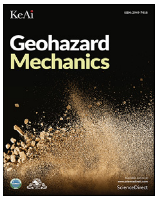
Geohazard Mechanics 1 (2023) 297–307

Contents lists available at ScienceDirect

Geohazard Mechanics

journal homepage: www.keaipublishing.com/en/journals/geohazard-mechanics



Monitoring and evaluation of disaster risk caused by linkage failure and instability of residual coal pillar and rock strata in multi-coal seam mining

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ARTICLE INFO

Keywords:
Multi-seam mining
Residual coal pillar
Linkage instability
Rock burst
Monitor and evaluation

ABSTRACT

Comprehensive research methods such as literature research, theoretical analysis, numerical simulations and field monitoring have been used to analyze the disasters and characteristics caused by the linkage failure and instability of the residual coal pillars-rock strata in multi-seam mining. The effective monitoring area and monitoring design method of linkage instability of residual coal pillar-rock strata in multi-seam mining have been identified. The evaluation index and the risk assessment method of disaster risk have been established and the project cases have been applied and validated. The results show that: ①The coal pillar will not only cause disaster in single-seam mining, but also more easily cause disaster in multi-seam mining. The instability of coal pillars can cause not only dynamical disasters such as rock falls and mine earthquakes, but also cause surface subsidence and other disasters. ②When monitoring the linkage instability of residual coal pillar-rock strata, it is not only necessary to consider the monitoring of the apply load body (key block), the transition body (residual coal pillar) and the carrier body (interlayer rock and working face), but also to strengthen the monitoring of the fracture development height (linkage body). ③According to the principles of objectivity, easy access and quantification, combined with investigation, analysis, and production and geological characteristics of this mining area, the main evaluation indexes of the degree of disaster caused by linkage instability of residual coal pillar-rock strata are determined as: microseismic energy, residual coal pillar damage degree, fracture development height. And the evaluation index classification table was also given. ④According to the measured value of the evaluation index, the fuzzy comprehensive evaluation method was used to calculate the disaster risk degree in the studied mine belongs to class III, that is, medium risk level. The corresponding pressure relief technology was adopted on site, which achieved a good control effect, and also verified the accuracy and effectiveness of the risk evaluation results.

1. Introduction

To ensure the safe, green, and efficient mining of coal resources, a lots of coal pillars need to be left around the stope. The stability of the coal-rock combination system formed by the residual coal pillar and overlying strata is crucial to the safety of the stope, overlying strata and even the surface [1–3]. The failure and instability of coal pillar and overlying strata may also cause major dynamic disasters such as casualties [4,5]. Therefore, it is necessary to study the monitoring and evaluation of disaster risk caused by the linkage failure and instability of residual coal pillar and rock strata.

Numerous scholars have conducted a lot of research on the disaster phenomenon and mechanism of strong strata behaviors caused by coal pillar failure and instability. It is generally believed that the abutment pressure of the remaining coal pillar forms a large stress concentration in the coal seam working face. Affected by the mining disturbances of the lower coal seams, the abutment pressure of the coal pillars and the caving movement of the roof rock are superimposed on each other, and the instability of the coal pillars causes the local roof to suddenly cut and fall. Then the overlying coal pillar and the roof rock collapse at the same time, resulting in strong strata behaviors appearing in the mining coal seam [6–11]. Studies have shown that when mining a single coal seam, coal

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https://doi.org/10.1016/j.ghm.2023.11.001
Received 16 August 2023; Received in revised form 1 November 2023; Accepted 1 November 2023

Table 1

Disasters and accidents caused by coal pillar failure and instability [9,19,20,37,39–42].

Coal mine	Disaster area	Time	Mining methods and technical parameters	Disaster and accident
Pingmei No.12 mine	Ji No.15	–	Overlying residual coal pillar, the average mining height is 3.3 m	The power is obvious, the coal rock is broken, the coal wall and the roof are unstable; stress concentration, coal and gas outburst accidents easily occur; the support is difficult and the support effect is poor
Tashan coal mine	No.3–5 joint coal seam	–	The size of coal pillar varies greatly, ranging from 6 to 63 m, with an average mining thickness of 12.56 m	The mine pressure is strong, and the roof rock is broken seriously; When the anchor cable is played, it is necessary to repeatedly pass through the hole when the charge is difficult; Frequent abnormal sound, serious film
Shiya joint office coal mine	3^{-1} coal seam	2004.10	Buried depth 183 m, room and pillar mining, mining height is 6 m	Large area of roof collapse, mine earthquake magnitude of 4.2; there were sounds like firecrackers under the shaft two days before the collapse; subsidence area causing damage to buildings, land, etc
Silaogou Mine	No.14 coal seam	2009.02	Overlying residual coal pillar, mining height 3.54 m	280 m roadway severely damaged; Floor heave 0.3–1.2 m; The overall displacement of the belt conveyor is 0.5–1.5 m
Daliuta Mine	2^{-2} coal seam	2011.08	The mining height is 3.6 m, the buried depth is 86 m, and the spacing of coal seam is 23.31 m	Work face No.66-79 support column is crushed, No.60-93 support safety valve is damaged. There is no obvious separation of strata and slope in the advance section of both sides of the roadway. The advance supporting monomer of the two lanes did not shrink significantly, and the supporting condition was normal. There is an obvious collapse crack of the advanced working face at 36 m away from the return passage. No cracks appeared near the position of the pressure frame
Chang Xing well field	–	–	Room type goaf, the average buried depth is 170 m and the average mining height is 3.5 m	A large area of goaf collapsed, with a total area of $6.31 \times 10^5 m^2$; Mine earthquake magnitude 2.1–3.3; High-rise buildings shook slightly
Shigetai Mine	3^{-1} coal seam	2013.12	Room and pillar goaf, Buried depth 124 m, mining height 4.1 m	9 incidents of shelf compression; 121 scaffolds were pinned down; work face closed for 52 days
SanheJian Mine	No.7 coal seam	2015.01	Top residual coal pillar, the distance between coal seams is 20~30 m, and the coal thickness is 2.2 m	The coal body shifted to the right 1.5 m and the anchor rod was pulled out; the shed legs are tilted and bent; the seismic energy is 4.8×10^4 J
Xinzhou Kiln mine	No.11, 14 coal seam	1995.101996.032001.06 2016.01 2018.02	Columnar goaf, the mining depth is 30,100 m, below the isolated coal pillar	The surface collapse area is about 128,000 m^2; the single column bends and falls into the bottom coal; five collapses of different scales occurred afterwards; the maximum width of the surface crack is 5 m; five microseismic events larger than 105 J occurred in the previous week
Yujialiang Mine	4^{-3} coal seam	2018.02	Room and pillar goaf, the buried depth is 102 m, the mining height is 1.7 m, and the seam spacing is 22 m	Pressure frame accident; the coal wall Blasting Gang; the top beam of the support is pressed into the shearer
Jinhuagong Mine	No.12 coal seam	–	Overlying residual coal pillar, mining depth of 356–360 m	Roof height 2–10 m; slope severity; working face shutdown; hydraulic support press frame
Shan Meng deep mining area A	3^{-1}101Busy work auxiliary transport lane	2018.03	The average buried depth is 707 m, nearly horizontal coal seam; the average coal thickness is 6.36 m and the width of coal pillar is 40 m	The whole roadway was destabilized by impact in the 260 m range outside the advance support. The scene was accompanied by strong shock waves and strong tremors. Floor impact occurs in roadway, instantaneous floor heave, maximum floor heave up to 2.0 m. The impact deformation of the left and right sides of the roadway is serious, and the maximum shrinkage is 0.8 m
Shan Meng deep mining area B	No.2 coal seam 402 block	2018.10	Comprehensive mechanized coal mining, one time mining full height, average buried depth of 720 m, nearly horizontal coal seam. The thickness of coal seam varies from 5.64 to 7.33 m, and the width of coal pillar is 350 m	Two large energy mine earthquakes occurred during the mining process. The first one has an energy of 5.08×10^5 J and a magnitude of 2.06, and the other one has an energy of 1.16×10^6 J and a magnitude of 2.25. At the time of the incident, the earthquake was clearly felt on the ground. There is a loud sound of coal cannon on the site of the working face, the shaking at the end of the slide is obvious, and the shaking at the head is slight. Within 200 m in front of the working face, a large amount of slag has fallen from the roof, and deformation has occurred at the shoulder corner of the roadway in some areas
Xuzhuang coal mine	No.7 coal seam	2019.05	Buried depth of 680–700 m, overlying residual coal pillar, coal thickness of 6.02 m	A strong mine earthquake event with a maximum energy of 119 kJ; the slagging of coal seam, the sound of coal blast and the vibration are severe; the phenomenon of sucking and sticking is frequent
Liuhuanggou mine	(4–5)06 face	2019.12	Overlying residual coal pillars, the mining depth is 323,333 m, large seam thickness, large dip Angle	Mine quake, magnitude 3.1; loud sound of coal cannon; roof shaking off slag; hydraulic support press frame

