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Drilling large diameter cross-measure boreholes to improve gas drainage in highly gassy soft coal seams

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ABSTRACT

Reducing gas content via cross-measure boreholes is one of the primary gas control technologies in China, where most outburst-threat coal seams are soft and highly gassy. Regardless of the significant costs associated with drilling boreholes, the gas drainage rate remains low because of the low permeability of the soft coal seam and the small influence zone of a single borehole. In this paper, the effect of increasing borehole diameter on coal seam permeability is discussed and a new method for drilling large diameter cross-measure boreholes by using the water-jet technique is proposed. Numerical modeling results indicate that the plastic zone and the effective influence zone of one borehole expand as borehole diameter increases, and the interaction between adjacent boreholes is strengthened. The field test shows that when the borehole diameter is 1.0 m, the effective influence zone radius reaches 4 m which is 2.67 times larger than that of an ordinary borehole. After using the new method, the number of cross-measure boreholes per hundred meters and the length of cross-measure boreholes per meter can reduce by 32.5% and 42.9%, respectively. In addition, the gas drainage rate reaches 52.1%, and the monthly excavation length of coal roadway increases from 50–70 m to 109 m.

1. Introduction

China produced and consumed 47.4% and 50.3% of the world's coal in 2013, respectively (BP plc, 2014). However, 754 collieries in China are coal and gas outburst mines (State Administration of Coal Mine Safety of China, 2009), and 48% of state-owned coal mines are highly gas content collieries (ChinaOSH, 2006). Gas disasters are still regarded as the most serious disasters threatening the safety of the Chinese coal mining industry (Lu et al., 2010). For single, highly gassy soft coal seam without protective coal seams, gas pre-drainage through cross-measure boreholes is the main method for controlling gas disasters. Cross-measure boreholes, which are shorter and more stable than in-seam boreholes, are typically drilled vertically from a rock roadway which is below the caving zone of the original coal seam. Because these boreholes are often drilled 1–2 years before excavation, there is significant time for gas pre-drainage (Lu et al., 2009).

A large quantity of cross-measure boreholes are needed to effectively control gas before excavation in soft coal seams. For example, at least 3000–5000 cross-measure boreholes must be drilled to reduce gas content in soft coal seam to meet the requirements of constructing a 1000 m roadway. Although drilling cross-measure boreholes is costly, the gas drainage rate of China is only 23%, which is substantially lower than that in other coal mining countries (Lu et al., 2009). Technically, the major reasons why gas drainage rate remains low are: 1) the low permeability of coal seams, and 2) the small influence zone of single borehole.

To improve the gas drainage rate, many pressure-relieving and permeability-increasing methods via boreholes have been presented by scholars including deep-hole presplitting explosion (Liu et al., 2008), methane driven by gas injection (Yang et al., 2013), and water-jet techniques (Lin et al., 2013). The deep-hole presplitting explosion method requires complex construction technology, and its application is subjected to various national policies and laws due to the high risks associated with its implementation process. Methane driven by gas injection has little utilization due to its complexity, low influence radius and high cost. However, the water-jet technique has been widely used in gas control because of its superior cutting capacity and low cost. For instance, Lu et al. (2009, 2011) took advantage of water-jet to create artificial

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fractures and increase coal permeability around boreholes. Lin et al. (2012) and Shen et al. (2012) developed equipments and techniques which could cut several disc spaces around the completed borehole utilizing water-jet, this procedure reduced the stress and increased the coal seam permeability effectively. However, the artificial fractures slotted by the jet can only be maintained for a short time as the soft coal seam normally has a low strength and is easily deformed, which greatly restricts the improvement of gas drainage. Lu et al. (2010) presented a new method, in which long, in-seam boreholes would be made by using water-jet between the coal seam and the roof/floor to provide an effective flow channel for gas. Unfortunately, this method is not suitable for cross-measure boreholes, the water-jet technique, however, can be used to drill large diameter cross-measure boreholes rather than to slot the coal seam and eventually solve the problem of low gas drainage rate.

