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Hazard detection and comprehensive control technologies of the integrated resource coal mine goafs in China

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ABSTRACT
Goaf disaster has become a major problem for the integrated resource coal mines in China. Based on an analysis of goaf disaster types and characteristics, hazard detection and comprehensive control technologies are systematically put forward. The control technologies include goaf hazard detection technologies which combine ground survey with undermine detection; the goaf risk classification and assessment technologies combined with risk degree classification, qualitative with quantitative evaluation; the goaf disaster monitoring technologies which combine local and regional monitoring with joint monitoring undermine and on the surface; the goaf comprehensive control technologies which combined open stripe grouting with roof caving on the surface or undermine; and the goaf safety guarantee technologies which combine matching funds and policy support with administrative supervision. The results show that goaf disasters are divided into four types according to the disaster forms in integrated resource coal mines. The four types are comprised of the abandoned old goafs or permeable pit shafts, goaf fires including coal combustion and gas explosions, the poisonous and harmful gas in goaf emissions, and the abnormal geological disasters. The goafs have the characteristics of unknown distribution, different kinds of disaster types, concealment, and unpredictability. The control principles were summarized and put forward in the form of an advance summary of ground survey, an undermine detection follow up, hazard assessment and evaluation, in-place monitoring and supervising, comprehensive control for disaster reduction, and a guarantee of safety measures.
KEYWORDS: integrated resource coal mines; goafs; ground survey; undermine detection; monitoring; disaster prevention and control; safety guarantee.

1. INTRODUCTION

Since September 2005, China has been carrying out the integration of coal mines, The number of coal mines has been reduced from 25,000 in the year 2005 to 11,000 in the year 2014.

The integrated resource coal mines have experienced a series of hazards and accidents, such as water, fire, or roof hazards caused by unknown goafs due to the original local small coal mines often having a lack of basic data. The problem of goaf hazards has become a major trouble facing the integrated resource coal mines in China.

Aimed at coal mine goaf hazards, much research has been carried out on the instability mechanism of goaf pillars and roofs (Liu et al., 2014; Wang et al., 2008; Zhang et al., 2008), geophysical detection technology (Li et al., 2011b; Liu et al., 2012), and comprehensive prevention and control technologies (Li, 2011a; Li et al., 2014; Li W and Li J, 2015; Zhang et al., 2013) in coal mine goafs. However, there is a lack of systematic analysis concerning the goaf types, characteristics, detection, and control technologies. Based on the analysis of goaf hazard types and characteristics, hazard detection and comprehensive control technologies are systematically put forward. The available technologies include the goaf hazard detection technologies which combine ground surveys with undermine detection; the goaf risk classification and assessment technologies combined with qualitative and quantitative risk degree classification evaluation; the goaf hazard monitoring technologies which combine local and regional monitoring with joint monitoring undermine and on the surface; the control technologies which combine open stripe grouting with roof caving on the surface or undermine; and the goaf safety guarantee technologies which combine matching funds and policy support with administrative supervision. The present study aims to construct a system and framework for the hazard detection and comprehensive control technologies of the integrated resource coal mine goafs in China.

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2. MAIN TYPES OF INTEGRATED RESOURCE COAL MINE GOAF HAZARDS IN CHINA

According to the statistics of State Administration of Coal Mine Safety in China, since the year 2000, there have been 103 accidents of coal mines goaf hazards in integrated resource coal mines. Based on the complex geological conditions, the goaf hazards were divided into four types according to the hazard forms. These four types are comprised of the abandoned old goafs or permeable pit shafts, goaf fires including coal combustion and gas explosions, the poisonous and harmful gas in goaf emissions, and the abnormal geological disasters, including goaf collapse, ground subsidence, and mine earthquakes induced by sudden large-scale goaf collapse.

Statistics show that the total number of abandoned old goaf or permeable pit shaft accidents is the largest, accounting for 61% of all accidents. Roof limestone water is responsible for 44.4% of abandoned old goaf water disasters. Roof aquifer waters, including roof sandstone water and roof limestone water are the main waters filling the goafs.

3. CHARACTERISTICS OF INTEGRATED RESOURCE COAL MINE GOAF HAZARDS IN CHINA

There are four characteristics of integrate resource coal mine goaf hazards in China.

