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Safety technologies for the excavation of coal and gas outburst-prone coal seams in deep shafts

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ABSTRACT

An analysis of the stress distribution characteristics of shaft working faces in deep underground coal mines was performed using theoretical analyses and field tests. The analysis of the outburst risk within the studied shaft demonstrated that a funnel-shaped pressure relief zone existed below the working face, and a zone of concentrated stress surrounding the shaft was a critical area for a potential outburst disaster. We then divided the process of coal excavation within the shaft into four stages to manage and propose improved technical, drainage and protective measures as well as other requirements. When using the processes and requirements provided, the Haizi and Taoyuan coal mines, which are located in the Huaibei mining region and have depths of up to 1000 m, realized safe and rapid excavation through outburst-prone coal seams. It was determined that the technical systems developed in this paper could provide for safe coal excavation in deep shafts, which could be established as new regulations for rapid and safe coal extraction in outburst-prone coal seams.

1. Introduction

Due to the complicated geological structure within coal mines in China, gas-related disasters, particularly coal and gas outburst events, are becoming more serious. Compared to mining activities worldwide, China has experienced the greatest frequency and intensity of outburst-related disasters [1]. In the 2008 report of National Coal Mine Accident Analysis, coal and gas outburst accidents became the dominant type of gas-related disaster in coal mines in China, and outbursts accounted for 58.82% and 51.50% of all gas-related accidents and deaths, respectively [2].

With the rapid sustainable development of China's economy, the demand for coal is increasing, thereby leading to an increase of the extent and depth of mining. The depth of coal mining in China has increased at an average of 10 m per year, and certain mines are extending their depth at a rate of 20–50 m per year. Increasing in mining depth leads to a rise in ground stress, gas pressure and gas content [3,4], and the number and intensity of outburst events has increased in China each year. Several shallow and non-outburst coal seams are gradually becoming outburst-prone coal seams. In particular, many coal mines in the central and eastern developed areas of China, where shallow coal seams are nearly exhausted due to long-term mining, have been converted to deep mining projects (depths between 800 and 1500 m). For example, mining depths have increased to 500–900 m within the Huaibei Coal Mine Group with an average depth of 700 m. Of these coal mines, 12 of 22 coal mines are considered coal and gas outburst-prone mines. As the depth of mining has reached 800 m in the Huainan Coal Mine Group, 15 sets of producing mines are now coal and gas outburst-prone mines, and all 18 coal seams are at risk for outbursts.

Methane hazards have not yet been fully avoided in deep mines due to the complexity of the causative mechanisms [5], and several coal mines with high outburst risks have been closed due to a lack of effective methods for predicting or preventing outbursts [1]. At the same time, numerous new deep shafts of up to 1000 m depth have been constructed in the Huaibei, Huainan and Xuzhou mining areas. Excavating coal and gas outburst-prone coal seams within shafts is one of the most serious safety problems in mine construction. This problem is exacerbated as the designed depths of newly built and expanded mining shafts continuously increases; for example, the planned depth of a second auxiliary shaft at the Wangfenggang coal mine is 1017.5 m, and the hybrid shaft of the Kongzhuang coal mine is 1088 m. In addition, as coal mining projects in coal and gas outburst-prone seams in deep shafts have expanded, the technical difficulties have intensified, which readily induces dynamic gas phenomena, thereby resulting in increasing numbers of accidents, deaths or injuries to coal miners [6]. On January 5,

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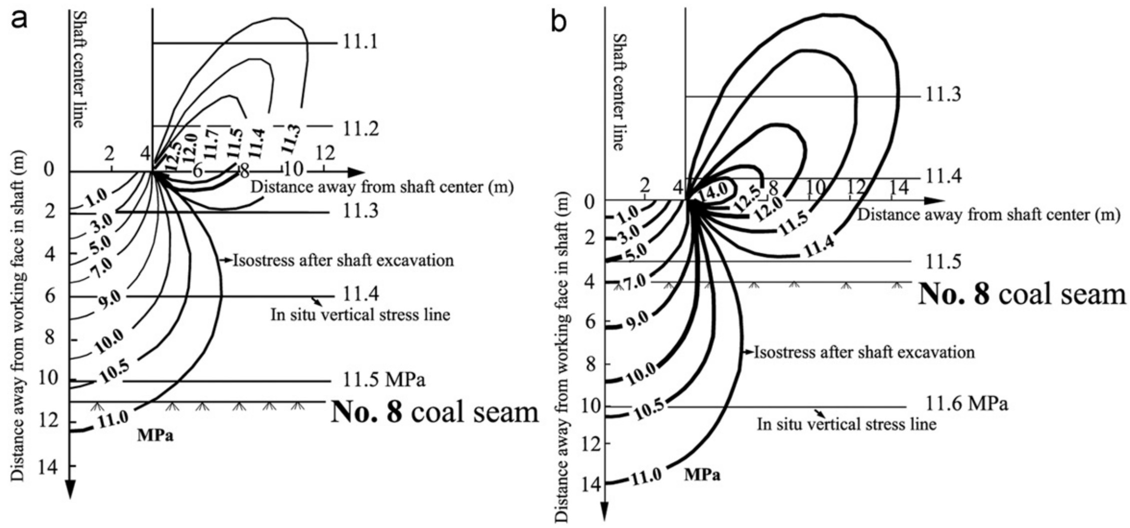

Fig. 1. Vertical stress distribution at the working face 11 m (or 4) from the No. 8 coal seam in the vertical shaft based on finite element analysis. (a) Vertical stress distribution at the working face 11 m from the No. 8 coal seam in the vertical shaft based on finite elememt analysis and (b) vertical stress distribution at the working face 4 m from the No. 8 coal seam in the vertical shaft based on finite elememt analysis.

2006, a catastrophic coal and gas outburst disaster occurred during the excavation of coal seam in a vertical shaft of the Wangfenggang coal mine of Huainan Coal Mine Group. The coal and gas outburst volumes were up to 2831 t and 292,700 m^3, respectively, which resulted in 12 deaths and a direct economic loss of total 4830,000 RMB. On July 29, 2006, a coal and gas outburst occurred when uncovering coal from a water pocket at the bottom of the auxiliary shaft during the construction of the Mengjin coal mine of the Henan Yima Coal Mine Group; this event resulted in a coal outburst volume of 900 t, a gas volume of 10,000 m^3, 8 deaths, and a direct economic loss of 4127,600 RMB.