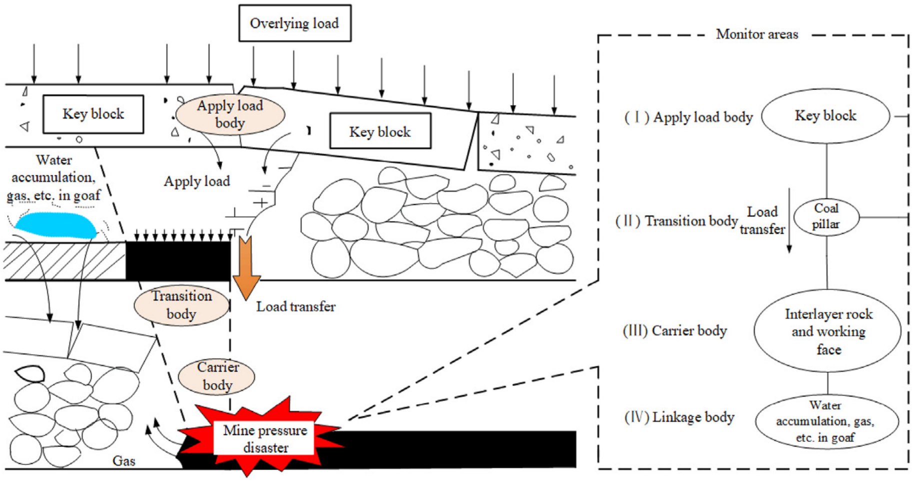


Fig. 1. Monitoring area of linkage instability of residual coal pillar and rock strata (Modified from Ref. [43]).

Table 2
Calculation formula for height of caving zone and fracture zone.

Overburden lithology (uniaxial compressive strength and main rock names)	Caving zone height/m	Fracture zone height/m
Hard (40–80 MPa, quartz sandstone, limestone, sandy shale, conglomerate)	$H_m = \frac{100\sum M}{2.1\sum M + 16} + 2.5$	$H_{li} = \frac{100\sum M}{1.2\sum M + 2.0} \pm 8.9$
Medium hard (20–40 MPa, sandstone, argillaceous limestone, sandy shale, shale)	$H_m = \frac{100\sum M}{4.1\sum M + 19} + 2.2$	$H_{li} = \frac{100\sum M}{1.6\sum M + 3.6} + 5.6$
Soft (10–20 MPa, mudstone, argillaceous sandstone)	$H_m = \frac{100\sum M}{6.2\sum M + 32} + 1.5$	$H_{li} = \frac{100\sum M}{3.1\sum M + 5} + 4.0$
Very weak (<10 MPa, bauxite, weathered mudstone, clay, sandy)	$H_m = \frac{100\sum M}{7.0\sum M + 63} + 1.2$	$H_{li} = \frac{100\sum M}{5.0\sum M + 8.0} + 3.0$

pillar failure and instability can easily lead to disaster accidents such as roof fall [12]. In the multi-seam mining, affected by disturbances of the lower coal seams, the failure and instability of the coal pillars will cause other effects besides roof falls. When the coal face mining under the short distance coal seam is overlying and overlying coal pillar, the strong strata behavior phenomenon is easy to appear in the coal seam. This phenomenon results in serious coal wall flapping, large opening of support safety valves and bulging of two lanes [13–15]. There will even be hydraulic support live column sharp contraction, support compression, hurricane impacts and other mining pressure disasters. In serious cases, it will also cause major disasters such as mine earthquake, surface collapse and casualties [16–18]. For example, since 1991, the Xinzhouyao Coal Mine had suffered many disasters and collapses of different scales due to the failure and instability of isolated coal pillars. These disasters caused the surface collapse area of about 128,000 m^2, the maximum width of surface cracks was 5 m, and several microseismic events larger than 105 J were generated [19,20]. The Liuhuanggou Coal Mine was unstable in the overlying strata due to the destruction and instability of the residual coal pillars in December 2019. As a result, the mine not only produced strong strata behavior, such as strong coal cannon sound, roof vibration and slag removal, hydraulic support, and press frame, but also produced mine earthquake of magnitude 3.1 [9]. A typical example abroad was the large-scale instability accident of pillar group in South Africa in 1960. The accident caused the collapse of nearly 2 km^2 of the goaf, and 437 miners were killed by the disaster caused by pillar instability [21]. In 1998, the failure and instability of pillar in a coal mine in the United States caused mine earthquake [22].

From the disasters caused by rock movement induced by coal pillar instability, it can be found that the coal pillar-rock linkage instability mainly causes large deformation of roadway, roof collapse, and strong strata behaviors hazards such as shelf compression and rock burst [6,23,24]. In the mine pressure prevention, coal mine safety regulations provisions [25]: It is necessary to take comprehensive control measures such as evaluation and prediction, monitoring and early warning, prevention and treatment, effect inspection and safety protection when mining coal seams with strata behaviors manifestation [26–29]. Disasters induced by the instability of the coal column rock link are different from those caused by simple coal pillar failure, rock strata failure and instability. The disaster caused by the coal pillar-rock linkage instability is wider and more serious [7–12]. Therefore, based on monitoring, it is necessary to comprehensively evaluate the disaster risk caused by the coal pillar-rock linkage instability. Risk assessment can realize a quantitative evaluation of the impact and loss possibility caused by the linkage instability disaster of coal pillar and rock strata to people's life, property, and other aspects. At the same time, risk assessment can provide support for further control techniques [30–34]. In addition, with the emergence and development of a series of new theories such as system science and nonlinear dynamics, nonlinear dynamics inversion method, grey system method and fuzzy comprehensive evaluation method based on coal seam impact inclination test are gradually used in disaster assessment [35–38]. Most of the existing research results focus on disaster monitoring due to failure of residual coal pillars or roof breaking, and lack of comprehensive monitoring and evaluation of disaster risk caused by the residual coal pillar-rock linkage instability in multi-seam mining.

