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Line prediction technology for forecasting coal and gas outbursts during coal roadway tunneling

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ABSTRACT

The advantages and disadvantages of existing methods for predicting coal and gas outbursts in coal roadways were analyzed, and the primary factors influencing coal and gas outbursts, including the expansion energy of the initially released gases, were studied. To this end, a theoretical formula for calculating the amount of gas released from boreholes during drilling was deduced. In addition, it was determined that the gas emission per unit borehole length was related to the ground stress, gas pressure, and coal strength around the borehole during drilling. By collecting these continuously released gases from boreholes during drilling, that is, by adopting line prediction technology, the influence of those parameters (ground stress, gas pressure, coal strength) on the outburst process can be determined, and the outburst hazard can be predicted. To test this approach, a specially developed line prediction device was applied to the No. 3 coal seam of the Xinyuan coal mine, Shanxi Province, China. The test results demonstrate that the gas emissions per meter of borehole, Q_{Lm}, measured by the line prediction technique differed between outburst and non-outburst samples. Additionally, compared with existing indices used for predicting coal and gas outbursts in coal roadways, including K_1 and S_{max}, the line prediction technique was more sensitive and could reflect the outburst hazard in front of working faces more accurately.

1. Introduction

Coal and gas outbursts are complicated dynamic phenomena whereby a considerable amount of gas and crushed coal are released from the interior wall of a coal seam to the roadway in a very short time. These outbursts also give rise to certain dynamic effects in the rock, which can cause significant damage and affect the safety and productivity of coal mines and the workers in them. China witnessed 47 gas accidents in coal mines in 2014, from which 266 people died. In the first three quarters of 2015, there were 25 gas accidents in China, which led to the deaths of 89 people and accounted for 42.9% of all large accidents in coal mines. Of those gas accidents, coal and gas outbursts accounted for approximately 30% (China's State Administration of Work Safety (2015)). As one of the countries experiencing the most severe coal and gas outbursts, China has pushed for the accurate prediction of outburst hazard as a means of increasing safety during production in coal mines (Zhou et al., 2014; Lin et al., 2015; Yi et al., 2016). In particular, statistical studies have indicated that outbursts occur most frequently during coal roadway tunneling because the tunneling usually takes place in original coal seams and involves notably long tunneling lengths.

In recent years, scholars have proposed many new methods for predicting coal and gas outbursts, including direct and indirect forecasting methods. In China, the direct forecasting methods (also called index methods) prescribed in the *Provisions of the Prevention of Coal and Gas Outburst* (China's State Administration of Work Safety (2009)) have primarily been adopted in coal mines. These methods include the indices (D and K) method, the drilling gas inrush initial velocity method, the R-index method, and the index method of drill cuttings, which have all played parts in predicting coal and gas outbursts in coal roadways. For example, these methods can identify a batch of working faces with no outburst

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hazard and thus accelerate the tunneling speed. However, there are drawbacks to these methods in practical application. For instance, different outburst prediction indices are sensitive to different outburst hazards and may have different critical values, depending on the specific coal mine. Furthermore, outburst accidents have taken place in coal mines where the detected indices were below the critical thresholds. Such accidents in Guizhou, Henan, Shanxi, and elsewhere in China in recent years have resulted in significant casualties and property loss.

The indirect methods for forecasting coal and gas outbursts can be divided into physical and mathematical forecasting methods. The former includes such methods as the acoustic emissions-based method (Zou et al., 2005; Huang and Zhao, 2006; Gao et al., 2014; Wang, 2015) and the electromagnetic radiation-based method (Frid and Vozoff, 2005; Wang et al., 2005, 2015; Sa et al., 2006; Zhao, 2015; Wang et al., 2014). Compared with traditional direct methods, physical forecasting methods are characterized by their simple operation, low labor costs and rapid operation. However, these methods suffer from large prediction error due to difficulties with the inhomogeneity of the coal, the anti-interference performance of the signals, and the precision of data identification. Mathematical forecasting methods include the set pair theory-based method, catastrophe theory-based methods (Liu et al., 2012; Wen et al., 2015), the extension clustering method (Guo et al., 2009), the fuzzy analysis method (Carr and Tah, 2001), neural network methods (Karacan, 2009; Cao et al., 2015), and support vector machine methods (Bredensteiner and Kristin, 1999; Lu et al., 2005; Sun and Li, 2010). By establishing models using existing data, these mathematical methods can analyze the weight ratio of various factors for their quantitative calculation. However, in newly excavated areas with different geological conditions, the weight ratios of various factors used for predicting coal and gas outbursts are expected to change, and the lack of original data makes determining the new weight ratios difficult. Without this information, a prediction using mathematical forecasting methods can easily fail.