Previously, excavations of coal seams in shafts were mainly based the 'Detailed Regulations on Coal and Gas Outburst Prevention' of China [7] and experiences of the Soviet Union. These regulations and experiences set the coverage of uncovering a coal seam as 2 m around the shaft and a gas drainage rate larger than 30%. When coal seams are shallow, gas content and gas pressure can be quite low, and the vertical shafts are not particularly vulnerable to outbursts [8]. Previously, it was common to blast the outburst coal seam with partial drilling or no drilling, although there was a high risk of an outburst with this approach. Nowadays, publications on coal excavation techniques in vertical shafts are rare, and these articles generally appear in magazines and are focused on prevention and control measures in the field. In this present study, the stress distribution characteristics and outburst risks were determined based on measured parameters in the vertical shaft of the Luling coal mine in the Huai coal field. A rigorous technical process, a set of overall techniques and several specific operations are provided. Two successful cases with different features are introduced, namely a new auxiliary shaft of the Taoyuan mine and the deep giant shaft of the Haizi coal mine and. In this paper, it was found that the technical system stipulated could be useful for safe coal mining in deep shafts, and new regulations that can be set up to ensure the safety of coal excavation during shaft construction.

2. Stress distribution characteristics and outburst risk analysis of shafts working face

2.1. Stress distribution characteristics

Coal and gas outburst are extremely complex dynamic phenomena in underground coal mines and are usually caused by multiple factors, such as geological features, gas pressure and physical properties of coal [8–12]. In general, the coal uncovering of crosscuts is more likely to cause outbursts than the excavation of coal roadway, because the coal mass of crosscut excavations is located at an area of large concentrated stress besides being surrounded by roof and floor rocks. Outbursts readily occur during blasting, as it weakens the coal mass, allowing the elastic strain energy and the potential energy in the gas that is under pressure to initiate and drive an outburst. Numerous cases in China and abroad have shown that outbursts are most likely to occur during the excavation of coal seams in crosscuts and in rock shafts or roadways where nearly 80% of large outburst cases have occurred. Uncovering coal seams mainly occurred at crosscuts, vertical shafts and inclined wells in China. In the "1.5" shaft accident at the Wangfenggang mine in Huainan, there was no outburst after uncovering the entire coal seam by blasting with a 2-m rock pillar eliminated the outburst risk surrounding the shaft; however, the outburst occurred when crossing the coal seam at a later time. This event indicated that the stress distribution of the working face is clearly different between crosscuts and vertical shafts.

The finite element method for analyzing the stress distribution of working faces in mine shafts was used during coal excavation in the new auxiliary shaft of the Luling mine. We measured the

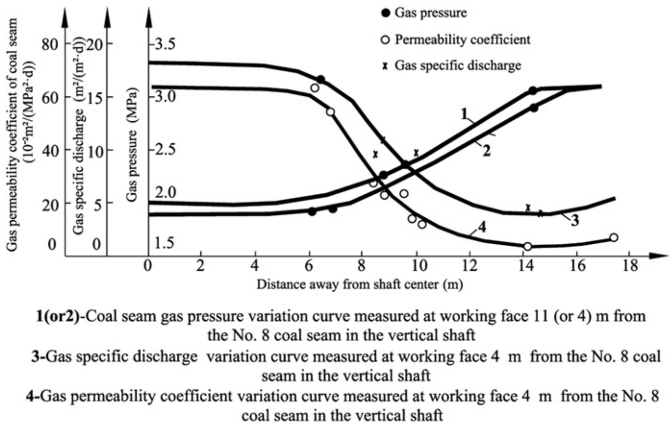

Fig. 2. Graph of the gas flow parameters measured at the working face 11 m (or 4) from the No. 8 coal seam in the vertical shaft.

stress and permeability prior to the excavation of the No. 8 coal seam [13], as shown in Figs. 1 and 2.

The No. 8 coal seam occurred at a depth of 483 m in the new auxiliary shaft with a coal thickness of 11.8 m and dip angle of 20°. The No. 8 coal seam was an outburst-prone coal seam, the measured gas pressure was 3.1 MPa, and a major outburst accident had previously occurred. Based on the measured data shown in Figs. 1 and 2, we determined that the stress at the working face of the shaft was distributed according to the following rules.

(1) When the working face approaches a coal seam, the stress distribution was divided into three zones in the front (i.e., complete) part of the pressure relief zone and the original stress zone. The pressure relief zone has a funnel-like shape, and the maximum pressure relief zone was located at the center of the 'funnel', which was surrounded by the partial pressure relief zone. In the front of the working face, the pressure relief level of the coal-rock mass was reduced with the distance from the shaft center line. As the distance between the coal seams and the working face decreased, the extent of pressure relief in a certain zone of the coal seams increased.
(2) There was a zone of concentrated stress surrounding the shaft. As the working face approached the coal seams, the range and peak values of concentrated stress increased. The area of stress concentration was about 0–12 m surrounding the shaft, and the outburst breakthrough point occurred at the corner, the intersection of the base and wall of the shaft.
(3) At the same depth, the stress distribution was different around the shaft wall. The peak and influential range of concentrated stress at the upper side of the coal seam along the trend were greater than those on the lower side due to effect of gravity stress of rock mass as well as the combined effects of concentrated stress and gas pressure.

2.2. The outburst risks of coal excavation in the shaft

Based on the stress distribution characteristics around the working face of the shaft, as shown in Fig. 3, it is found that the outburst risk in front of the heading face is relatively low because the front pressure relief zone reduced the upward outburst energy of the coal-rock mass that lies ahead. Even so, the retention of a reasonable section of rock pillar is essential to impede the occurrence of an outburst under the heading face in the shaft, because when the rock pillar is not strong enough to stop the combined effects of the gas pressure and ground stress, it may also cause an outburst accident. When the heading face penetrates into the outburst-prone coal seams, the exposed shaft wall is under the combined effect of the gas pressure and ground stress. If the range of the protection barrier surrounding the shaft was not sufficient to resist the combined effect without high strength support in time, the coal mass in the concentrated zone would lose stabilization and break, thereby resulting in the occurrence of a coal and gas outburst. Therefore, outbursts readily occur at the corner, the intersection of the base and wall of the shaft that is affected by the concentration of stress when the heading face advances into the coal seams, especially at the upper coal seam along the trend surrounding the shaft due to the stress concentration of gravity stress, concentrated stress and gas pressure.

