seams in the lower part of the hard thick magmatic rock makes the coal body containing a large amount of gas, which is the major source of gas in bed separation space. Affected by the excavation of coal seam, bed separation space begins to come into being under the magmatic rock. Coal body expansion and deformation release the gas adsorption in coal body. With the retreating of working face, the amount of gas

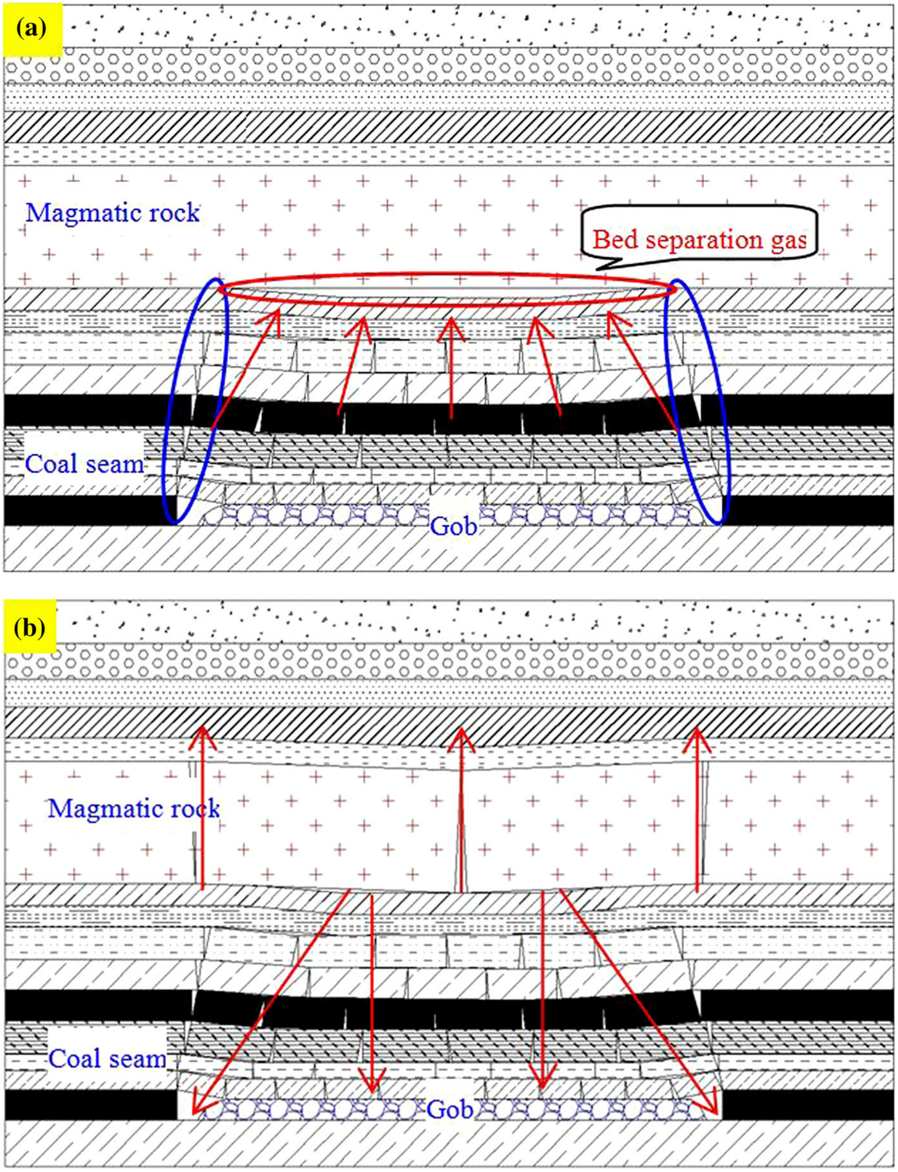

Fig. 14 The effect of hard thick magmatic rock on the bed separation gas outburst. **a** Fracture development and gas accumulation, **b** process of gas outburst accident under hard thick magmatic rock

effusion keeps increasing. Hard thick magmatic rock, with compact structure and good integrity, can effectively prevent the gas from escaping to the upper space, eventually there will be large amount of gas accumulating in the bed separation space under the magmatic rock. The dynamic process of gas rising, diffusion and accumulation is shown in Fig. 14a. The blue oval area in the figure is "O"-shaped circle, and the arrows indicate the accumulation of gas.

As shown in Fig. 14b, when the hard thick magmatic rock sudden lose stability, instantaneous release of elastic energy has a strong impact on the bed separation gas, and when separation space disappears, a majority of bed separation gas through the "O" ring into the working face and roadway, another part of the gas escapes through cracks to the upper space.

