Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 551–558

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Width design for gobs and isolated coal pillars based on overall burst-instability prevention in coal mines

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ARTICLE INFO

Article history:
Received 26 September 2015
Received in revised form
3 December 2015
Accepted 5 December 2015
Available online 24 May 2016

Keywords:
Width design
Skip-mining
Isolated coal pillar
Overall burst-instability ratio
Abutment pressure

ABSTRACT

An investigation was conducted on the overall burst-instability of isolated coal pillars by means of the possibility index diagnosis method (PIDM). First, the abutment pressure calculation model of the gob in side direction was established to derive the abutment pressure distribution curve of the isolated coal pillar. Second, the overall burst-instability ratio of the isolated coal pillars was defined. Finally, the PIDM was utilized to judge the possibility of overall burst-instability and recoverability of isolated coal pillars. The results show that an overall burst-instability may occur due to a large gob width or a small pillar width. If the width of the isolated coal pillar is not large enough, the shallow coal seam will be damaged at first, and then the high abutment pressure will be transferred to the deep coal seam, which may cause an overall burst-instability accident. This approach can be adopted to design widths of gobs and isolated coal pillars and to evaluate whether an existing isolated coal pillar is recoverable in skip-mining mines.
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1. Introduction

With the increase of mining depth and intensity, rockburst has become a common safety problem for underground coal mines, especially in China (Dou and He, 2001; Brady and Brown, 2004). In 2011, there were over 142 coal mines facing rockburst hazards and from 2006 to 2013, more than 35 rockbursts occurred leading to over 350 deaths and thousands of people injured. For instance, a rockburst in Sunjiawan coal mine in 2005 resulted in 214 people killed and 30 injured. After six years, a rockburst in Qianqiu coal mine in Henan Province, China killed 10 people and left 75 people trapped underground (Dou et al., 2009; Chen et al., 2011; Jiang et al., 2013; Yang et al., 2014).

Various researchers have proposed quantities of hypotheses on rockburst mechanism. Cook et al. (1966) proposed an energy theory to understand rockburst mechanism through laboratory experiments in South America. Zubelewicz and Mroz (1983) concluded that rockbursts resulted from static and dynamic stresses. Kidybiński (1981) proposed some indices to classify the potential liability of coal seams to rockbursts. In addition, a number of theories were put forward to explain the mechanism of rockburst such as stiffness theory (Petukhov and Linkov, 1979), rockburst tendency theory (Kidybiński, 1981; Pan et al., 2010; Qi et al., 2011; Song et al., 2014), strength theory (Li, 1985), "voussoir beam" and "key strata" theory (Qian and He, 1989; Qian and Miao, 1995; Qian et al., 2003), and overlying strata spatial structure theory (Jiang, 2006; Jiang et al., 2006; Wang et al., 2009; Hou and Huo, 2012). Recently, some key researches were conducted on the strength changes in coal due to fluid migration, which also contribute to coal failure. Water and carbon dioxide (CO_2) saturation of coal leads to high reduction in its strength (Perera et al., 2011; Vishal et al., 2013, 2015). However, most of the previous studies of rockburst were confined to limited zones of a single working face with solid coal seam on both sides. For isolated coal pillars, the previous studies are not available. This paper proposed a new method to recycle isolated coal pillars in skip-mining mines based on overall burst-instability prevention.

At present, many high-quality coal resources in China cannot be extracted due to rockburst hazards. Besides, rockbursts frequently occur because of unreasonable widths of gobs and isolated coal pillars. Gucheng coal mine in Shandong Province, China is a typical skip-mining mine facing rockburst hazards. Therefore, this paper took Gucheng coal mine as engineering background and proposed width design methods of gobs and isolated coal pillars based on rockburst prevention. A gob abutment pressure calculation model in side direction was established to obtain the influence scope of the high abutment pressure and then the overall burst-instability

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2015.12.006
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ratio was evaluated for the design of isolated coal pillars. Coal mine microseismic system and rockburst online monitoring system were utilized to monitor the mining activities in longwall mining.

2. Site description for Gucheng coal mine

The Gucheng coal mine, owned and operated by Linyi Coal Group Company, is located in Shandong Province, China. Currently, the mining activity at the Gucheng coal mine advances to the Mining Area #31, as shown in Fig. 1. The panel has an overburden depth of about 1000 m. The longwall fully mechanized top coal caving method is used to retreat the panel. The coal seam thickness ranges from 8.4 m to 13.2 m with an average dip angle of 12° (see Table 1). Thick sandstone exists in the overlying strata of the Mining Area #31. Therefore, a large amount of elastic strain energy can be accumulated in the process of mining. The seam is overlain successively by 18.7 m of medium sandstone as the main roof and 1.88 m of mudstone as the immediate roof. The thick main roof can cause periodic dynamic pressure which may induce rockbursts. The isolated coal pillar is set between two gobs (as shown in Fig. 1, after mining of two panels, the isolated coal pillar was left). The width of the panel is 100 m according to the current production capacity. Therefore, it is of vital importance for designing the width of the isolated coal pillar to prevent overall burst-instability accidents when recovering the isolated coal pillars.