Based on the analysis presented above, we consider that the enough protection barrier, which is formed by the coal-rock masses surrounding the shaft whose outburst risk has been eliminated, is essential for safety excavation. Therefore, the key

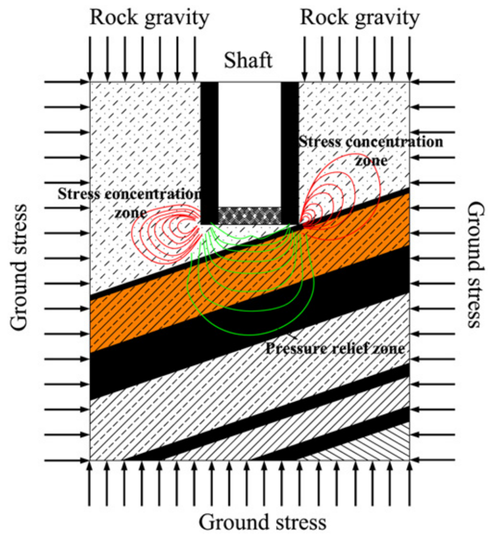

Fig. 3. Graph of the stress distribution of the vertical shafts.

technology of coal uncovering in shafts is to release the outburst energy within a certain range surrounding the shaft.

3. Process and management requirements of coal excavation in shafts

3.1. Process of coal excavation in shafts

To ensure the continuity and safety of the entire process of coal excavation, we provide the following definition of coal mining work based on gas control methodology, namely that regional outburst prevention measures are initially adopted, and additional local prevention measures. The entire process begins at a normal distance greater than 10 m from the coal seam; this distance is 20 m in complex geological structures or rock broken zones and ends at a distance of 2 m normal to the coal seam after uncovering the coal seam. The complete process is shown in Fig. 4.

Safety measures during coal excavation in the shaft would be taken at the following four stages: at 10 m normal distance away from the coal seam (20 m for complex geological structures or rock broken zones), at 7 m normal distance, 5 m normal distance and 1.5–2 m normal distance. The safety measures contain an advanced prediction, regional prediction, regional outburst prevention measures, a regional effect test and coal excavation by remote shooting.

(1) Advanced and regional prediction. At 10 m normal distance from the coal seam, we drill three exploration boreholes to determine the layer positions, sample the coal seam and measure the gas pressure. Using these exploration boreholes, we can ascertain the position of the working face relative to the coal seam and draw plane figure and sectional drawing of geologic condition. If there are enough coal sample available, the coal samples from the boreholes are then used to measure the initial rate of gas emission ΔP, the coal consistency coefficient f [1], and the gas content. To minimize the cost and duration of this measure, the boreholes can also be directly sealed for gas pressure [14]. All the measured gas parameters combined with the gas dynamic phenomena during drilling can be used to predict the outburst risk of coal seam ahead of the workface.

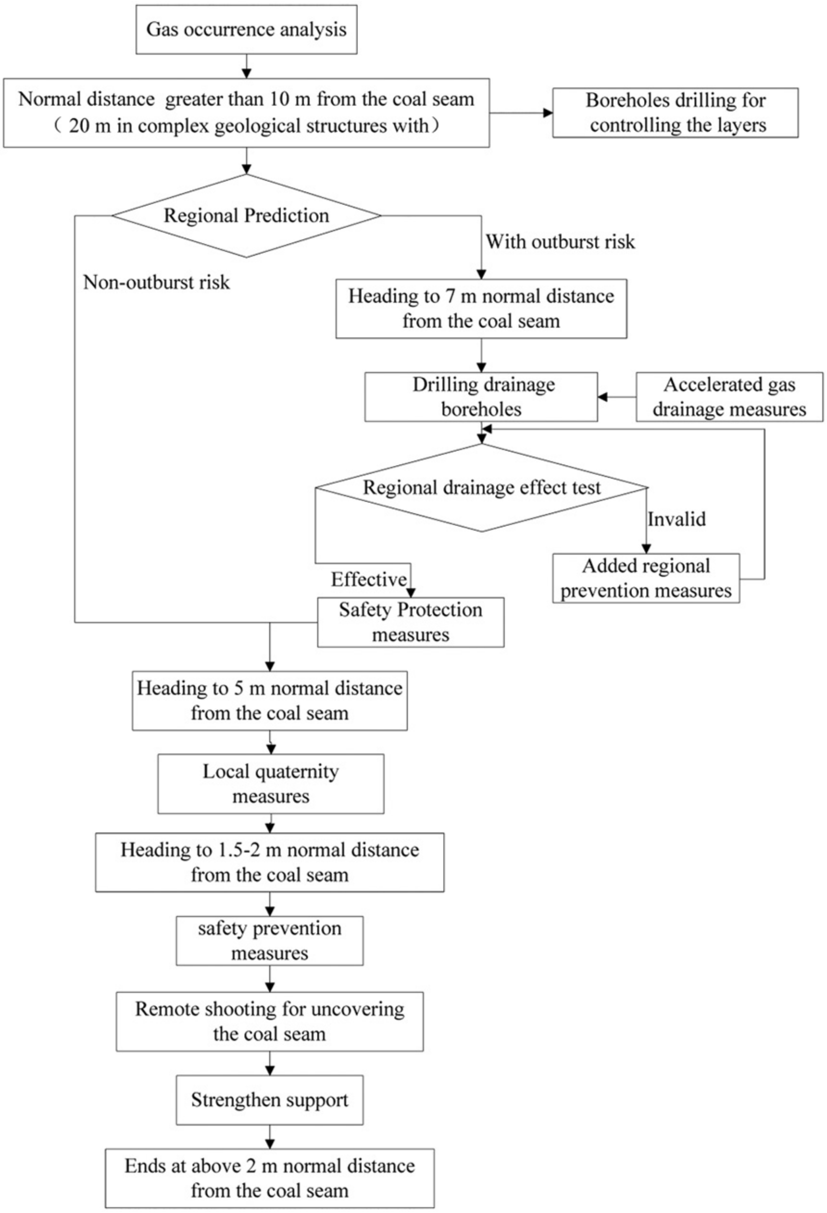

Fig. 4. Flow chart of safety technology for coal excavation in shafts.