The 10414 working face 2# gas drainage borehole through the bed separation zone of magmatic rock, after the first breaking of magmatic rock, bed

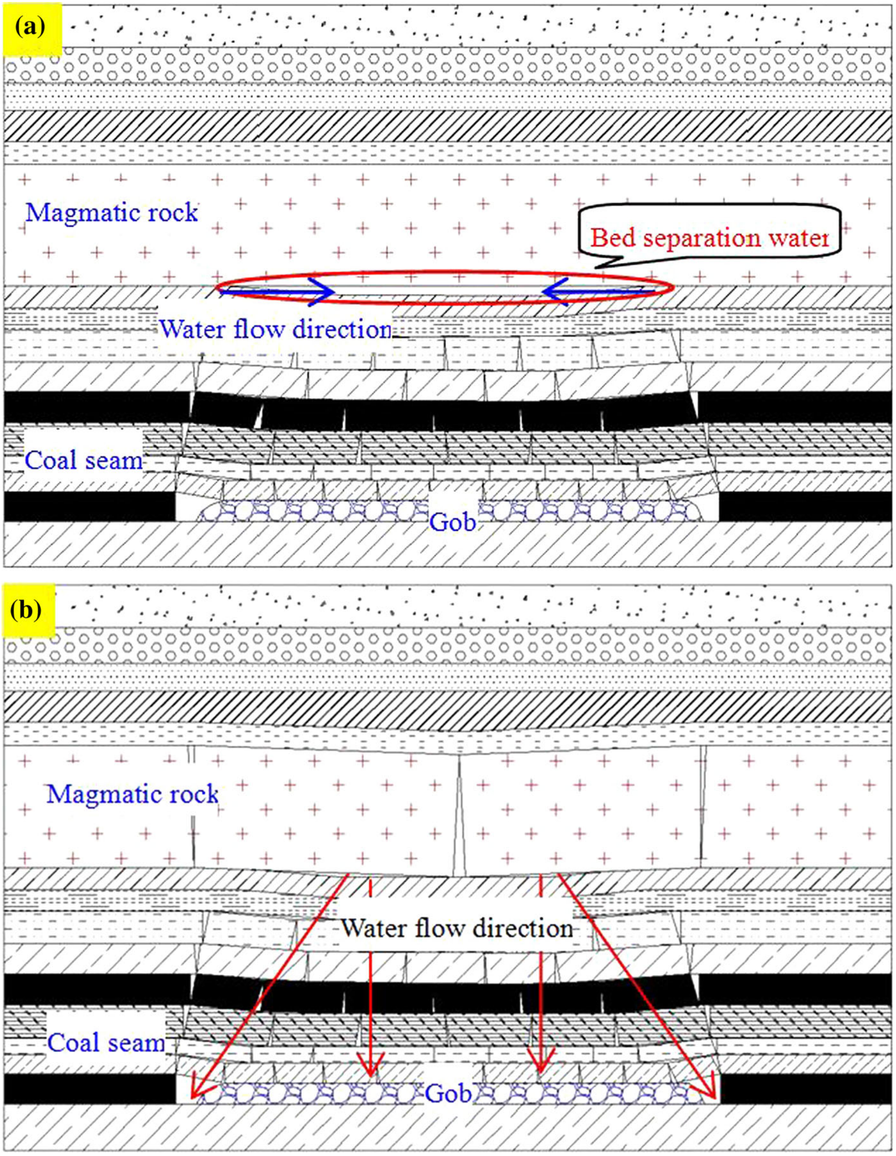

Fig. 15 Sketch of the influence of hard thick magmatic rock on water inrush. **a** Bed separation development and water accumulation, **b** process of water inrush accident under hard thick magmatic rock

separation gas was sprayed to the surface under the strong impact force, causing gas-jet phenomenon.

5.1.2 The Effect of Hard Thick Magmatic Rock on the Bed Separation Water Inrush

According to the similar simulation experiment, it is known that the soft rock (usually is mudstone) between the magmatic rock and the adjacent sub-key stratum is in the whole bending and sinking, and the integrity is good, which can effectively prevent the loss of water. When the lower strata of magmatic rock is aquifer, water under the action of negative pressure of bed separation flows into the main key stratum bed separation space along the bedding fractures, finally bed separation space tend to store large amounts of water (Fig. 15a).