3. The mechanical model

3.1. Establishment of gob abutment pressure calculation model in side direction

Calculation of gob abutment pressure is the basis of the width design for isolated coal pillars. Calculation results derived by theory of elasticity and numerical simulation are not practical and the parameters are difficult to be obtained. Therefore, it is necessary to investigate a calculation model available for engineering application. This paper calculated the influence scope of gob abutment pressure in side direction using a mechanical model to obtain the maximum and minimum pillar widths (Fig. 2a). There are n key strata above the coal seam and the separation fronts of key strata are connected by a line that is defined as strata movement line. The radius of the pressure arch is half of the gob width by experiment (Jiang and Ma, 2002). The abutment stress of the coal seam consists of two parts: one is the gravity stress σ_q and the other is the transferring stress $\Delta\sigma$ by key strata above the gob (Liu et al., 2011). The formula is written as follows:

Table 1
Mining conditions for Gucheng coal mine.

Thickness of coal seam (m)	Dip of coal seam (°)	Mining depth (m)	Immediate roof	Main roof
8.4–13.2	12	1000	Mudstone (1.88 m thick)	Medium sandstone (18.7 m thick)

$$\sigma = \Delta\sigma_i + \sigma_q \tag{1}$$

Half of the weight of the i-th key stratum will be transferred to the coal seam and the distribution shape of $\Delta\sigma_i$ is an isosceles triangle as shown in Fig. 2b. As a result, the formula of $\Delta\sigma_i$ is denoted as

$$\Delta\sigma_i = \begin{cases} \sigma_{\max i} x \tan\alpha / H_i & (0 \le x < H_i \cot\alpha) \\ 2\sigma_{\max i}[1 - x/(2H_i \cot\alpha)] & (H_i \cot\alpha \le x < 2H_i \cot\alpha) \\ 0 & (x \ge 2H_i \cot\alpha) \end{cases} \tag{2}$$

where H_i is the distance between the center of the i-th key stratum and the floor of the coal seam, which can be expressed as

$$H_i = W + \frac{M_i}{2} + \sum_{j=1}^{i-1} M_j \tag{3}$$

where W is the half width of the gob, and M_i is the thickness of the i-th key stratum.

$\sigma_{\max i}$ is the maximum value of the $\Delta\sigma_i$, which can be written as follows:

$$\sigma_{\max i} = \frac{Q_i}{H_i \cot\alpha} \tag{4}$$

where Q_i is the half weight of the i-th stratum above the gob, which can be calculated by

$$Q_i = \frac{L_i \gamma_i M_i}{2} \tag{5}$$

where γ_i is the average strata bulk density; L_i is the length of the i-th stratum, which can be expressed as

$$L_i = 2W + 2H_i \cot\alpha \tag{6}$$

$\Delta\sigma$ is the sum of $\Delta\sigma_i$:

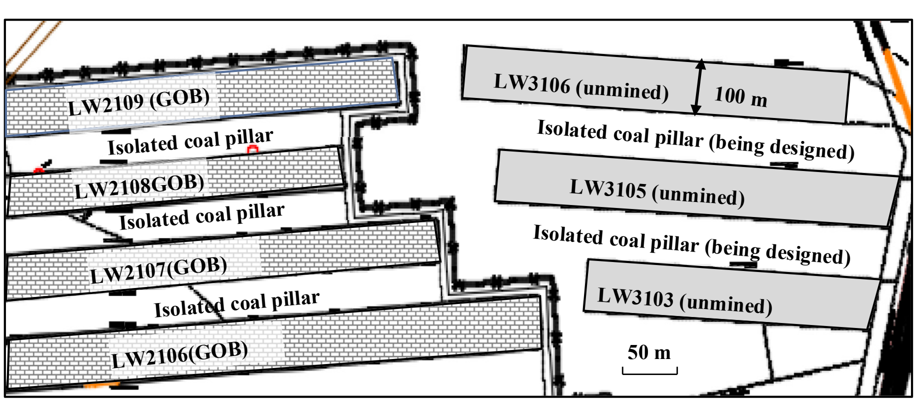

Fig. 1. Plan view of the Mining Area #31 of Gucheng coal mine. “LW” denotes the longwall.