(2) Regional outburst prevention measures. At 7 m normal distance from the coal seam, we drill several boreholes after the prediction of a non-outburst coal seam. For a coal seam at risk for an outburst, we must take regional outburst prevention measures (such as the drilling of drainage or extraction boreholes) and accelerated gas drainage measures (e.g., coal sluicing and hole cleaning). When the regional effect test is effective for measuring the residual gas pressure or content, which must be reduced below 8 $m^3 t^{-1}$ and 0.74 MPa, respectively. After that we use a metal skeleton and grout injection into the boreholes to strengthen the coal seam. Otherwise, we should add regional prevention measures to lessen the outburst risk.

(3) At 5 m normal distance from the coal seam, we adopt local quaternity prevention measures in excavated outburst or non-outburst risk areas. Composited indexes (D and K values) [7] and drill cuttings gas desorption indexes (K_1 and Δh_2 values) [15] are used for predicting the local outburst risk of the working face. After an outburst risk area is predicted, local prevention measures must be implemented. Due to the large quantity of drilling work that is required during coal excavation in the shaft, it is recommended that the outburst risk be completely eliminate at the 7 m range so that the addition of boreholes as local measures is not required at the 5 m assessment.

(4) From a normal distance of 5 m to coal seam, sampling observation by drilling exploration method should be continuously used to ensure the minimum distance required for blasting during tunneling. When advancing to 1.5–2 m from the coal seam, we use remote shooting to uncover the coal seams until the entire process is completed under the implementation of several necessary safety prevention measures.

3.2. *Management requirements*

3.2.1. *The sequence of boreholes drilling*

According to the stress distribution characteristics of the shaft working face, we know that the shaft bottom is a pressure relief zone. To prevent jet orifices and save drilling time, drilling work proceeds from the inner circle outward, and jump drilling is adopted in push drilling or strong jet orifice areas, i.e., the drill rig can be relocated to the site of draining boreholes for a period of time to provide enough time for jet orifice holes to release gas. Two drilling rigs can be arranged, but simultaneous drilling through the coal seam is not allowed.

3.2.2. Arrangement and requirements of exploration boreholes

Before the working face reaches 10 m normal distance from coal seam, at least three exploration boreholes should be drilled to penetrate into full-thickness coal seams until the floor (or bottom) is more than 0.5 m. One of the holes is drilled into the upper side of the coal seam along the trend, and others are arranged along the strike. The controlling range is not less than 12 m from the shaft wall. Two boreholes are coring holes and are used to record the rock core data in detail, which provides a clear determination of the master coal seam thickness, changes in dip angles, geological structures and the occurrence of gas. If faults, folds or abnormal coal-rock masses are found, we must increase the number of exploration boreholes.

3.2.3. Processing of prediction results

When coal seams are predicted to have a non-outburst risk in the shaft at 7 m normal distance from the coal seam, we do need not take measures for shallow coal seams with depths less than or equal to the critical depth of the coal seam gas weathering zone. However, because prediction techniques continue to be unreliable [10,16], it is suggested that a number of boreholes are drilled for releasing gas and the deep-level ground stress simultaneously even when non-outburst risk coal seams are predicted. Local quaternity prevention measures are requested to be used in excavated outburst or non-outburst risk areas.

3.2.4. Range requirements of drainage boreholes

The minimum controlling range of regional outburst prevention measures should be not less than 12 m from the shaft wall in nearly horizontal, gently inclined or inclined coal seams; the downslope controlling range can be reduced to 6 m in steeply inclined coal seams. If the boreholes cannot penetrate through the full thickness of the coal seam, the advance distance should be maintained at greater than 15 m in the coal seam.

The minimum controlling range of local outburst prevention measures should be no less than 5 m from the shaft wall in nearly horizontal, gently inclined or inclined coal seams; the downslope controlling range can be reduced to 3 m in steeply inclined coal seams. Drilling holes ahead of the coal excavation working face should penetrate the total thickness of the coal seam when possible. If the full thickness of the coal seam is not penetrated, sectional construction can be adopted, although the drilling length through the coal seam should be not less than 15 m during the first section, and a distance of at least 5 m coal seam within the boreholes controlling range must be maintained when advancing into the coal seam.

3.2.5. Arrangement of effect test boreholes

The test points should be arranged in positions where there has been a low density of previous drilling with a larger spacing between holes and within less time for drainage. The distance between the test point and the previous drilling holes should be equal. We should add appropriate test points in areas of complex geological structures. Four test points should be located in the top, middle and two sides of the drainage area using penetration boreholes, and at least one point is required at not more than 2 m from the edge of the coal excavation.

3.2.6. Effectiveness identification of drainage boreholes

The identification of the effectiveness of the prevention measures includes following several aspects:

a) Drilling construction satisfies the design requirements, and the borehole arrangement is uniform.
b) Residual gas pressure < 0.74 MPa, or residual gas content $< 8\ m^3\ t^{-1}$.
c) Gas drainage rate $> 50\%$.
d) The quantity of coal obtained by sluicing is greater than 2% of the total amount in the coal seams that are being controlled.
e) Gas desorption indexes $K_1 < 0.4\ mL\ g^{-1}\ min^{-1/2}$ (wet coal) and $\Delta h_2 < 160$ Pa (wet coal) in drilling cuttings.

4. Safety technologies for coal excavation in shafts

To achieve economical, safe, efficient and fast coal uncovering in mine shafts, we divide outburst prevention and control measures into three types of measures: the primary technical measures (e.g., drainage or extraction boreholes), accelerated gas drainage measures (e.g., coal sluicing and hole cleaning) and safety protection measures (e.g., coal seam strengthening using metal skeletons and grout injection).