Because indirect forecasting methods are not mature enough, in terms of applicability in the field, direct forecasting methods are still preferred for predicting coal and gas outbursts in coal roadways in China. However, because direct prediction methods are typically point predictions, that is, they usually measure a certain point or position along the coal seam in front of the working face, they fail to predict the outburst hazard within a certain range in front of the working face. In order to develop a more effective index for predicting coal and gas outbursts in coal roadways, it is necessary to analyze the primary factors that contribute to the outburst hazard during coal roadway tunneling (Tang and Jiang, 2015; Qi et al., 2015). This research proposes that the best measures used to predict outburst hazard in coal roadways are the amount of gas continuously released from boreholes along with the distribution of gas release during the drilling process. Finally, by carrying out a field test, a new index, the gas emissions per linear meter of borehole Q_{Lm}, which combines these measures was developed for use in predicting coal and gas outbursts.

2. Determining a new index for predicting coal and gas outbursts in coal roadways

When the heading face of coal roadways is advanced to certain a position, the ground stress in front of that heading face will result in the generation of a fracture zone in the coal, within which gases are likely to dissipate. Therefore, the distribution of gas pressure in the coal seam in front of the working face will keep changing as work proceeds. To be specific, positions close to the working face have a low gas pressure because there exists a pressure-release zone. In contrast, deeper coal seams will have higher gas pressures. As shown in Fig. 1, the pressure gradient curve at depth gradually extends over time (from t_1 to t_6). In the beginning, this expansion is notably fast, but then it slows and finally stabilizes with time. In addition to the ground stress and gas pressure, the coal strength also has an influence on coal and gas outbursts. In areas with high ground stress and gas pressure, outbursts are more likely to happen if there are soft coals present. To predict the outburst hazard in coal roadways, it is necessary to determine whether any soft coal under high gas pressure is present within the range of prediction in front of the working face, as well as the position of that soft coal and the related outburst hazard. In addition, because the prediction of coal and gas outbursts in coal roadways occurs concurrent with the tunneling process, the prediction must be convenient and less time-consuming, further complicating the problem.

To determine the outburst hazard in the coal at a certain position, the prediction indices have to be able to reflect the intensity of the ground stress, gas pressure, and coal strength or their influences on the outburst process. It is impractical to measure these three factors directly at various points, in front of the working face of a coal roadway because gas pressure and coal strength are hard to measure rapidly, and the ground stress may not be able to be measured at all. Because predictions in coal roadways must usually reach more than 10 m from the working face, evaluating the hazard directly would require time-consuming measurements of the different parameters at each point. To avoid this, only those comprehensive indices that are able to reflect the influence of all factors on the outburst process can be used to predict an outburst hazard effectively.

According to the spherical shell theory (Jiang and Yu, 1995), during an outburst the ground stress merely destroys the coal and increases its surface energy. However, the factor actually related to the outburst process is not the surface energy but is the amount of gas initially released from the destroyed coal seam. How effectively these initially released gases expand is known as the expansion energy W_P (Jiang and Yu, 1995), and the greater the expansion energy of the initially released gases in the coal is, the more likely it is that an outburst will occur in a given coal seam. The amount of expansion energy in the initially released gases reflects the influences of the ground stress, gas pressure, and coal strength on the outburst process; therefore, expansion energy can be treated as a comprehensive index for determining the outburst hazard.

After performing dozens of simulated outburst tests, it was discovered that when the W_p reached 42.98 mJ/g, a weak outburst is expected to occur; while the W_p hit 103.8 mJ/g, a strong outburst is expected to occur once the coal seams are uncovered (Jiang and Yu, 1995; Jiang, 1998; Jiang et al., 2015). The expansion energy of the initially released gases has accurately predicted the outburst hazard in the uncovering of rock cross-cut coal, and helped to uncover dozens of coal seams safely. However, under conditions involving coal roadway tunneling, because the gas pressure in the coal that is in front of working faces is non-uniformly distributed, the expansion energy of the initially released gases at each point in the coal seam cannot be directly measured. Hence, the expansion energy of the initially released gases cannot be used to predict coal and gas outbursts in coal roadways directly. However, because the amount of gas released from the destroyed coal seams at the onset of a burst can be described in terms of volume, as well as in terms of energy, measuring the volume of gas emissions from a destroyed coal seam can be used to determine the outburst hazard instead.

At present, the most commonly used method for predicting outbursts in coal seams is to drill into the coal seam using a twist drill pipe which is driven by a coal electric drill, to measure the outburst parameters at fixed points directly, or by collecting samples from within the coal seam. When predicting outbursts in coal mines, coal seams are usually drilled continuously over lengths of