Firstly, the distribution of abandoned old goafs is unknown due to disorderly exploitation and lost historical mining data. The goafs have become a major security risk.

Secondly, the goafs have different kinds of hazard types. The occurrence of accidents in coal mine goafs is the result of the combined action of mining, geology, and management. In addition, the goaf hazards may be triggered by other hazard types, such as water or fire hazards.

Thirdly, the goafs are concealed and accidents happen suddenly. Generally speaking, unless the surface collapses or cracks, there is underground dynamic mine pressure, abnormal gas concentration, or water inrush, the goaf hazards are often difficult to find. Once they occur, they are difficult to control.

Fourthly, goaf hazards are unpredictable. Because of the different geological and mining conditions, the occurrence of goaf accidents are not regular, and are difficult to predict. In recent years, some coal mine groups and research institutes have carried out related research, but the prediction of goaf hazards is still in the exploration stage.

4. DETECTION TECHNOLOGIES OF INTEGRATED RESOURCE COAL MINES GOAFS HAZARD

The analysis of 103 cases of coal mine goaf accidents showed that most of the accidents were induced by unknown abandoned old goafs. The detection technologies were limited and proper safety management was not in place.

In recent years, cities in Midwest China such as Ordos City, Yulin City, Linfen City, and Jincheng City have carried out coal mine goaf detection work within the scope of whole cities, and have achieved remarkable results. These practical experiences provide reference for the integrated resource coal mine goaf prevention and control.

4.1 Ground survey

Most of the integrated resource coal mine goafs cannot be reached. Ground surveys are the most suitable method to adapt underground advanced geological detection or drilling methods in lanes near abandoned goafs. Ground survey includes field reconnaissance and surveying, geophysical ground detection, and ground drilling. The work process involves data collection and analysis, exchanging with coal mine technical personnel, field reconnaissance and surveys (including remote sensing geological surveys), range determination, geological detection methods and scheme design, data acquisition, data processing and interpretation, drilling verification and data reinterpretation, report preparation, return visits to the results, revising reports, and the final report submission.

The main methods for goaf geophysical ground detection are the shallow seismic method, the high density resistivity method, the controlled source audio frequency magnetotelluric method, and the Eh4 magnetotelluric method.

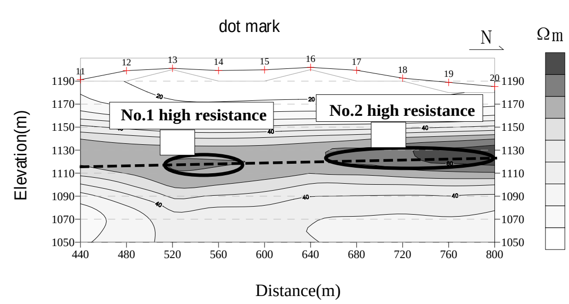

Figure 1: The typical apparent resistivity comprehensive profile including goafs.

The typical apparent resistivity comprehensive profile including goafs is shown in Figure 1. The darker color indicates higher resistivity. Between the distances of 510m to 590m and 650m to 800m, there are two higher apparent resistivity regions from which the presence of old abandoned goafs were deduced. They were verified by drilling boreholes.

4.2 Undermine detection

For integrated resource coal mines, especially those that are threatened by water inrush hazards, it is recommended to adapt the principles of ‘forecasting in advance, detection before tunneling or mining’. Undermine detection includes undermine drilling detection, geophysical detection, and geochemical detection. Undermine drilling detection is the conventional method, while geochemical detection is often used to detect water quality or source when water inrush hazards may happen. Undermine geophysical detection involves advanced detection in tunnels, inner working face detection, as well as roof and floor detection.

Advanced detection in tunnels is mainly used in the detection of abandoned goafs and their water distribution, fault, collapse columns, or other abnormal structures in front of tunnel. Conventional geophysical detection methods are the mine transient electromagnetic method, the mine DC resistivity method, the mine seismic method including the Rayleigh wave method, and the reflected wave method.

The typical apparent resistivity comprehensive profile of advanced detection in tunnels is shown in Figure 2. The blue color indicates lower resistivity. In front of the left tunnel about 60m from the tunnel face there exists a lower resistivity region, from which water bearing goafs were deduced. The water in the lower resistivity region was later drained.