Based on this, this paper firstly investigates and analyzes the disasters characteristics induced by the failure and instability of coal pillar in some mining areas. Then, the effective monitoring areas and monitoring design methods of the linkage instability of coal pillars and rock formations in multi-coal seam mining were determined. At the same time, based on the confirmed effective monitoring area and monitoring design methods, the evaluation index of the disaster was established, and the disaster evaluation method was also proposed. Finally, taking multi-seam mining in 307 panel area of a mine as an example, the evaluation method was applied and verified. The above is all that has been done in this article, with the aim of providing a theoretical basis for the risk assessment of linkage instability of residual coal pillars-rock strata during and after the multi-seam mining process.

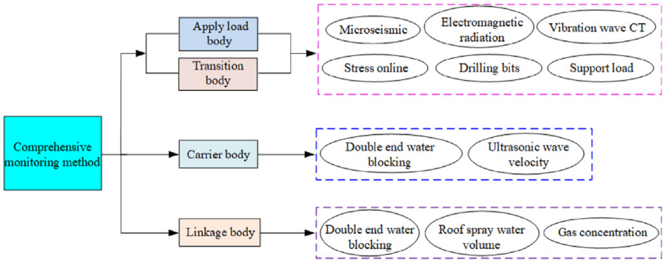


Fig. 2. Comprehensive monitoring method for linkage instability of residual coal pillar and rock strata.

2. Disaster characteristics of rock strata instability induced by coal pillar failure and its comprehensive monitoring method

2.1. Disaster characteristics of rock strata instability induced by coal pillar failure

Multi-seam mining exists widely in most mining areas in China. Taking Datong mining area as an example, there are mainly Jurassic and Carboniferous double-series coal seams in this area, which is rich in coal resource. The residual coal pillar of Jurassic coal seam in Datong mining area mainly includes: knife pillar type residual coal pillar, room pillar type residual coal pillar, strip residual coal pillar, short wall type residual coal pillar, roadway mining residual coal pillar, barn type residual coal pillar, skip mining residual coal pillar and so on. The formation time of Jurassic coal pillar in Datong mining area was up to 70 years [19,20]. The stability of Jurassic coal pillar is greatly affected by the change of surface building load, mining disturbance of lower coal seam, water accumulation and air oxidation in goaf. This will further lead to local or large-scale damage and instability, resulting in surface collapse or strong mining earthquakes and other disasters. The mining pressure occurrence disasters caused by the instability of the residual coal pillar in Datong mining area and some multi-seam mining areas are shown in Table 1.

After a comprehensively analyzing the statistics of disaster accidents caused by the instability of residual coal pillars from mines in Tables 1 and it can be found that the disaster accidents caused by the instability of residual coal pillars in mines have the following characteristics :

Table 3
Setting of microseismic monitoring and early warning value for rock burst risk [50–52].

Degree of danger	The stopping face	Driving roadway	Degree of risk
A Safe	1) The energy is 10^2–10^3 J, and the maximum Emax is $< 5 \times 10^3$ J 2) $\sum E < 10^5$ J/5 m propulsion degree	1) The energy is 10^2–10^3 J, and the maximum Emax is $< 5 \times 10^3$ J 2) $\sum E < 5 \times 10^3$ J/5 m propulsion degree	Low risk
B Weak danger	1) The energy is 10^2–10^5 J, and the maximum Emax is $< 1 \times 10^5$ J 2) $\sum E < 10^6$ J/5 m propulsion degree	1) The energy is 10^2–10^4 J, and the maximum Emax is $< 5 \times 10^4$ J 2) $\sum E < 5 \times 10^4$ J/5 m propulsion degree	General risk
C Medium danger	1) The energy is 10^2–10^6 J, and the maximum Emax is $< 1 \times 10^6$ J 2) $\sum E < 10^7$ J/5 m propulsion degree	1) The energy is 10^2–10^5 J, and the maximum Emax is $< 5 \times 10^5$ J 2) $\sum E < 5 \times 10^5$ J/5 m propulsion degree	Medium risk
D Strong danger	1) Energy 10^2–10^8 J, maximum $<$ Emax $<1 \times 10^7$ J 2) $\sum E < 10^8$ J/every 5 m propulsion degree	1) The energy is 10^2–10^7 J, and the maximum Emax is $> 5 \times 10^6$ J 2) $\sum E < 5 \times 10^6$ J/5 m propulsion degree	High risk
E Great danger	1) The energy is 10^2–10^9 J, and the maximum Emax is $> 1 \times 10^7$ J 2) $\sum E > 10^8$ J/5 m propulsion degree	1) The energy is 10^2–10^7 J, and the maximum Emax is $> 5 \times 10^6$ J 2) $\sum E > 5 \times 10^6$ J/5 m propulsion degree	Major risk

① From the point of view of the occurrence location, the working face where the strata behaviors appear due to the failure and instability of the residual coal pillar is generally shallow buried depth. The distance between its location and the overlying coal layer is relatively small, and it is concentrated under the remaining coal pillar of the overlying coal seam.

② From the view of the damage caused by strata behaviors, there are mainly single pillar bending, hydraulic support pressure frame, bottom heave or sheet wall, roof falling and even large energy mine earthquake. Some of them also caused the surface collapse, resulting in the damage of the ground building.

③ The residual coal pillar not only causes disasters due to pillar failure and instability in single-seam mining, but is more likely to cause various disasters and accidents in multi-seam mining. In addition, the disaster accidents caused by the failure and instability of coal pillar decrease year by year, but they still exist, and once the disaster accidents occur, the damage and loss are serious.

2.2. Monitoring area of rock instability induced by coal pillar instability

Effective selection of the monitoring area has an important influence on the accuracy of monitoring of pillar-rock linkage instability. The monitoring area should be determined before selecting the monitoring method of pillar-rock linkage instability. A large number of scholars and field engineers have analyzed the occurrence of strata behavior accidents during the mining of the remaining coal pillars in the overlying coal seams and put forward many monitoring and control measures. The dynamic pressure development of the residual coal pillar from the overlying coal seam is divided into three main control links, as shown in Fig. 1 [43]: ①The load source, that is the apply load body, which mainly refers to the weight of the key block formed by the breaking of the upper rock layer and the rock layer bearing the upper part. ② Load transfer, that is the transition body, mainly refers to the overlying coal seam load transfer role of the residual coal pillar. ③The load bearing, that is the carrier body, which mainly refers to the rock layer between the overlying rock and the residual coal pillar from the overlying coal seam when the coal seam is mined. It carries the load passed down from the residual coal pillar and so on, resulting in the dynamic pressure accidents such as sheet side, bottom heave, pillar bending and breaking and press frame during mining.