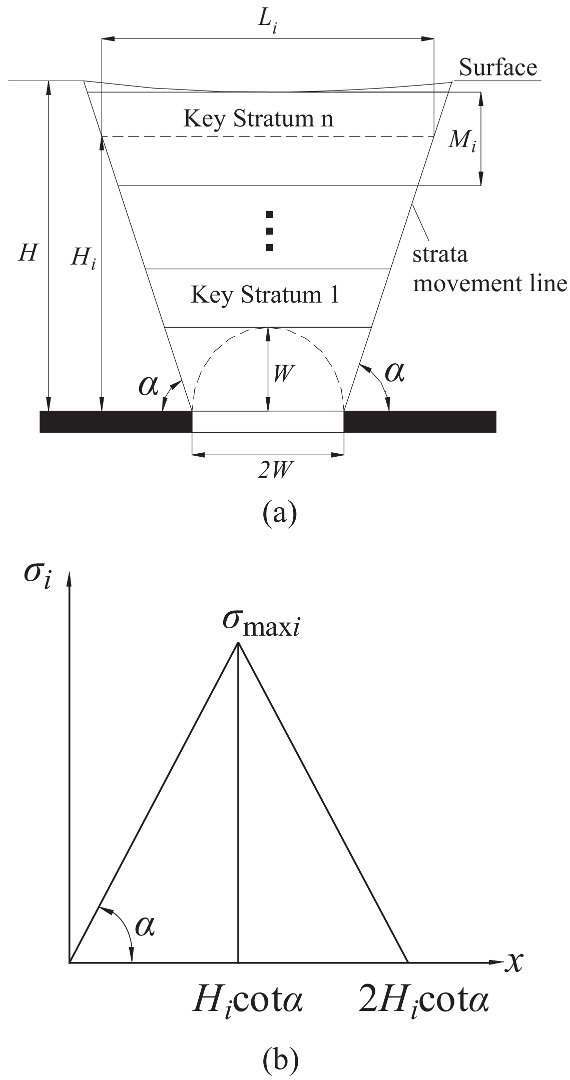

Fig. 2. Calculation model.

$$\Delta\sigma = \sum_{i=1}^{n}\Delta\sigma_i \tag{7}$$

The gravity stress σ_q is a piecewise function, which is shown as follows:

$$\sigma_q = \begin{cases} \gamma W & (x = 0 \rightarrow W\cot\alpha) \\ \gamma x\tan\alpha & (x = W\cot\alpha \rightarrow H\cot\alpha) \\ \gamma H & (x = H\cot\alpha \rightarrow \infty) \end{cases} \tag{8}$$

where H is the mining depth.

3.2. The seismic system

Poland ARAMISM/E system was installed in Gucheng coal mine. The system utilizes SPI-70 seismometers in SN/DTSS transmission stations to locate seismic events and determine burst energy. There are 16 component channels with one SP/DTSS cassette in the system. The system enables transmission of 1-, 2- or 3-axial velocity movements (X, Y, Z). The sampling of signals is conducted through 24-bit Sigma Delta converters, which can provide conversion and records of microseismic signals. The system can monitor the microseismic signals instantly, continually and automatically, as well as calculate the seismic energy larger than 100 J. In addition, the system can draw complete waveform and determine the force sources to evaluate danger extent of rockburst.

3.3. Side abutment pressure curve by seismic monitoring and theoretical calculation

The distribution of overlying strata of the Mining Area #31 is shown in Table 2. Fig. 3a demonstrates the strata movement angle with microseismic energy less than 10^4 J. The maximum height of microseismic events is 260 m and the projection distance from the gob is 60 m, from which we can calculate $\tan\alpha_1 = 260/60 = 4.33$, namely the movement strata angle $\alpha_1 = 77°$ (the strata movement line was drawn by connecting the head entry and the point of the highest microseismic event). With the same method, the other strata movement angles can be derived: $\alpha_2 = 79.2°$, $\alpha_3 = 79.3°$ and $\alpha_4 = 76°$. The average strata movement angle α is $(\alpha_1+\alpha_2+\alpha_3+\alpha_4)/4 = 78°$. The uniaxial compressive strength σ_c is equal to 18.5 MPa and the mining width $2W$ is equal to 100 m. By substituting the panel parameters into Eq. (1), the estimation curve of the gob abutment pressure in side direction can be derived (Fig. 4). Fig. 5 shows the distribution of the microseismic events which can demonstrate the position of the peak value. We figured out the position where the microseismic events firstly appear and the position where most microseismic events happen. The peak position of the abutment pressure is between the two positions. For Gucheng coal mine, the peak position is 29 m away from the working face. From Figs. 4 and 5, we can see that the calculation results are just similar to the microseismic monitoring results (an error of 2 m), which can illustrate the accuracy and availability of the abutment pressure calculation model.

3.4. Width of isolated coal pillars based on possibility index diagnosis method

For Gucheng coal mine, the width of LW3106 is 100 m, equal to that of LW3105. By superposition of the abutment pressures of LW3106 and LW3105, the distribution of abutment pressure in the isolated coal pillar can be derived, as shown in Fig. 6. The symmetry of the gob in each side makes a flat top for the pressure distribution.

The overall burst-instability ratio is defined as

$$I = \frac{a}{l} \tag{9}$$

Table 2
Strata distribution above Mining Area #31.