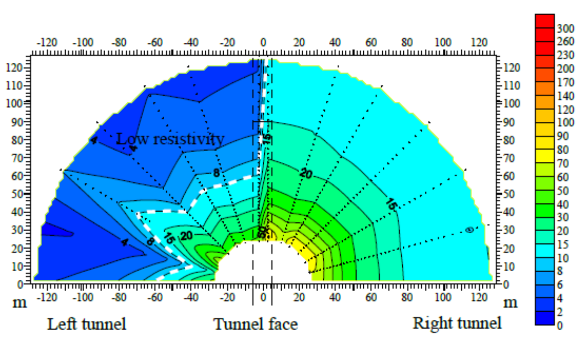

Figure 2: The typical apparent resistivity comprehensive profile of advanced detection in tunnel.

Inner working face detection is mainly used in the detection of fault, collapse columns, or other water bearing structures in the working face. The conventional geophysical detection methods are the mine DC electric perspective methods (including audio frequency electric perspective method and resistivity CT method), the radio wave perspective or CT methods, the mine reflected wave method, and the mine channel wave seismic method.

Roof and floor detection is mainly used in the detection of aquifers, impermeable layers, water conducting passages, limestone karst and its development, faults in the roof and floor, and fracture development zones. The conventional geophysical detection methods are the mine transient electromagnetic method, the electrical sounding and electrical section methods, the high-density resistivity method, and the mine reflected wave method or transmission wave method.

5. COMPREHENSIVE PREVENTION AND CONTROL TECHNOLOGIES FOR INTEGRATED RESOURCE COAL MINE GOAF HAZARDS

Based on extensive practice, the principles for the comprehensive prevention and control of integrated resource coal mine goaf hazards were summarized and put forward, including ground surveys in advance, undermine detection follow up, hazard assessment and evaluation, in-place monitoring and supervising, comprehensive control for hazard reduction, and guarantees of safety measures.

5.1 Goaf hazard assessment and evaluation

With changes in the ecological environment of coal mines, mining conditions, mining methods, and intensity, goaf hazards have become a dynamic process. It is important to carry out risk grading classification and assessment, qualitative evaluation, and quantitative evaluation of goaf hazards.

The qualitative evaluation of goaf hazards mainly includes the Safety Checklist Analysis Method, the Accident Tree Analysis Method, the Event Tree Analysis Method, and the Preliminary Hazard Analysis Method. The quantitative evaluation of goaf hazards mainly includes the Fuzzy Comprehensive Evaluation Method, the Analytic Hierarchy Process Method, and the Index Classification Method. The Index Classification Method is often used to determine the impact of various mining and geological factors and establish a risk classification index.

For example, There are 20 influence factors for old abandoned goafs in Shendong mining area. They are mining height, dip angle of coal seam, buried depth of goafs, fault distribution near goafs, uniaxial compressive strength of overlying rock and coal pillars, principal stress differences between maximum and minimum, the direction of ground stress, the accumulation of water in goafs, spontaneous combustion in goafs, goaf area, the ratio between coal pillar width and height, the ratio between mined and remained, the conditions of roof control, ground subsidence conditions, the goaf seal conditions, the surrounding coal seam mining conditions, whether the goafs instability events happened or not, the distribution of surface buildings above goafs, and the remain time of goafs.

The Index Classification Method is used to comprehensively assess the risk of old abandoned goafs in Shendong mining area. The Index W is listed in formula as follows,

$$W = \sum_{i=1}^{n} G_i \Big/ \sum_{i=1}^{n} G_{i\max} \tag{1}$$

In formula (1), $G_{i\max}$ represents the maximum rating value of number i influence factor, G_i represents the actual rating value of number i influence factor, and n represents the number of influence factors.

Five risk grading classification was divided as Grade I risk (especially significant risk, $W \geq 0.85$), Grade Ⅱ risk (significant risk, $0.75 \leq W < 0.85$), Grade Ⅲ risk (greater risk, $0.65 \leq W < 0.75$), Grade Ⅳ risk (general risk, $0.50 \leq W < 0.65$), Grade Ⅴ risk (less risk or no risk, $W < 0.50$). 154 old abandoned goafs were assessed using the Index Classification Evaluation System in Shendong Mining area. The results are shown in Table 1.