In fact, "three belts" such as caving zone, fracture zone and bending subsidence zone will be formed after the mining of the roof of the working face after the mining of the lower coal seam. The water, gas and stored CO_2 in the goaf of overlying coal seam will enter the coal seam under exploitation along the fracture zone and caving zone, and this will affect the safety of the work surface [44]. Multi-seam mining will not only cause the roof of the coal seam to break and collapse, but also further affect the stability of the roof of the upper coal seam. At the same time, multi-seam mining also leads to an increase in the overall fracture height. The height of caving zone and fissure zone can be calculated according to the equation in Table 2 of *the Code for Coal pillar Maintenance and coal Pressure Mining in Buildings, water Bodies, Railways and Main Shafts*.

Therefore, when monitoring the linkage failure of coal pillar and rock strata, it is not only necessary to consider the monitoring of the apply load body, the transition body, and the carrier body, but also to strengthen the monitoring of the fracture development height caused by the linkage failure of coal pillar and rock strata. These disasters caused by the linkage failure are called linkage disasters, and the corresponding area is the linkage monitoring body.

2.3. Monitoring method of rock stratum instability induced by coal pillar failure

Based on the above linkage instability characteristics of the residual coal pillar-rock strata and the monitoring area, it can be seen that the residual coal pillar-rock linkage instability caused by the mining of the

Table 4
Damage degree of floor rock corresponding to different acoustic wave velocities [53].

Pillar wave velocity v/($m\cdot s^{-1}$)	0~2000	2000~2500	2500~4000	4000~5000	5000~7500
Qualitative description	Coal pillar pole fracture	The coal pillar is very broken	The coal pillar is relatively broken	The coal pillar is relatively complete	The coal pillar is very complete
Degree of risk	Major risk	High risk	Medium risk	General risk	Low risk

Table 5
Risk degree classification corresponding to fracture development height [55–57].

Fracture development height/m	0~15	15~30	30~45	45~60	> 60
Degree of risk	Low risk	General risk	Medium risk	High risk	Major risk

lower coal seam is mainly a process in which the load imposed by the carrier is transferred to the carrier body through the transition body, resulting in the isokinetic pressure disaster of the pressure frame. Residual coal column-rock linkage instability will cause the fracture development height to increase further, which will have some impact on the mining of the coal seam face. The monitoring of the residual coal pillar-rock linkage instability should be carried out according to the above areas, namely, apply load body (key block), the transition body (residual coal pillar), the carrier body (interlayer rock and working face) and the linkage body (fracture development height, etc.). However, the disaster characteristics caused by the residual coal pillar-rock linkage instability are different in each region, so different monitoring methods should be used based on the disaster characteristics in different regions.

1) For the applied load body, the key block formed by the breaking of the upper rock layer, a certain dynamic pressure is formed on the working face when it is broken. Therefore, the monitoring of this area is mainly to monitor the ore pressure of the working face. 2) The residual coal pillar, that is the transition body is used as the medium to transfer the load. From the above studies and analysis, it can be found that whether the residual coal pillar failure plays a crucial role in the whole coal pillar-rock linkage instability failure. The main monitoring for this area is the damage degree of the remaining coal pillar. The damage degree of the remaining coal pillar can be monitored by ultrasonic wave speed. In general, the larger the wave velocity, the smaller the damage of the residual coal pillar, and the smaller the wave velocity, the greater the damage of the residual coal pillar [45–47]. However, it is necessary to determine the position and size of the coal pillar before monitoring the damage degree of the residual coal pillar, to avoid monitoring errors caused by the monitoring position not being in the coal pillar. According to the mining plan provided by the mine, the location of the residual coal pillar can be roughly determined. For the monitoring of the size of the residual coal pillar (the size of the coal pillar will change under the influence of the damage of the sheet wall, etc.), the borehole detector is usually drilled. The change photos in the borehole captured by the borehole detector show that the breakage in the borehole is more serious when the borehole is in the spalling area of the residual coal pillar. When the borehole is located in the residual coal pillar, the inside of the borehole is more dense, and the closer to the center of the residual coal pillar, the more dense the inside of the borehole. 3) The interlayer rock and working face of the carrier are the bearing areas of the load, and the residual coal pillar-rock linkage instability is mainly manifested in this area. The phenomena include roof subsidence, floor heave, sheet wall, pillar bending and breaking, and other major mine pressure accidents. Therefore, the monitoring of this area mainly carries on the monitoring of stress, deformation, and ore pressure appearance. The same method is used to monitor the strata behavior development in the carrier area. 4) The coal pillar-rock linkage instability will further increase the height of fracture development in coal face. The monitoring of the linkage area is mainly to monitor the fracture and fracture development in the overburdened rock. Based on the above analysis, a comprehensive monitoring method of residual coal pillar-rock linkage instability in multi-seam mining is proposed, as shown in Fig. 2.

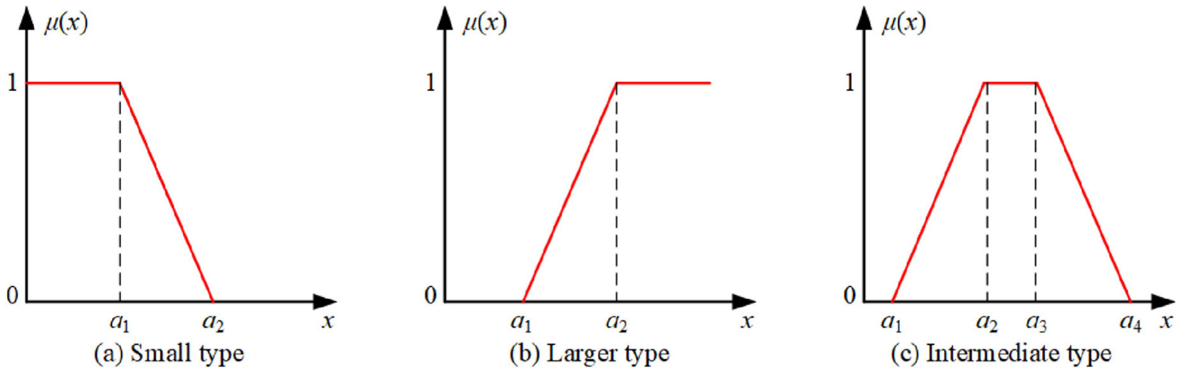
From the perspective of applying load body and carrier body and load bearing formation behavior, the monitoring methods that can be adopted include microseismic monitoring, electromagnetic radiation monitoring, vibration wave CT monitoring, stress online monitoring, drilling chip monitoring and support load monitoring. The above 6 methods can be implemented for real-time monitoring and give accurate quantitative values. Among them, microseismic events can be used as a dynamical load source to start a rock breakout, and the activity law of microseismic events before a rock breakout has been explored. The relationship between the occurrence rule of microseismic events and rock burst is revealed, and the occurrence of rock burst can be predicted.

Starting from the coal pillar left by the transition body which plays the role of load transfer, the monitoring methods that can be adopted include borehole detectors and ultrasonic wave velocity monitoring. The data provided by the mine can determine the location and general direction of the coal pillar. The damage degree of the remaining coal pillar can be obtained by the borehole detector and ultrasonic wave velocity monitoring.

From the angle of disaster caused by the residual coal pillar-rock linkage instability, the monitoring methods can be adopted, including borehole monitor and double-end water stopper detection. The residual coal pillar-rock linkage instability will further increase the height of fracture development. The increase of fracture development height will cause the water in the goaf of No.8 coal seam to flood into the working face of No.11 coal seam. And the water in the goaf of No.7 coal seam will

Table 6
Classification table of various indexes of residual coal pillar-rock stratum risk degree.