Strata	Thickness (m)	Bulk density (kg/m^3)
Top soil	272	1960
Fine sandstone	33.7	2873
Medium sandstone	67.9	2580
Fine sandstone	141.9	2701
Fine sandstone	26.3	2873
Medium sandstone	114.2	2580
Fine sandstone	18.2	2873
Medium sandstone	79.6	2580
Mudstone	85.5	2510
Siltstone	131.6	2667
Coal seam #2	0.82	1380
Medium sandstone	18.7	2580
Mudstone	1.88	2510
Coal seam #3	8.8	1380

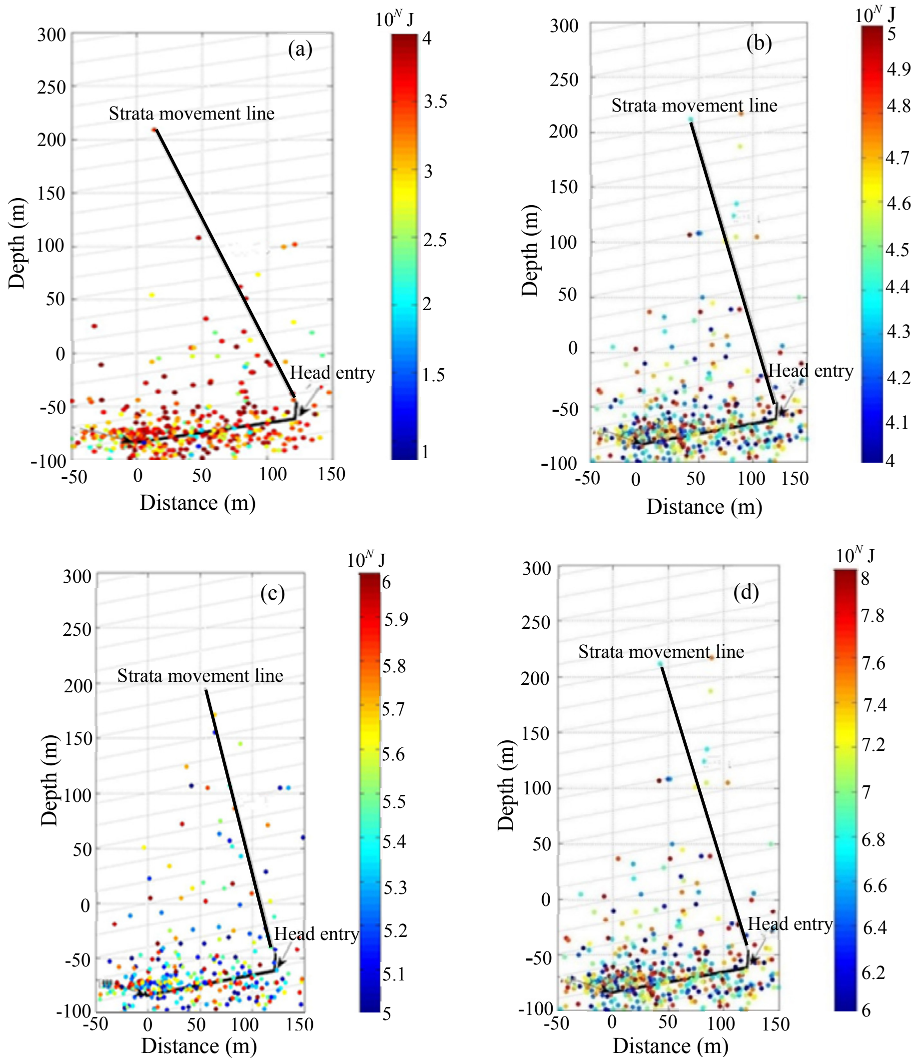

Fig. 3. Strata movement angle revealed by microseismic events. (a) Mining tremors with energy less than 10^4 J; (b) Mining tremors with energy between 10^4 J and 10^5 J; (c) Mining tremors with energy between 10^5 J and 10^6 J; (d) Mining tremors with energy over 10^6 J.

where a is the pillar width with pressure greater than $3\sigma_c$, and l is the width of the isolated coal pillar.

Based on fuzzy mathematics and engineering experience, the possibility index diagnosis method (PIDM) was put forward by Jiang (Liu et al., 2011), which was successfully applied in many evaluation cases of rockburst. The PIDM calculated the membership degrees of overall burst-instability ratio and elastic strain energy index to determine the possibility of rockburst occurrence. The method was written in the Rockburst Evaluation Statute in China (Yu, 2008; Wei, 2015). This paper utilized PIDM to judge the possibility of overall burst-instability and recoverability of isolated coal

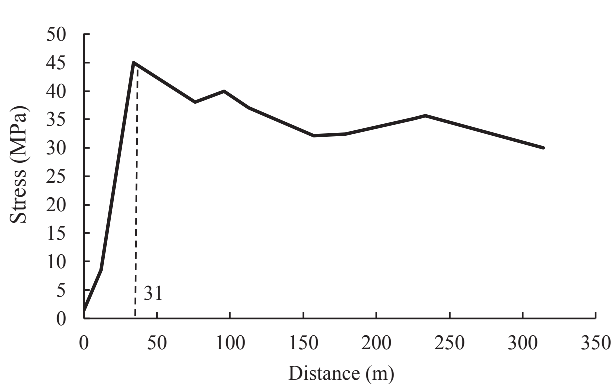

Fig. 4. Gob abutment pressure in side direction.