4.1. The primary technical measures

The main outburst prevention measures include gas dilution by ventilation and drainage boreholes [17,18]. Its principle of eliminating outbursts is to remove the coal-rock mass in concentrated areas of stress by drilling, which causes pressure relief and the deformation of coal surrounding the drilling space due to the

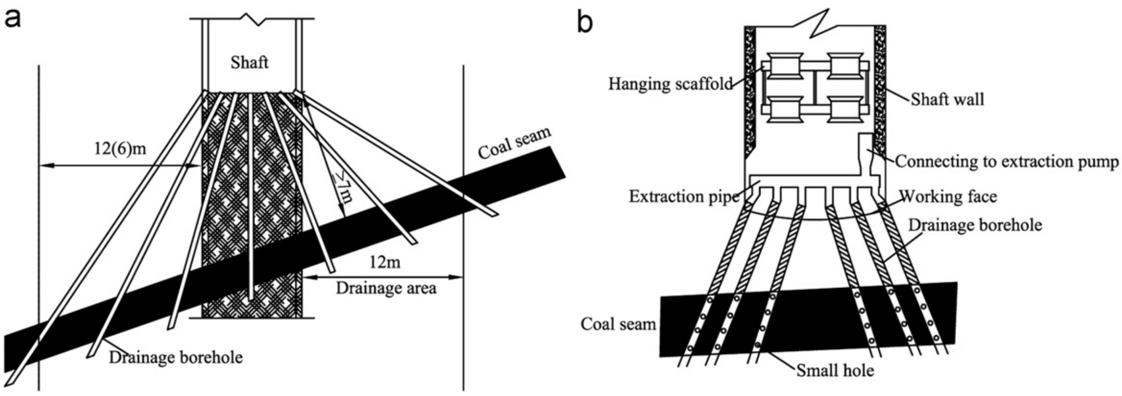

Fig. 5. The arrangement of the drainage boreholes. (a) Configuration of drainage boreholes and (b) diagram of extraction pipes connection.

action of inelastic deformation energy, thereby lowering the stress concentration peak and increasing the coal seam permeability. By extracting the coal seam gas in the vicinity of the borehole, the gas outburst energy and gas pressure are reduced, the coal strength is enhanced, and the outburst risk is eliminated. A last a protection barrier around shaft wall is formed for preventing coal and gas outbursts.

Drainage boreholes must satisfy the following conditions:

(1) The controlling range is in accordance with the range requirements.
(2) The diameter of borehole should be in the range of 75–120 mm, and the space between each hole is determined by the coal seam permeability and the drainage time that is allowed in the production plan (typically not more than 3 m at the final hole bottom).
(3) Penetration boreholes should attempt to drill through the full-thickness of the coal seam in one drilling.
(4) Continuous drainage or natural discharge before uncovering the coal seam should be kept.
(5) Natural drainage is suitable for coal seams with relatively high permeability and sufficient time to discharge. For low-permeability seams and poorly-drained working faces in the shaft, coal sluicing and hole cleaning can be used to improve the gas drainage.

A sketch of the drainage borehole arrangement is shown in Fig. 5.

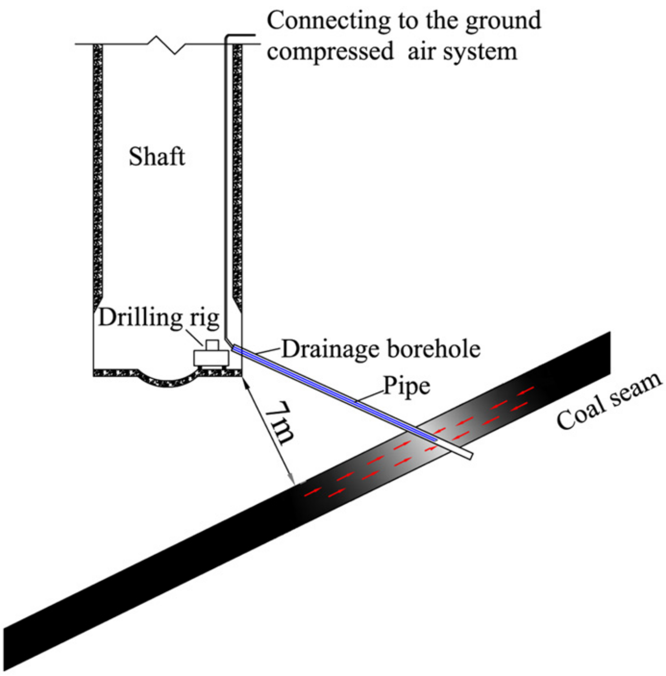

Fig. 6. Diagram of coal sluicing and hole cleaning technology.

4.2. Accelerated gas drainage measures

In the shaft, the gas drainage boreholes are nearly vertical downward-facing holes which are easy for hydrops, and the holes are prone to collapse along the section crossing the coal seam. Therefore, an innovative method for improving and accelerating gas drainage, i.e., coal sluicing and hole cleaning technology, is used. Generally, the method is thought to be effective when the quantity coal obtained by sluicing is greater than 2% of the total amount of coal in the seams being controlled.

Coal sluicing and hole cleaning technology accelerates gas drainage through two main processes. First, these methods can be used to flush out hydrops in holes and reduce the resistance to gas emission. Second, collapsed and accumulated coal in the drilling holes, as well as a certain volume of coal-rock mass around the holes, can be flushed out. Thus, coal sluicing and hole cleaning provides space for the movement and deformation of the following coal mass, thereby transferring the deep-seated concentrated stress, enlarging the pressure relief range, and increasing the coal permeability to promote gas emission. Specifically, we set a metal DN15 pipe at the bottom of the drilling hole connecting to air compressor with 4–5 MPa pressure and continuously sweep the drilling holes for a period time (as shown in Fig. 6). For severe hole collapses and shrinkage, we should use a drill rig and metal pipe with small holes through main boreholes that can be used to protect the hole in areas of roof or floor collapse.

4.3. Safety protection measures

After identification of the effectiveness, we can use metal skeletons, grout injection and other assurance measures to

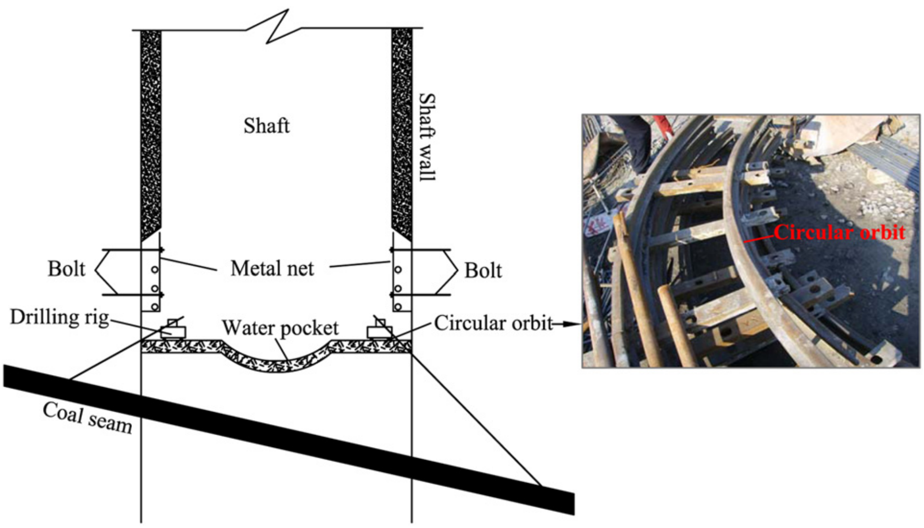

Fig. 7. Diagram of the circular orbit and concave water pocket used for drilling.