Index	Sort				
	Low risk	General risk	Medium risk	High risk	Major risk
	I	II	III	IV	V
Microseismic energy/J	0~5000	5001~100,000	100,001~1000000	1000001~5000000	> 5000000
Damage degree of coal pillar/($m\cdot s^{-1}$)	5001~7500	4001~5000	2501~4000	2001~2500	0~2000
Crack development height/m	[0, 15]	(15, 30]	(30, 45]	(45, 60]	> 60



(a) Small type (b) Larger type (c) Intermediate type

Fig. 3. Semi trapezoidal and trapezoidal membership function distribution diagram [58].

also flood along the fissure, which will affect the mining of the working face of No.11 coal seam. Therefore, the monitoring of the increase of fracture development height caused by the residual coal pillar-rock linkage instability can avoid the linkage disaster accidents caused by the coupling failure and instability to a certain extent.

It should be pointed out that in field engineering practice, the above monitoring methods do not need to be implemented all the time when monitoring the residual coal pillar-rock linkage instability. It should be carried out according to the actual engineering geological characteristics of the site, mining technical conditions, impact risk degree, and the applicability, cost-effectiveness, and safety of various monitoring methods. The appropriate combination of monitoring methods is selected for different zones, and the technical parameters are designed and optimized.

3. Evaluation method of disaster caused by linkage instability of residual coal pillar and rock strata

3.1. Evaluation index selection

At present, the commonly used risk assessment methods include risk factor analysis method, fuzzy comprehensive evaluation method, internal control evaluation method, analytical review method, qualitative risk assessment method and risk rate risk assessment method [44,48]. Fuzzy comprehensive evaluation method is a comprehensive evaluation method based on fuzzy mathematics. This comprehensive evaluation method transforms qualitative evaluation into quantitative evaluation according to the membership degree theory of fuzzy mathematics. It has the characteristics of clear and systematic results and can better solve fuzzy and difficult to quantify problems. Therefore, this method is suitable for the evaluation and solution of various non-deterministic problems [49]. The problem of residual coal pillar-rock linkage instability is complicated. Its instability is not only related to the donor, the transition body, and the carrier, but also causes a series of linkage disasters. Therefore, the fuzzy comprehensive evaluation method will be used to evaluate the disaster caused by the residual coal pillar-rock linkage instability.

To make a fuzzy comprehensive evaluation of the degree of disaster caused by the residual coal pillar-rock linkage instability, we should first have a comprehensive understanding of the existing main evaluation indexes and their influencing factors. Therefore, this paper adopts the principle of randomness to investigate the disaster accidents caused by coal seam over pillar mining at home and abroad. The coal mining investigated has both single-seam mining and multi-seam mining working face. The working faces investigated include those with larger buried depth and those with shallow buried depth. In accordance with the principles of objectivity, easy access and quantification, and combining with the characteristics of multi-seam mining in Datong mining area, high rock strength in roof and floor, many coal pillars left over, and strong strata behavior, this paper has established the main evaluation indexes of the degree of disaster caused by the residual coal pillar-rock linkage instability: ① Microseismic energy, which reflects the damage degree of the force object and carrier.② The damage degree of the residual coal pillar reflects the damage degree of the load transfer medium. ③The height of fracture development, to a certain extent, can reflect the overburden damage degree caused by the coal pillar-rock linkage instability.

3.1.1. Microseismic energy

The failure and residual coal pillar-rock linkage instability may cause disasters such as dynamic pressure appearance. The idea of dynamic pressure monitoring is based on the premise that there are precursors to the occurrence of dynamic pressure, and the possible future dynamic pressure disasters can be predicted according to these precursors [50–52]. Therefore, the identification of dynamic pressure precursor information and the determination of early warning value play an important role in dynamic pressure disaster monitoring and early warning. Considering the speed of the mining and driving, influence on the evolution of rock fracture movement, literature [50–52] classifies the risk of dynamic pressure disasters by taking the energy measured by microearthquakes as a judgment index. The settings for its warning value are listed in Table 3, and this index is defined as M in this paper.

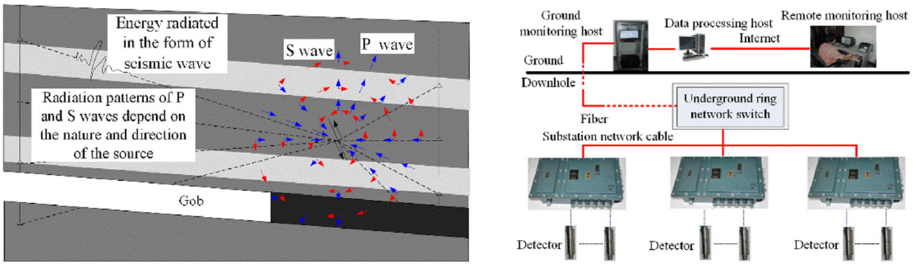
3.1.2. Damage degree of residual coal pillar

As a transition body for load transfer, the failure degree of the residual coal pillar plays a crucial role in the residual coal pillar-rock linkage instability. Under the compression of overlying rock, the residual coal pillar will gradually fail over time. In addition, the mining disturbance during the mining of the residual coal pillar in the lower coal seam will aggravate this progressive failure. After the location of the residual coal pillar is accurately obtained by the borehole detector, the degree of breakage of the residual coal pillar can be measured by the ultrasonic wave speed. The damage degree of the residual coal pillar corresponding to different acoustic wave velocities is shown in Table 4, which is defined as *G* in this paper.

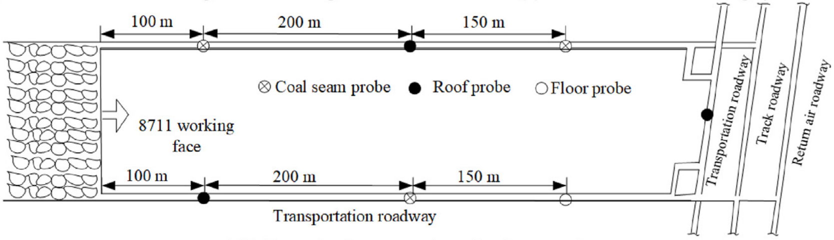
The wave velocity change reflects the damage degree of the residual coal pillar. Generally speaking, the smaller the wave velocity, the lower the integrity of coal and rock, and the higher the damage degree of the residual coal pillar; the higher the wave velocity, the higher the integrity of coal and rock, and the lower the damage degree of the residual coal pillar [47,53].

3.1.3. Fracture development height

Residual coal pillar-rock linkage instability will further increase the development height of the overburden fracture. The water in the goaf of overlying coal seam will flood into the coal face along the fracture zone [54]. Therefore, the fracture development height can reflect the degree of disaster caused by the residual coal pillar-rock linkage instability to a



(a) Microseismic monitoring schematic diagram (b) Microseismic monitoring systems



(c) Microseismic system detection layout scheme

Fig. 4. Structure diagram of microseismic monitoring system and detection layout scheme.

certain extent. The height of the overburden collapse zone and the fracture zone can be calculated from the formulas in Table 2. However, it can be concluded from previous numerical simulation and similar material simulation tests that the development height of overburden fractures in multi-seam mining will be larger than the data calculated by the formula in Table 2. In other words, the exploitation of lower coal seam under multi-seam mining intensifies the development of overlying rock cracks [55]. Therefore, according to previous studies [55–57], this paper established the height of fracture development as one of the evaluation indicators of the degree of disaster risk caused by the multi-seam mining residual coal pillar-rock linkage instability. As shown in Table 5, the fracture development height is the value at which the amount of overburden further caving caused by the mining disturbance of multi-seam mining increases, respectively, based on the calculation of the formula in Table 2, and the fracture development height index is defined as *H*.