Table 1: The risk assessment results of old abandoned goafs in Shendong mining area.

Coal mine name	Goafs num.	Grade				
		I	Ⅱ	Ⅲ	Ⅳ	Ⅴ
DALIUTA	39	0	0	1	38	0
SHANGWA	7	0	1	3	3	0
HALAGOU	8	0	0	5	3	0
WULANMULUN	12	0	0	0	12	0
BULIANTA	10	0	0	0	10	0
SHIGETAI	7	0	0	1	6	0
LIUTA	9	0	0	5	4	0
CUNCAOTA1	2	0	0	0	2	0
CUNCAOTA2	8	0	1	0	6	1
YUJIALIANG	48	0	0	3	45	0
BAODE	4	0	0	1	3	0
Total	154	0	2	19	132	1

5.2 Monitoring and supervisory technologies of goafs

The monitoring and supervisory systems of goafs are far from established in normal coal mines, besides lots of monitoring equipment being installed within some advanced coal corporations in China. The monitoring currently involves the displacement monitoring of overlying strata destruction, the surface subsidence monitoring, and the monitoring of coal pillar stability. The goaf monitoring systems may borrow the experiences of seismic network layout for rock burst monitoring, develop micro-seismic monitoring technology, automatic monitoring technology of internal displacement of rock mass, and temperature on-line monitoring technology.

A set of monitoring systems was developed in the Shendong mining area involving micro-seismic monitoring, working face pressure monitoring, borehole stress monitoring, rock mass internal displacement monitoring, ground borehole television watching, and surface displacement monitoring, which all provided basic research for dynamic pressure control when mining under room and pillar goafs. In addition, borehole seismic technology was introduced for overburden failure monitoring of goafs in Yitai Coal Group.

The comprehensive monitoring system of goafs is shown in Figure 3.

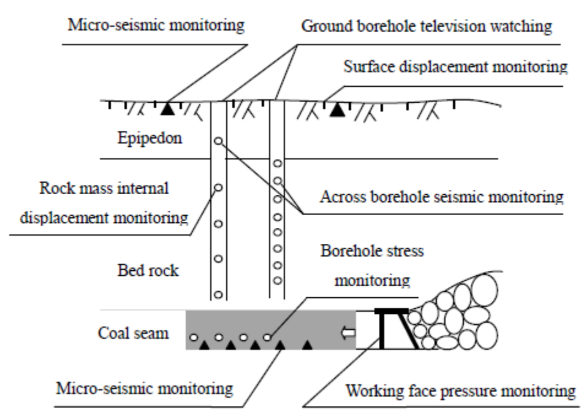

Figure 3: The comprehensive monitoring system of goafs.

5.3 Comprehensive control technologies of goafs

For abandoned old goafs or permeable pit shafts, goaf fires including coal combustion and gas explosion, and poisonous and harmful gases in goaf emissions, ground surveys and undermine detection should be carried out. The design of water drainage, ventilation, and fire control should then be put forward. Finally, special measures should be made according to the goaf hazard types and degree.

For the abnormal geological hazards including goaf collapse, ground subsidence, mine earthquakes induced by sudden large-scale goaf collapse, the open stripe is adopted where there are no important buildings on the surface of the goaf and the buried depth is less than 100m. In addition, the grouting method is often adopted where there exists important buildings, and the roof caving method is adopted where the goaf recovery rate is more than 40% and the coal beneath the goaf needs to be mined.

5.4 safety measures for guarantee of goafs

The safety technologies mainly involve matching funds, policy support, and administrative supervision.

First of all, the matching of funds by the government or coal groups should be implemented. Secondly, goaf detection, preventionl and control should be supported by the state, provincial, and industrial policy. Thirdly, administrative supervision by the government and the coal industry is an important link in preventing goaf hazards. In addition, technical measures are another fundamental guarantee of safety.

6. CONCLUSIONS

China faces a long and hard process in the prevention and control of integrated resource coal mine goaf hazards, because goafs have the characteristics of unknown distribution, different kinds of hazard types, concealment, and unpredictability. The following control principles should be implemented: ground surveys in advance, undermine detection as a follow up, hazard assessment and evaluation in time, monitoring and supervising in place, comprehensive control for hazard reduction, and guaranteed safety measures.

7. ACKNOWLEDGEMENT

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