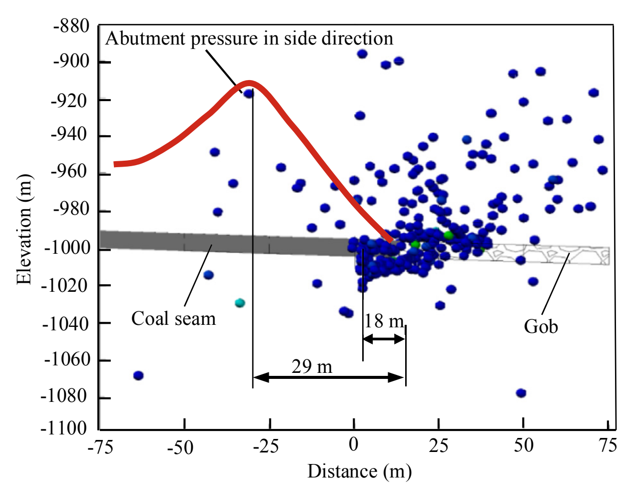

Fig. 5. Gob abutment pressure in side direction obtained by tremors.

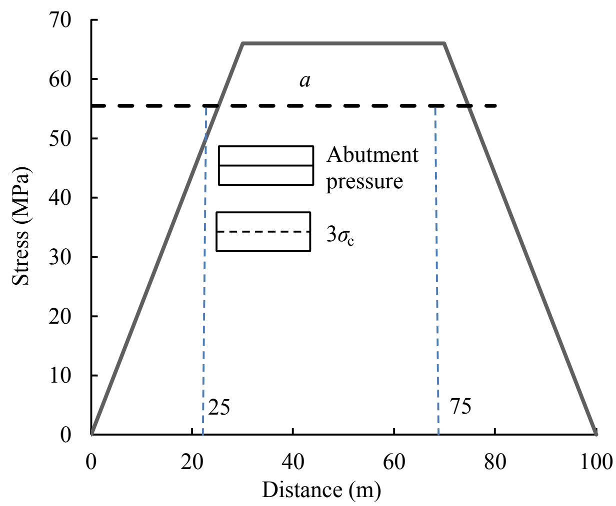

Fig. 6. The calculated abutment pressure curve of isolated coal pillars.

pillars. This method can also be used to design widths of gobs and isolated coal pillars to prevent overall burst-instability while mining. Therefore, it is convenient to predict the dynamic disaster and verify the reasons after the burst happens.

The membership of overall burst-instability ratio U_I is defined as

$$U_I = \begin{cases} 0.5I & (I \le 0.5) \\ 2.5I - 1 & (0.5 < I < 0.8) \\ 1 & (I \ge 0.8) \end{cases} \tag{10}$$

The membership of elastic strain energy index $U_{W_{ET}}$ is defined as

$$U_{W_{ET}} = \begin{cases} 0.3W_{ET} & (W_{ET} \le 2) \\ 0.133W_{ET} + 0.333 & (2 < W_{ET} < 5) \\ 1 & (W_{ET} \ge 5) \end{cases} \tag{11}$$

where W_{ET} is the strain energy storage index.

The possibility index of rockburst occurrence U is the arithmetic mean value of U_I and $U_{W_{ET}}$:

$$U = \frac{U_I + U_{W_{ET}}}{2} \tag{12}$$

According to possibility index of rockburst occurrence U, the possibility of overall burst-instability and recoverability of isolated coal pillars were derived (Table 3).

3.5. Width design for isolated coal pillars

From Table 3, when U varies from 0 to 0.8, the isolated coal pillar is recoverable without overall burst-instability. When W_{ET} value of Gucheng coal mine is 5.32, we have $U_{W_{ET}} = 1$ (Eq. (11)). According to Eqs. (9), (10) and (12), the corresponding widths of the isolated coal pillar can be obtained, as listed in Table 4.

According to Table 4, when the pillar width is 46–125 m, there must be some de-pressing measures to guarantee the recovery safety of the isolated coal pillar such as the large-diameter long hole method. As for other widths of long wall panels, the same methods can be used to derive reasonable widths of isolated coal pillars. First, the distribution curve of the abutment pressure of the isolated coal pillar should be obtained by superposition of abutment pressure of each longwall panel to calculate the overall burst-instability ratio I. Second, the strain energy storage index (W_{ET}) should be tested. Third, U_I and $U_{W_{ET}}$ should be calculated. Fourth, the possibility index of rockburst occurrence U should be deduced. Finally, the possibility of overall burst-instability and recoverability of isolated coal pillars can be determined according to Table 3.

Table 3
Possibility of overall burst-instability and recoverability of isolated coal pillars.