To sum up, this paper selected microseismic energy (*M*), damage degree of residual coal pillar (*G*) and fracture development height (*H*) as evaluation indexes. In this paper, considering the classification standards, norms and related literature of the degree of disaster caused by the linkage instability of residual coal pillar-rock strata at home and abroad, the degree of disaster caused by the linkage instability of residual coal pillar-rock strata was divided into five grades I ~ V. Table 6 shows the thresholds for each risk level.

3.2. *Fuzzy evaluation method of disaster degree*

3.2.1. *Principle of fuzzy comprehensive clustering method*

Fuzzy cluster analysis is a mathematical method that uses a fuzzy mathematical language to describe and classify things according to certain requirements. Generally, the fuzzy matrix is constructed according to the attributes of the research object itself, and on this basis, the clustering relationship is determined according to a certain membership degree, to objectively divide the types [58]. The fuzzy comprehensive clustering method comprehensively considers the impact of multiple factors on the disaster risk degree caused by the residual coal pillar-rock linkage instability in multi-seam mining and gives a quantitative evaluation. In this paper, the microseismic energy, the damage degree of residual coal pillar and the height of fracture development were considered comprehensively to evaluate the disaster degree caused by the residual coal pillar-rock linkage instability.

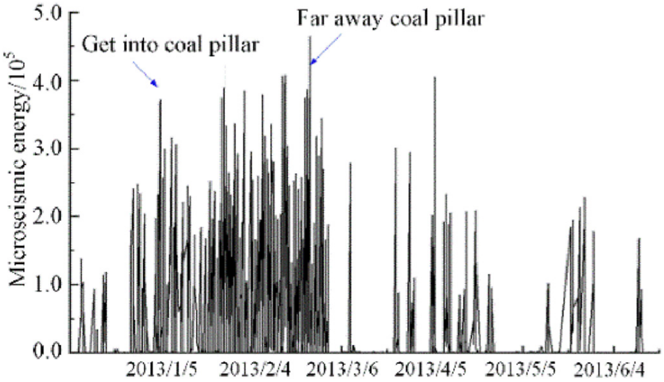
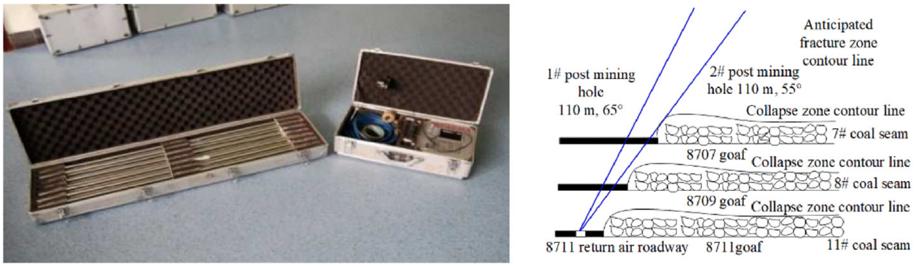


Fig. 6. Variation trend of microseismic energy with time.

The basic idea of using fuzzy comprehensive clustering method to evaluate the degree of disaster caused by the residual coal pillar-rock



(a) Physical drawing of the borehole viewer (b) Drilling layout

Fig. 5. Schematic diagram of monitoring the damage degree and fracture development height of residual coal pillar.

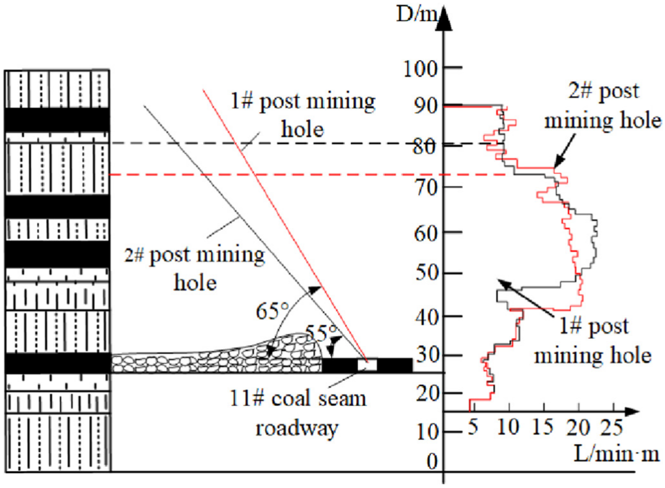


Fig. 7. Detection results of overburden fractures in working face of No.11 coal seam.

Table 7

Measured value of No.11 coal seam of this coal mine.

Working face name	Microseismic energy $M/10^5$ J	Damage degree of residual coal pillar $G/(\mathrm{m{\cdot}s^{-1}})$	Crack development height H/m
No.11 Coal seam working face	4.6	2583	50.8

linkage instability is to replace "belonging" or "not belonging" with "belonging degree". That is, to evaluate the degree of disaster caused by the residual coal pillar-rock linkage instability and the degree of risk. The degree of disaster caused by this kind of the residual coal pillar-rock linkage instability is the largest, that is, the degree of disaster caused by this kind of residual coal pillar-rock linkage instability. First, the method needs to determine the influence index $U = \{u_1, u_2, u_3\}$ and the classification grade $V = \{v_1, v_2, v_3\}$. It is also assumed that the weight of each influence index is assigned to the fuzzy subset A on U, denoted as the weight fuzzy set $A = \{W_1, W_2, W_3\}$. Then, the fuzzy relation matrix is obtained by calculating the subordinate relation of the degree of disaster caused by the residual coal pillar-rock linkage instability by each influence index $\boldsymbol{R} = (r_{ij})_{n\times m}$. Then, according to eq. (3), the fuzzy relation matrix and index weight are fuzzy and normalized; Finally, the result of fuzzy comprehensive evaluation is the fuzzy cluster matrix $\boldsymbol{B} = \{u_1, u_2, u_3\}$ on V. This matrix is used to determine the classification of the degree of disaster caused by the residual coal pillar-rock linkage instability [58].

$$\boldsymbol{B} = A\cdot\boldsymbol{R} \tag{1}$$

3.2.2. Membership function and fuzzy relation matrix

The classification indexe for the degree of disaster caused by the residual coal pillar-rock linkage instability are shown in Table 5. After determining the classification standard of the degree of disaster caused by residual coal pillar-rock linkage instability, according to the different characteristics of each influencing index of the residual coal pillar-rock linkage instability, the fuzzy set of the judging index is determined respectively, that is, the membership function of the index. The dimensions corresponding to the disaster degree indexes caused by residual coal pillar-rock linkage instability are different. Therefore, to carry out fuzzy classification of the actual monitoring data on the engineering site, it is necessary to carry out dimensionless processing of the indicators.