enhance coal strength for guaranteeing the safe excavation of coal in shafts. Skeleton materials can choose 8 kg m^{-1} steel rails, sectional steel or steel pipe with a diameter no less than 50 mm. Skeletons are typically installed along the outside of the shaft in the range 2 to 4 m, and the length of the skeletons into the coal floor is no less than 0.5 m. For soft coal seams, solidifying materials (e.g., grout or polymer materials) can be injected into the coal through drainage holes prior to coal uncovering to enhance the strength of the coal.

4.4. Specific operations for drilling

4.4.1. Circular orbit

To enhance the drilling speed and achieve convenient rig placement within vertical shafts, we can lay a circular orbit adjacent to the shaft wall with a spacing of 650 mm between the orbit tracks, as shown in Fig. 7. Steel 10# channels, which are welded using 22 kg m^{-1} steel rails and strengthened with screws, can be used as sleepers that are fastened to the floor using three bolts. The lateral distance between the orbit and the shaft wall is approximately 500 mm for comfortable drilling. When drilling, we use 300 × 300 mm steel channels to fix the drill rig in a circular orbit; the rig then slides along the orbit for drilling. This technology not only saves the human, material and financial resources but also shortens the drilling time and increases the work efficiency.

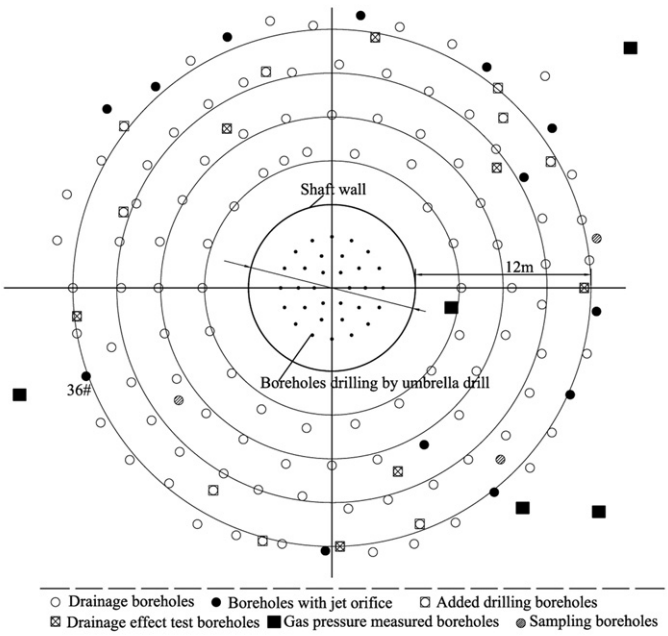

Fig. 8. The final configuration of boreholes at the No. 8-2 coal seam in the new auxiliary shaft.

4.4.2. Concave water pocket

Within shafts, there is considerable trickling water, and construction conditions are poor, which causes drainage holes collapses, deformations in soft rock areas, and increased rock powder and hydrops in drilling holes. To assure the smooth flow and rapid drainage of gas in sufficient time to eliminate an outburst, we dig a concave water pocket in the center of working face before drilling, as shown in Fig. 7. The surrounding area is 400 to 500 mm higher than center of the pocket, and a 100-mm-thick concrete floor is spread along the concave surface. This pocket allows concentrated water to drain easily, accelerates the drainage by reducing the flow of water into the drainage boreholes, and allows workers to conveniently walk near the working face. At the same time, the water pocket is conducive to locating and trepanning of drilling holes, which can improve the precision of drainage boreholes.

5. Examples

5.1. The new auxiliary shaft at the Taoyuan coal mine

The Taoyuan coal mine is located in the town of North Yangzhai, which is in the southern part of Suzhou City, Anhui Province, China. To extend the depth of development, the new auxiliary shaft was built at the Taoyuan coal mine with a designed depth of 855.55 m. During the construction of the shaft, it would cross 10 coal seams, including the No. 7-2 and No. 8-2 coal seams, which were outburst-prone seams. The No. 8-2 coal seam was uncovered at a depth of 771.3 m; the measured gas pressure was 4.31 MPa, and the gas content was 13.92 m^3 t^{-1}. There were 15 jet orifices, and the maximum quantity of coal from the orifice of the single hole was approximately 7 t (from the 36# hole). The gas desorption index K_1 was 0.4 mL g^{-1} min$^{-1/2}$ (wet coal), and Δh_2 was 250 Pa (wet coal). Safety technologies for coal excavation were also used, and the actual controlling range was 12 m surrounding the shaft. Boreholes outside of the shaft wall were constructed using drill rigs, and boreholes inside the shaft were constructed using an umbrella drill. The borehole diameter was 94 mm, and the spacing between each borehole was less than 3 m. A total of 165 boreholes were drilled for the No. 8-2 coal seam, among which 133 holes were made using drill rigs, 32 holes using umbrella drills. And 4 holes were sealed for pressure measurement and 7 holes were used for effect tests. The final construction of the boreholes is shown in Fig. 8.

After approximately 48 day of gas drainage, 26,493 m^3 of gas were exhausted, and the gas drainage rate reached 66.9%. The coal-sluicing quantity of the No. 8-2 coal-rock seam group was approximately 80 t, which accounted for 2.1% of the coal reserve

Table 1
Statistics of related investigation indexes for the new auxiliary shaft.