As shown in Fig. 15b, when the hard thick magmatic rock sudden lose stability, the strong impact force released by magmatic rock breaking transfers to the lower weak strata, the weak strata are broken by the strong impact force formatting the water inrush

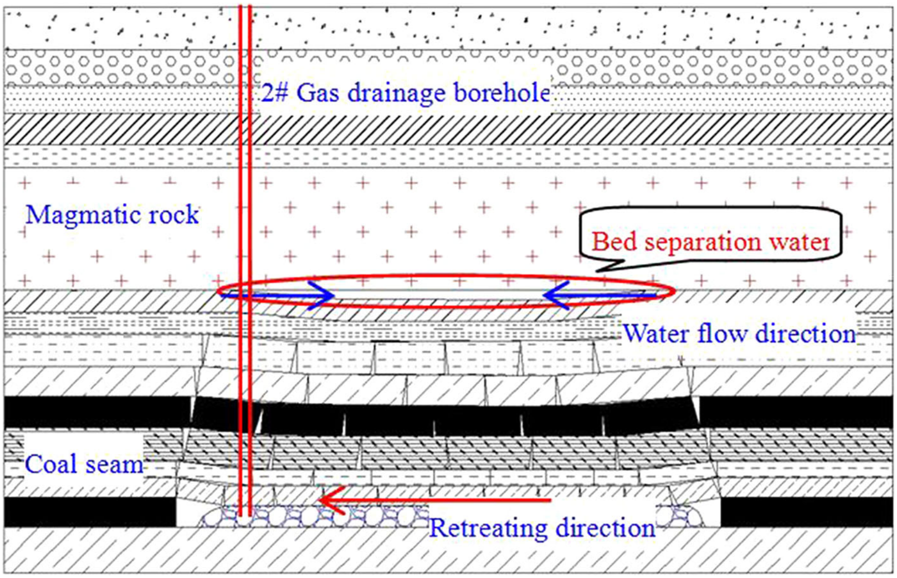

Fig. 16 Position of 2# gas drainage borehole in Yangliu coal mine

channel and resulting in the occurrence of water inrush accident.

In Fig. 16, the bed separation space and mining space are connected by 2# gas drainage borehole, but because of the 2# gas drainage borehole in the shallow area of bed separation, which is conducive to the accumulation of water. Before the breaking of magmatic rock, the water level is lower than the height of borehole and bed separation connection point. The amount of water flowing into the bed separation space is greater than the amount of water loss; water will gradually accumulate in the bed separation space, thus forming a large number of bed separation water. With the breaking of magmatic rock, broken rock compress bed separation water in a short period of time runs along the path of least resistance 2# gas drainage borehole into the gob behind the working face.

With the similar simulation experiment results, magmatic rock influence on the bed separation of gas outburst and water inrush accidents mainly occur during the initial breaking, and periodic breaking will not cause the bed separation of gas outburst and water inrush accidents.

5.2 Analysis of the Mechanism of the Fracture Development and Disaster Causing Mechanism by the Hard Thick Magmatic Rocks in the Continuous Deformation Zone

When the hard thick magmatic rock is in the continuous deformation zone, magmatic rock only occurs in very small bending and subsidence. There will be a large amount of gas and water in the bed separation space under the magmatic rock, but because the magmatic rock can keep stable state, and will not cause bed separation of gas outburst and water inrush accidents.

When mining in the adjacent working face, gob size reaches the ultimate stable span causing the magmatic rock breaking and the zone magmatic rock in transfer from continuous deformation zone to fractured zone. Under this circumstance, once the magmatic rock is broken, its effect on the gas outburst and water inrush accident is as same as that when the hard thick magmatic rock is in the continuous deformation zone. Water and gas accumulated in the lower bed separation space of the magmatic rock when mining in the last working face is easy to become a potential risk of gas outburst and water inrush accident.

6 Conclusions

1. Along the working face advancing direction, the height of bed separation under the magmatic rock increases in the trend of “Increase–Stability–Decrease”, and the width of bed separation increases linearly. The width of bed separation reaches the maximum before the first breaking of magmatic rock, the bed separation completely close after the breaking. There are no obvious bed

separations during the period breaking of magmatic rock. Along the direction of the height of roof, the development of bed separation is characterized by bottom-up jump based on the key strata.

2. The analyzed results of "Three zone" height is obtained by the discriminating method of overlying strata Three Zones which is based on the key strata theory and the S–R instability theory in line with the actual facts.
3. When the hard-thick magmatic rock is in the fractured zone, large amounts of gas and water are easy to accumulate in the bed separation space and "O" ring space around the gob. The first breaking of magmatic rock may induce bed separation gas outburst and water inrush. When the hard-thick magmatic rock is in the sagging zone, the long-term stability of magmatic rock will not cause serious disasters. However, with the adjacent working face mining, bed separation gas and water often become a safety hazard. Magmatic rock influence on the bed separation of gas outburst and water inrush accidents mainly occur during the initial breaking, while periodic breaking will not cause the bed separation of gas outburst and water inrush accidents.

Acknowledgements This study was supported by the National Natural Science Foundation of China (51374139), the natural science foundation of Shandong Province (ZR2013EEM018) and the Graduate Innovation Fund of Shandong University of Science and Technology (No. YC150307).

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