U	Possibility	Recoverability
0–0.6	Possible	Recoverable
0.6–0.8	Probable	Recoverable with de-pressing measures
0.8–0.9	Very likely	Unrecoverable
0.9–1	Almost certain	Unrecoverable

4. Case study

4.1. Site description for Zhaolou coal mine

Zhaolou coal mine, belonging to Yanzhou Group Company, is located in Shandong Province, China. Currently, the mining activity at the Zhaolou coal mine advances to LW1305, as shown in Fig. 7. The panel has an overburden depth of about 970 m. The longwall fully mechanized top coal caving method is used to retreat the panel. LW1305 is adjacent to LW1304 (mined) with the width of 215 m in the north and LW1306 (mined) and LW1307 (mined) with the total width of 410 m in the south. The width of LW1305 is 136 m. The coal seam thickness ranges from 2.1 m to 8.6 m (about 6.02 m in average) with an average dip angle of 3° (see Table 5). The seam is overlain successively by 8.32 m of medium sandstone and 2.78 m of mudstone as main roof and immediate roof, respectively. The thick main roof can cause periodic dynamic pressure, which may induce rockbursts when mining. The elastic strain energy index W_{ET} is 5.03, the strata movement angle α is 84° and σ_c is 22 MPa by measurement.

4.2. Installed monitoring system

Rockburst online monitoring system KJ550 was installed to monitor the stress change of LW1305 (Fig. 8). Ten groups of stress sensors were installed in the tail entry and head entry, respectively. The sensors are universal stress sensors with precision of 0.01 MPa. Every group includes a deep-hole sensor (14 m) and a shallow-hole sensor (8 m) with the distance of 0.5–2 m. The first group of the stress sensor is 30 m away from the working face and the next group is 20 m away from the last group in order to make sure the monitoring length is about 200 m. The monitoring began on July 25,

Table 4
Widths of the isolated coal pillar with U from 0 to 0.6.

U	Widths of the isolated coal pillar (m)
0–0.6	>125
0.6–0.8	125–46

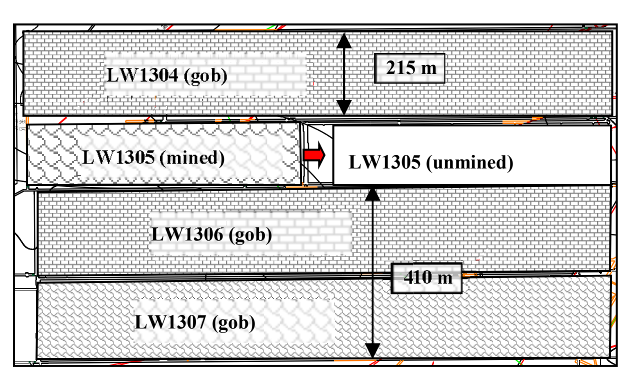

Fig. 7. Sketch map of LW1305.

Table 5
Mining conditions for Zhoulou coal mine.

Thickness of coal seam (m)	Dip of coal seam (°)	Mining depth (m)	Immediate roof	Main roof
6.02	3	970	Mudstone (2.78 m thick)	Medium stone (8.32 m thick)

2015 and ended on July 29, 2015 when an overall burst-instability accident occurred.

4.3. Overall burst-instability accident occurrence

Influenced by the unreasonable width of the isolated coal pillar, an overall burst-instability accident occurred on July 29, 2015. Totally, 38 hydraulic supports were damaged in the head entry and the height of the entry reduced from 3.8 m to 3.1 m. In the working face, the shearer was damaged and a large amount of coal was burst out. Besides, in the head entry, the floor heave reached 0.5–1 m. Fig. 9 shows the photos of the accident.

4.4. Accident analysis

The relative stress change in the coal may forecast rockburst occurrence. A sudden decrease of the shallow-hole stress curve demonstrates the failure of the entry and a sudden increase of the deep-hole stress curve illustrates that the stress is transferred to the deep coal seam, which may develop into an overall burst-instability accident. Hence, a study of the stress curve is of vital importance for revealing the overall burst-instability mechanism.

From Fig. 10a and b, it can be found that, before the overall burst accident, the stress decreased abruptly in the shallow coal seam and increased in the deep coal seam, which suggested the failure of the shallow coal seam and high abutment pressure transferred to the deep coal seam. As we can see from Fig. 10c and d, with the

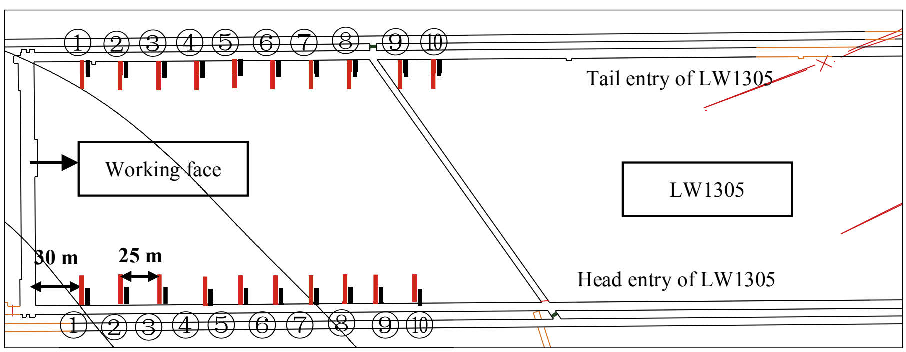

Fig. 8. Layout of monitoring system installed in the two entries of LW1305.