Coal seam	Original gas content (m^3 t^{-1})	Original gas pressure (MPa)	Residual gas content (m^3 t^{-1})	Residual gas pressure (MPa)	Critical regulatory value	
					Gas content (m^3 t^{-1})	Gas pressure (MPa)
8-2	13.92	4.31	4.71	0.02	8	0.74
Coal seam	Original gas desorption indexes (wet coal)		Residual gas desorption indexes (wet coal)		Critical regulatory value (wet coal)	
	Δh_2 (Pa)	K_1 (mL g^{-1} min$^{-1/2}$)	Δh_2 (Pa)	K_1 (mL g^{-1} min$^{-1/2}$)	Δh_2 (Pa)	K_1 (mL g^{-1} min$^{-1/2}$)
8-2	250	0.4	90	0.03	160	0.4

within the controlling range. Relevant investigation indexes are summarized in Table 1.

As shown in Table 1, the residual gas content, gas pressure and gas desorption indexes of the drilling cuttings were reduced below the critical values. Continuous gas bubbling in the boreholes turned into intermittent, which provided indirect evidence of the effectiveness of the gas drainage.

After the elimination of the outburst risk was demonstration, we tested the effectiveness of the control measures using gas desorption indexes when advancing to 1.5 m normal distance from the coal seam. Subsequently, we used remote shooting to uncover the coal seam. The maximum gas concentration was 0.62% at 0.5 h after blasting, and the average concentration was approximately 0.41%, as shown in Fig. 9.

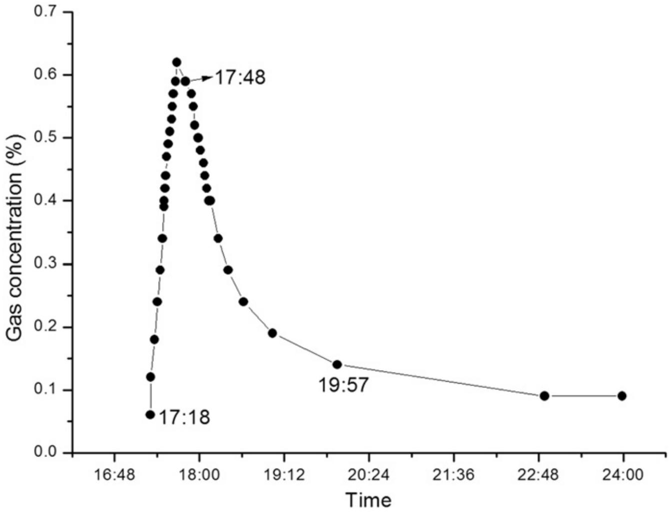

Fig. 9. Gas concentration variation with time after blasting.

5.2. *The deep giant shaft in the Haizi coal mine*

The Haizi coal mine is located in Suixi county, Huaibei city, Anhui province, China. The shaft is situated on the north side of the mine complex of the Haizi coal mine and is used for ventilation, materials transportation and worker access. The shaft is supported by reinforced concrete, the thickness of shaft wall is 550 mm, the nominal diameter is 7.6 m and the absolute diameter is 6.5 m. The shaft would intersect the main transport crosscut of the third level of the shaft station at 1029 m depth. The shaft would go through 16 seams and coal-streaks, including the No. 7 coal seam group (including the No. 7-1 and No. 7-2 coal seams) and the No.8 coal seam group (including the No. 8-1, No. 8-2 and No. 8-3 coal seams), which are outburst-prone coal seams. The No. 7-1, No.7-2, No.8-1, No.8-2, and No.8-3 coal seams would be uncovered at depths of 953.42, 955.65, 960.85, 965.02, and 973.89 m, respectively. The measured gas pressure of the No. 7 coal seam group was 1.7 MPa, and the gas content was 14.16 $m^3\,t^{-1}$; the gas pressure of the No. 8 coal seam group was 4.5 MPa, and the gas content was 19.28 $m^3\,t^{-1}$. Jet orifice phenomena were extensive during the initial drilling. The maximum quantity of coal from the orifice of the single hole was approximately 10 t, the absolute gas emission quantity was 9 $m^3\,min^{-1}$, and the gas concentration within the boreholes was almost greater 95%.

Gas drainage was achieved by the combination of drilling downward-facing boreholes inside the shaft together with the drilling of upward-facing boreholes from three levels of the shaft

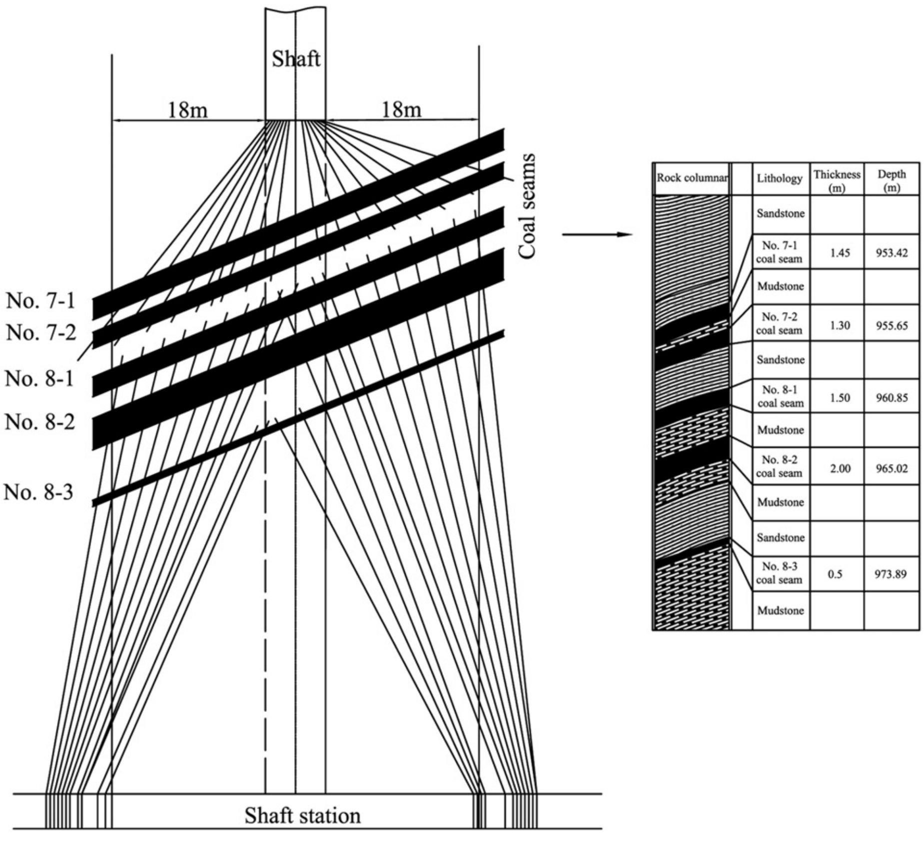

Fig. 10. Diagram of the drilling for the No. 7 and No. 8 coal seam groups in the deep giant shaft.