Table 8

Classification index weight table of measured value in the coal mine.

Subitem	Index		
	$M/10^5$ J	$G/(\mathrm{m{\cdot}s^{-1}})$	H/m
Actual value C_i	4.6	2583	50.8
Critical average C_{0i}	22.21	4200	42
Weight W_i	0.207	0.615	1.210
Normalized weight coefficient $\overline{W}_i$	0.10	0.30	0.60

Everyone has a different idea of what a vague concept is. So, the membership function is subjective when it is determined. But whether the membership function can be correctly selected or constructed is one of the keys to making good use of fuzzy control. In this paper, the membership function of trapezoidal distribution or semi-trapezoidal distribution was selected according to previous research and determination methods of fuzzy comprehensive evaluation membership function for different problems. The membership functions are divided into three types, as shown in Fig. 3. Each classification level corresponds to a different membership function. Where x is the actual value, a_1 and a_2 are the critical values of the two adjacent index grades, and the ordinate is the membership degree $\mu(x)$. The membership functions of the three types are as Eq. (2) ~ (5). Thus, the fuzzy relation matrix $\boldsymbol{R}$ of the disaster risk degree caused by the instability of the residual coal pillar and rock layer can be obtained, which is Eq. (5) [58].

$$\mu(x) = \begin{cases} 1, 0 \le x \le a_1 \\ \dfrac{a_2 - x}{a_2 - a_1}, a_1 < x \le a_2 \\ 0, x > a_2 \end{cases} \tag{2}$$

$$\mu(x) = \begin{cases} 0, 0 \le x \le a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, a_1 < x \le a_2 \\ 1, x > a_2 \end{cases} \tag{3}$$

$$\mu(x) = \begin{cases} 0, 0 \le x \le a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, a_1 < x \le a_2 \\ 1, a_2 < x \le a_3 \\ \dfrac{a_4 - x}{a_4 - a_3}, a_3 < x \le a_4 \\ 0, x > a_4 \end{cases} \tag{4}$$

$$\boldsymbol{R} = (\boldsymbol{r}_{ij})_{n\times m} = \begin{pmatrix} \mu_{11}\mu_{12}\cdots\mu_{1m} \\ \mu_{21}\mu_{22}\cdots\mu_{2m} \\ \mu_{n1}\mu_{n2}\cdots\mu_{nm} \end{pmatrix} = \begin{pmatrix} \mu_{11}\mu_{12}\mu_{13}\mu_{14}\mu_{15} \\ \mu_{21}\mu_{22}\mu_{23}\mu_{24}\mu_{25} \\ \mu_{31}\mu_{32}\mu_{33}\mu_{34}\mu_{35} \\ \mu_{41}\mu_{42}\mu_{43}\mu_{44}\mu_{45} \end{pmatrix} \tag{5}$$

Where μ_{ii} refers to the membership degree of the actual value of item i to class j.

3.2.3. Index weight determination

The index weight is determined according to the overweighting method. The greater the exceedance, the greater the impact on the degree of disaster risk caused by the residual coal pillar-rock linkage instability, and the greater the corresponding weight, that is [58]:

$$W_i = \frac{c_i}{c_{0i}} \tag{6}$$

Where, C_i refers to the actual value of the i indicator; C_{0i} is the average allowable critical value of the classification indicator at each level.

The weights of each indicator calculated according to Eq. (6) are relative weights, which need to be normalized for easy comparison, that is, the sum of weights of each indicator is equal to 1.

$$W_i = \frac{W_i}{\sum_{i=1}^{n} W_i}\text{ , }(i = 1\text{ , }2\text{ , }3) \tag{7}$$

Weight matrix:

$$A = \left(W_1\text{ , }W_2\text{ , }\cdots W_i\right) = \left(W_1\text{ , }W_2\text{ , }W_3\text{ , }\right) \tag{8}$$

3.2.4. Fuzzy clustering discrimination

By substituting Eqs. (2) and (5) into Eq. (1), the fuzzy clustering matrix can be obtained:

$$\boldsymbol{B} = A \cdot \boldsymbol{R} = (u_1, u_2, u_3, \ldots, u_n) = (u_1, u_2, u_3, u_4, u_5) \tag{9}$$

According to the principle of maximum membership, if the result vector of fuzzy synthetic cluster matrix **B** is μ_r, then the discriminant of the object belongs to class *r*:

$$\mu_r = \max_{1 \le j \le n} \{\boldsymbol{B}\} \tag{10}$$

3.3. Case study of disaster risk assessment caused by linkage instability of residual pillar-rock strata in multi-seam mining in 307 panel area

3.3.1. Lower coal seam face monitoring

The site monitoring is carried out along the channel at 8711 working face, 307 block of the mine, and the 8711 working face is mining Jurassic No.11 coal seam. The buried depth is 309.6–340.3 m, the average is 325 m, the strike length is 650 m, the tilt length is 200 m, the coal seam thickness is 0.8–3.8 m, the average is 2.3 m, the structure is simple. Geological and hydrological conditions are simple. The roof and floor are sandy mudstone, coarse sandstone, compact and hard. The working face adopts the comprehensive mechanized longwall backward all-caving mining method. The horizontal distance between the cutting eye of the 8711-working face of the No.11 coal seam and the residual coal pillar of the No.8 coal seam is about 180 m. During the advancing process of 8711 coal seam, the residual coal pillars of the upper No.7 and No.8 coal seams will be passed. This will cause No.11 coal seam 8711-working face hydraulic support crushing, roadway deformation serious mining pressure phenomenon.

Microseismic monitoring technology locates low frequency and high energy ($>10^2$ J) rupture events and calculates the released energy. Then the intensity and frequency of microseismic activity are calculated, and the potential rock burst is judged according to the location of microseismic event distribution. The principle of microseismic monitoring is shown in Fig. 4 (a), and the working face microseismic monitoring system is shown in Fig. 4 (a). A total of 7 probes are arranged in the 8711 working face area (Fig. 4 (b)). Among them, three probes are arranged in the transport groove of the working face, which are the roof probe, the coal wall probe, and the floor probe. They are located 100 m, 300 m and 450 m ahead of the working face. Three probes are arranged in the return air groove of the working face, namely the coal head probe, the roof probe, and the coal head probe. They are located 100 m, 300 m and 450 m in front of the working face. A probe is arranged in the plate transport lane, which is the roof probe and is in the middle of the two grooves. By analyzing the same microseismic event signal detected by multiple probes (4 or more), the location of the microseismic event and the microseismic energy can be obtained.

The damage degree and crack development height of the residual coal pillar are detected by borehole detector, double-end water plugging crack detection technology and ultrasonic wave velocity measurement technology in underground drilling. The distribution of cracks in overlying rock is scanned by borehole camera before the detection of double-end water plugging cracks in each borehole. The purpose of this is to: First is to reveal the fracture distribution of overburden rock through the drilling image expansion algorithm. Second is to use the double-end water plugging device to detect the serious crack development. Survey area and drilling layout: Three test areas are arranged in each roadway, and the interval of test areas is 70~120 m. There are 2 pre-mining holes and 2 post-mining holes in each measuring area of roadway I and roadway III. The development of overburden fractures after one and two mining can be obtained from the pre-mining and post-mining pores respectively. Two post-mining holes are arranged in each measuring area of roadway II and roadway IV, and the development of overlying rock fractures after three mining movements can be obtained. Among them, the construction and exploration of the pre-mining hole must be completed before the mining of the working face, and the construction and exploration of the post-mining hole must be started after the working face has pushed over the testing area for more than 70 m. The monitoring diagram of the damage degree and fracture development height is shown in Fig. 5.