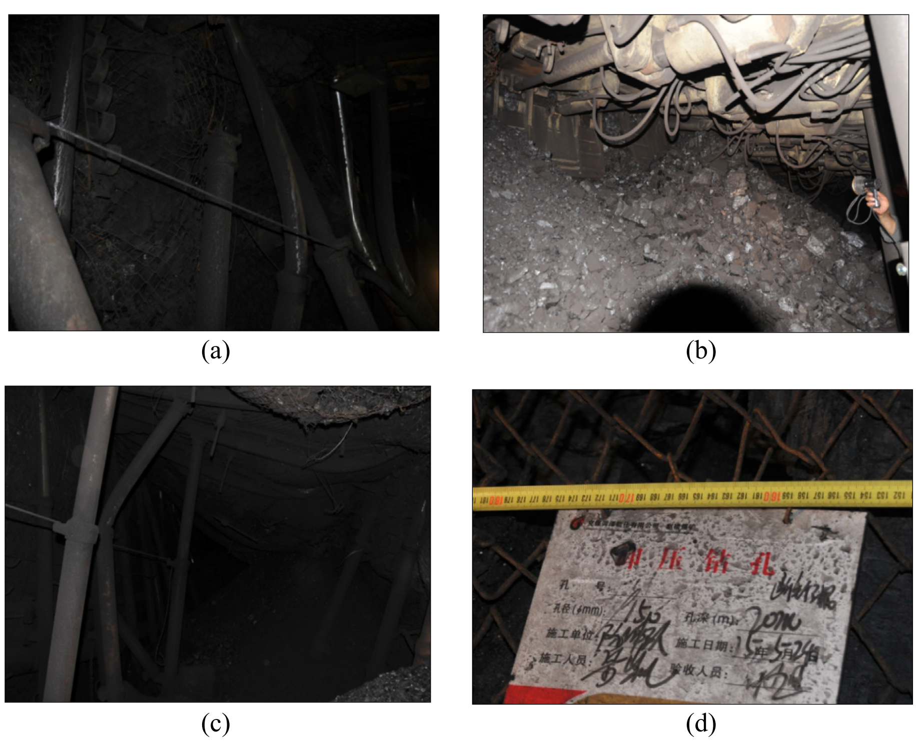

Fig. 9. Photos of site accidents: (a) The head entry, (b) The working face, (c) The tail entry, and (d) The de-stressing boreholes.