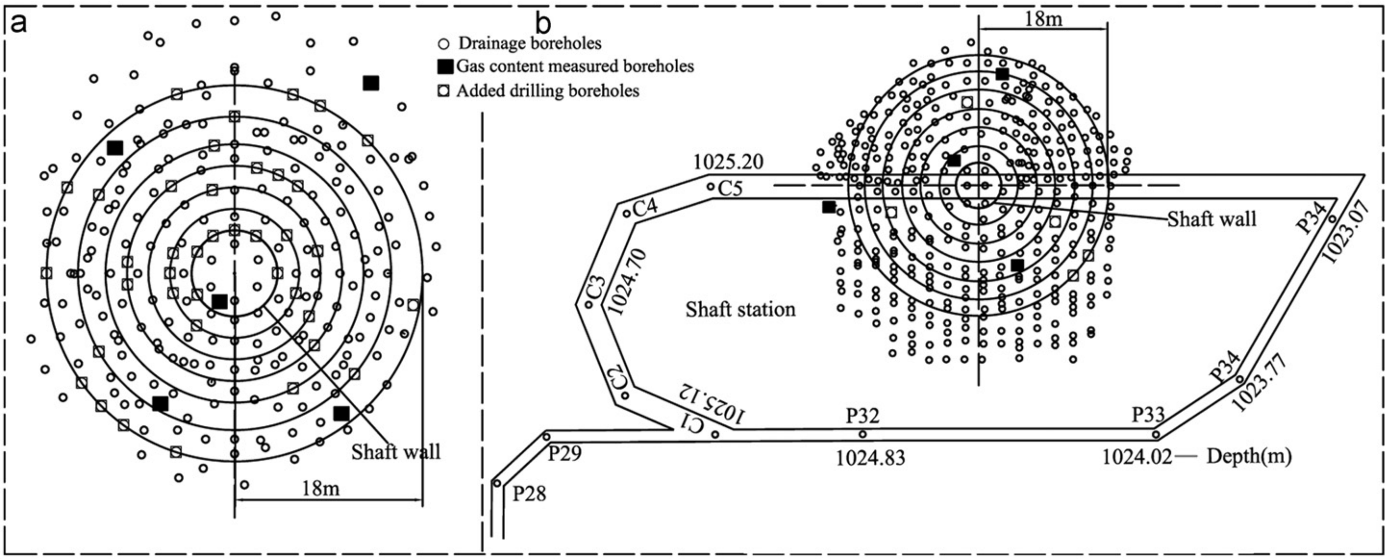

Fig. 11. The final configuration of the boreholes of the No. 7-2 and No. 8-3 coal seams in the deep giant shaft. (a) Final configuration of boreholes of the No. 7-2 coal seam and (b)final configuration of boreholes of the No. 8-3 coal seam.

Table 2
Statistics of related investigation indexes for the deep giant shaft.

Coal seam	Number	Original gas content ($m^3\,t^{-1}$)	Coal sluicing quantity (t)	Gas drainage rate (%)	Coal sluicing rate (%)	Residual gas content ($m^3\,t^{-1}$)	
						Calculated	Measured
7	7-1, 7-2	14.16	133.54	62.20	2.16	5.35	6.2
8	8-1, 8-2, 8-3	19.28	535		4.29	7.29	6.94

station. The No. 7 coal seam group was drilled from inside the shaft, whereas the No.8 coal seam group was drilled from the shaft station. A total of 249 boreholes were actually constructed for the No. 7 coal seam group, and 420 boreholes were drilled for No. 8 coal seam group. The controlling range was 18 m outside of the shaft wall, the borehole diameter was 94 mm, and the borehole spacing was 3 m. The construction situations are shown in Figs. 10 and 11.

The total quantity of gas released from September 2010 to May 2011 was 228,600 m^3, and the gas drainage rate reached 62.20%. The coal sluicing quantity of the No. 8 coal seam group was approximately 535 t, which accounted for 4.29% of the coal reserve in the controlled range. The coal sluicing quantity of the No. 7 coal seam group was approximately 133.54 t and accounted for 2.16% of the coal reserve in the controlled range. Specific indexes from the investigation are summarized in Table 2, and all data showed that the outburst indexes had been reduced below the critical values. During the drilling of effectiveness test boreholes, gas dynamic phenomena did not occur. Based on the test results, the risk of an outburst in coal seams in the shaft was eliminated. It is noteworthy that the gas desorption indexes (K_1 and Δh_2) were not successfully measured and the values were all zero, which were due to the large drilling distance beyond the parameters measuring limit.

6. Conclusions

The excavation of coal and gas outburst-prone coal seams in shafts is one of the most serious safety problems in shaft construction. As mining depths increase, the risk of coal and gas outbursts in coal seams in deep shafts also increases and technical difficulties are intensified. In the paper, we determined that a funnel-shaped pressure relief zone existed under the working face and that a stress concentration zone surrounding the shaft was the critical area for gas outburst disasters.

To ensure the continuity and safety of the entire process of coal excavation, we divided the process of coal uncovering into four stages of management and applied three types of gas prevention and control measures: the primary technical measures (e.g., drainage or extraction boreholes), accelerated gas drainage measures (e.g., coal sluicing and hole cleaning) and safety protection measures (e.g., coal seam strengthening using metal skeletons and grout injection). Specific procedures for drilling were also provided, including circular orbit drilling and the use of a concave water pocket. The coal seams in the shafts of the Taoyuan and Haizi coal mines in the Huaibei mining region occurred at great depths and with high gas pressure and contents. All related investigation indexes were reduced below the critical values after adopting safety technologies for coal excavation, and fast and safe coal uncovering was realized. The technical systems developed in this paper would allow coal excavation procedures for deep shafts to be programmed, which were set up as new regulations. And the regulations would ensure the safety of coal excavation in shafts and serve as a reference for uncovering outburst-prone coal seam in shafts.

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