The microseismic monitoring results during the mining of No.11 coal seam are shown in Fig. 6. The microseismic energy is relatively small before the No.11 coal seam is mined into the coal pillar, and it increases greatly when the coal pillar is mined. When mining under coal pillar, the microseismic energy changes little, but is at a relatively high value. The microseismic energy reaches the maximum value in the monitoring period, which is 4.6×10^5 J. Since then, although the microseismic energy value is constantly changing, the maximum value is smaller than the energy value of the coal pillar.

The water injection histogram of the overlying rock fracture detection hole in the working face of coal seam No.11 is shown in Fig. 7. In the range of 35.2 m–56.1 m depth (45.3 m–50.8 m vertical height) of hole No.1, the hole leakage is 9.6 L/min to 23.5 L/min. When the depth exceeds 72.6 m, the water leakage of the drilling hole quickly drops to less than 6.3 L/min. The same trend was observed in hole No.2 with a depth of 37.1 m–62.0 m (vertical height 42.6 m–50.8 m). By combining holes No.1 and No.2, it is concluded that the overburden fracture height is 50.8 m when the coal face of No.11 is mined.

Field measured data of microseismic energy, residual coal pillar damage degree and fracture development height were obtained according to microseismic monitoring, residual coal pillar damage degree and fracture development height monitoring of multi-seam mining site in Panel 307 of the coal mine, and the results are shown in Table 7.

3.3.2. Fuzzy comprehensive evaluation of disaster risk caused by linkage instability

The fuzzy comprehensive clustering method is used to classify the degree of disaster caused by the residual coal pillar-rock linkage instability in the 8711-working face of No.11 coal seam in 307 panel area of this coal mine according to the measured values of different evaluation indexes. The field measured values of each index are shown in Table 7.

The membership degree of each index is calculated according to Eq. (2) ~ (4), and its fuzzy relation matrix is obtained by substituting Eq. (5):

$$\boldsymbol{R} = \begin{pmatrix} 00.60.400 \\ 00.940.0600 \\ 000.610.390 \end{pmatrix} \tag{11}$$

After that, the weights of each index are calculated according to Eq. (6) ~ (8) and normalized (Table 8) to obtain the weighted fuzzy set:

$$A = (0.10, 0.30, 0.60) \tag{12}$$

According to Eq. (9), the fuzzy clustering matrix can be obtained:

$$\boldsymbol{B} = \boldsymbol{A} \cdot \boldsymbol{R} = (0.21, 0.19, 0.48) \cdot \begin{pmatrix} 00.60.400 \\ 00.610.3900 \\ 00001 \end{pmatrix} = (0, 0.35, 0.42, 0.23, 0) \tag{15}$$

According to the principle of maximum subordination, the degree of residual coal pillar-rock linkage instability in the 307 panel area of this coal mine belongs to class III, and the degree of residual coal pillar-rock linkage instability belongs to medium risk level.

In paper [47], the law of strata behavior development in the lower coal seam face was monitored on site. They found that when mining through the upper multiple residual coal pillars, the strong strata behavior phenomena such as the crushing of the support and the serious deformation of the roadway were caused. In addition, to prevent the appearance of strong strata behavior caused by the residual coal pillar-rock linkage instability, technologies such as upper residual coal pillar and floor blasting were adopted on site for pressure relief [47]. It is necessary to determine the location of the residual coal pillar before the implementation of the blasting relief technology of the upper coal pillar and the bottom coal pillar. The location of the coal pillar is mainly through drilling and peephole to drill the coal pillar, delineate the size and direction of the coal pillar [47].

By means of electromagnetic radiation monitoring and mine pressure observation, the effect of blasting pressure relief technology on upper coal pillar and floor is analyzed. The field measurement results show that the frequency and capacity of the electromagnetic radiometer are significantly weakened, and the energy is reduced by 68.2 %; the stress and pressure of coal body and pillar are obviously reduced [47]. A good control effect has been achieved for the disaster caused by the joint instability of coal pillar and rock layer, and the accuracy and effectiveness of the risk evaluation results have been verified.

4. Conclusion

1) The linkage failure and instability of residual coal pillar-rock strata have the following characteristics: From the position of occurrence, the working face where the strata behavior appears is generally shallow buried depth. The distance between them and the overlying coal layer is relatively small, and they are concentrated under the residual coal pillar of the overlying coal seam; From the form of mine pressure, there are mainly support bending, hydraulic support failure, floor heave or spalling, roof collapse and even large energy mine earthquake. Some also caused the surface collapse, resulting in the damage of the ground building.
2) When monitoring the linkage instability of residual coal pillar-rock strata, it is not only necessary to consider the monitoring of apply load body, the transition body and the carrier body, but also to strengthen the monitoring of the fracture development height caused by the linkage instability of residual coal pillar-rock strata, that is, the monitoring of the disaster of the linkage body. According to the monitoring methods of different bodies, a comprehensive monitoring method is established.
3) The main evaluation indexes of linkage failure and instability of coal pillar-rock strata are obtained. The indexes include microseismic energy, residual coal pillar damage degree, crack development height and so on. Based on the fuzzy comprehensive evaluation method, a quantitative evaluation method of the disasters caused by the linkage failure and instability of residual coal pillar-rock strata is proposed.
4) The fuzzy comprehensive evaluation is used to evaluate the disaster risk caused by the linkage failure and instability of residual coal pillar-rock strata during the multi-seam mining in 307-panel area. The evaluation results showed that the risk level was medium risk. Techniques such as upper coal pillar and floor blasting were adopted to relieve pressure. After pressure relief, the stress and pressure of coal body and coal pillar are obviously reduced, and a good control effect is achieved. This also verifies the accuracy and validity of the risk assessment results.

This paper provides a reference for the study and evaluation of the disaster risk caused by linkage instability of residual coal pillar-rock strata in multi-seam mining. However, the selection of evaluation indexes for the disaster in multi-seam mining is not comprehensive. In the next step, the evaluation index system should be improved based on increasing field engineering research and practice, to make the identification and evaluation methods of disaster risk more scientific. At the same time, it also provides a certain reference for the residual coal pillar-rock stability and risk evaluation after CO_2 injection in closed or abandoned mines. However, in application, certain adjustments should be made based on the production and geological conditions of the mine.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors acknowledge the financial support by the National Natural Science Foundation of China (Nos. 52304093, 52074168, 52079068, 41941019), Shandong Province Key Research and Development Program (No. 2019SDZY02), Shandong Taishan Scholars Climbing Program (No.tspd20210313), State Key Laboratory of Hydroscience and Engineering foundation (No. 2021-KY-04), Natural Science Foundation of Shandong Province Outstanding Youth Fund project (No. ZQ2022YQ49), the Taishan Scholars Project Special Fund (No.tsqn202211150) and the Anhui Engineering Research Center of Exploitation and Utilization of Closed/Abandoned Mine Resources (No. EUCMR202205).

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