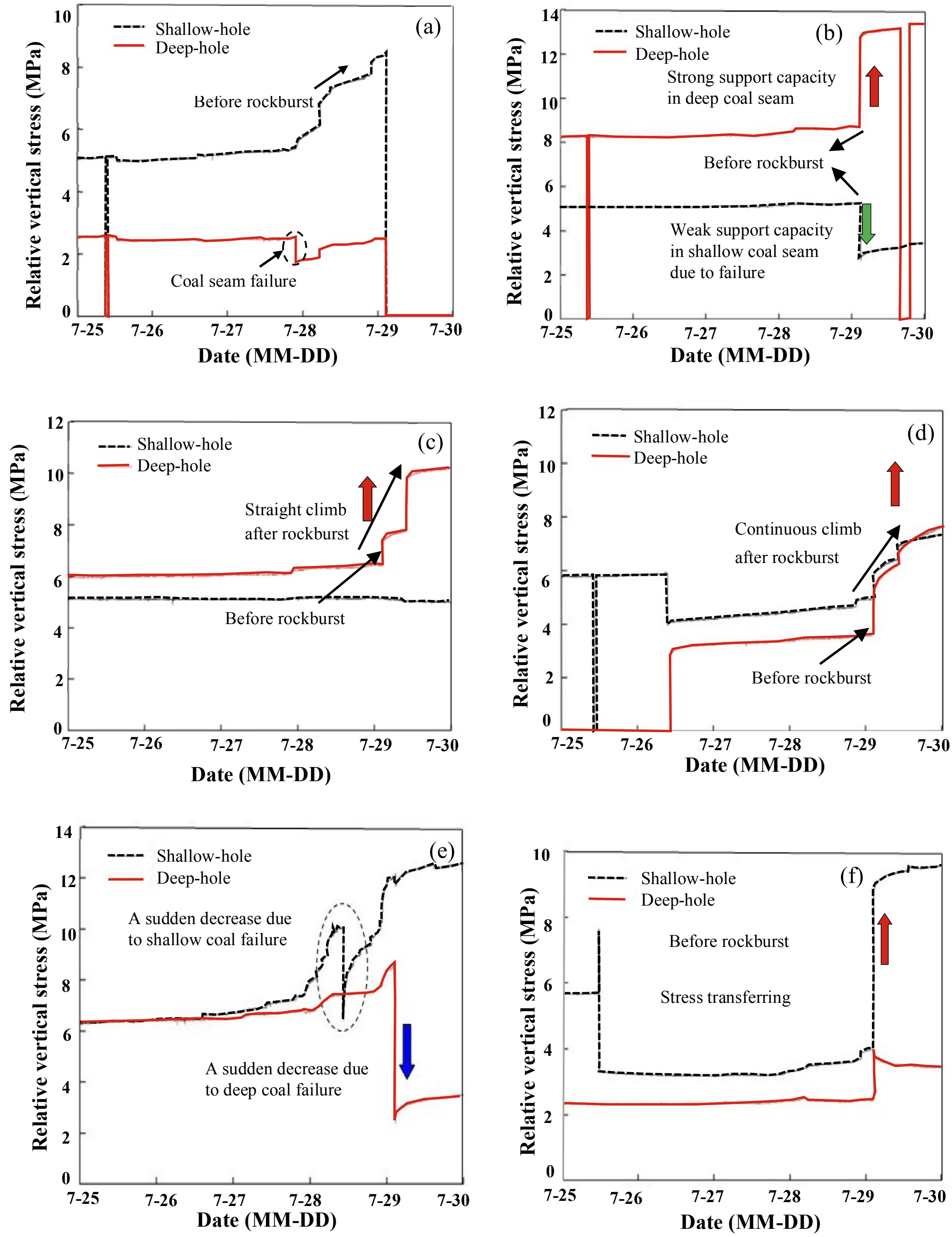

Fig. 10. Monitoring curves in 2015: (a), (b), (c) and (d) are the second, fourth, eighth and ninth group of sensors installed in the tail entry, respectively; (e) and (f) are the second and third group of sensors installed in the head entry, respectively.

stress curve of the deep coal seam continuously climbing, an overall burst-instability accident occurred when the stress reached the limit. Fig. 10e and f shows the abutment pressure transferred to the surrounding coal seam after the overall burst-instability accident.

Using Eqs. (1)–(8), the abutment pressure curve of LW1305 was derived (see Fig. 11). By Eqs. (9)–(12), we have $I = 63\%$, $U_I = 0.6$, $U_{W_{ET}} = 1$, and $U = 0.8$. Considering that the de-stressing boreholes (the depth of each borehole is 15 m, the distance between each borehole is 1.5 m, and the diameter of each borehole is 110 mm) have weakened the strength of the coal seam, U is assumed to be larger than 0.8. From Table 2, the possibility of overall burst-instability is very great (or almost certain) and the recoverability of the isolated coal pillar is unrecoverable. Therefore, an overall burst-instability accident occurred only 3 days after the beginning of the mining activity.

5. Conclusions

(1) A gob abutment pressure calculation model in side direction was put forward based on strata movement theory and key

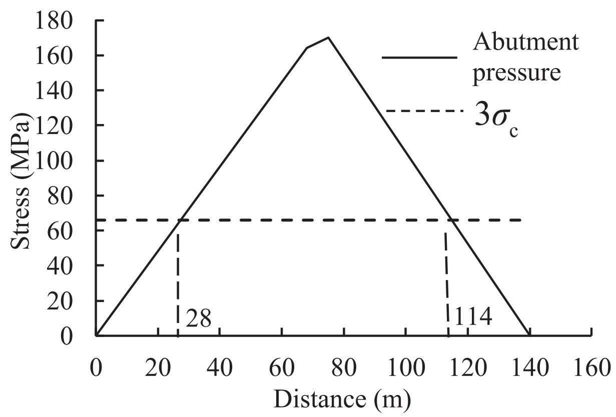

Fig. 11. Distribution curve of abutment pressure of LW1305.

strata theory. The abutment pressure distribution curve of the isolated coal pillar was plotted by the calculation model. Microseismic monitoring results show that this calculation model and distribution curve were suitable for abutment pressure calculation.

(2) The overall burst-instability ratio was defined and the PIDM was utilized to evaluate the possibility of an overall burst-instability accident and recoverability of an isolated coal pillar. By using the PIDM, rational widths of isolated coal pillars and gobs without overall burst-instability hazards can be designed and recovering an existing isolated coal pillar can be evaluated.

(3) An analytic solution for an overall burst-instability accident has been obtained by using PIDM and rockburst online monitoring system. Results showed that the relative stress change in the coal may forecast rockburst occurrence. Before an overall burst-instability accident occurs, the shallow coal seam will be destroyed first and then the high abutment pressure will be transferred to the deep coal seam, which can be reflected in the curve, which is helpful for overall burst-instability determination.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work was financially supported by the National Program on Key Basic Research Project (Grant No. 210CB226800), and the National Natural Science Foundation of China (Grant Nos. 51274022 and 51174016).

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