In this paper, the influence of borehole diameter on gas drainage was discussed and a new method of drilling large diameter cross-measure boreholes by using the water-jet technique was proposed. Meanwhile, the influence zone of large diameter cross-measure borehole was studied, and field tests of the new method were conducted.

2. How the increase of borehole diameter affects gas drainage

Coal permeability is recognized as the key physical parameter for gas drainage in coal reservoirs (Karacan et al., 2011; Pan and Connell, 2012). It is used to describe the ability of coal seam gas flow and is directly controlled by a range of fracture (cleat) characteristics, including size, spacing, connectedness, aperture and degree of mineral infill and orientation patterns (Laubach et al., 1998; Zheng et al., 2012). Coal is a kind of weak and dual porous rock with cleats and aperture, therefore, the coal permeability is sensitive to effective stress, pore pressure and coal matrix shrinkage due to gas desorption (Connell et al., 2010; Gray, 1987; Pan and Connell, 2012). Many scholars have primarily focused their research on the above factors, and a variety of models have been developed: Seidle et al. (1992) established a model for analyzing the relationship between permeability and different effective stress. Gray (1987) developed the first permeability model which considers the effect of sorption-induced matrix shrinkage. Palmer and Mansoori (1996) proposed a permeability model which is related to both pore pressure and coal swelling/shrinkage, and it has been used to match the field production data and laboratory test data. Shi and Durucan (2004) developed a permeability model based on the consideration of effective stress and gas adsorption-induced coal swelling, which has been widely used in reservoir simulation.

The existing permeability models are commonly adapted for effective stress redistribution caused by excavation of working face or roadway, or pore pressure changes and coal matrix shrinkage caused by borehole gas drainage. In their relationship, the coal permeability is assumed to be isotropic at all times and the initial permeability is typically considered to be constant. Therefore, coal permeability changes caused by the construction of the cross-measure boreholes are ignored as the drilling impact on the surrounding coal is considered to be negligible. However, this simplification is only suitable for coal seams with high permeability, such as coal seams in America and Australia.

For highly gassy soft coal seams in China, the majority of which took shape in Carboniferous-Permian period, coal's original fracture system was destroyed and hence the coal became a soft, low porosity medium with low permeability (Wang et al., 2012). Thus, it is important to evaluate the coal permeability changes caused by the drilling in the soft, low-permeability coal seams when analyzing the gas drainage, especially for those seams where methods have been used to decrease the pressure and increase permeability via boreholes. As the coal is a porous medium with complex structures, some simplifications and assumptions must be introduced firstly: 1) cross-measure boreholes are circular and vertically drilled into the coal seam; 2) the original coal seam is subject to hydrostatic stress, and uniaxial strain conditions exist with a constant vertical stress after drilling; and 3) the coal seam is homogenous and isotropic in the direction parallel to bedding planes.

Under above assumptions, the stress around cross-measure boreholes is considered to be axisymmetricaly distributed in the direction parallel to bedding plane. Because the tangential stress around the borehole in the deep coal seam is higher than the strength of coal, the plastic zone and the elastic zone appear (Hao et al., 2013; Qian et al., 2003). Assuming that the coal in plastic zone is in a limit-equilibrium state, which is a common assumption when studying stress, the radial stress and the tangential stress around a borehole can be described as follows (Brady and Brown, 2006; Jiang and Yu, 1998):

$$\sigma_r = \begin{cases} C\cdot\cot\phi\cdot\left[\left(\dfrac{2x}{R_0}+1\right)^{\frac{2\sin\phi}{1-\sin\phi}}-1\right], & x \le H \\ \sigma_0\cdot\left[1-\dfrac{4H^2}{(2x+R_0)^2}\right]+\dfrac{4H^2}{(2x+R_0)^2}\cdot C\cdot\cot\phi\left[\left(\dfrac{2H}{R_0}\right)^{\frac{2\sin\phi}{1-\sin\phi}}-1\right], & x > H \end{cases} \quad (1)$$

$$\sigma_t = \begin{cases} C\cdot\cot\phi\cdot\left[\left(\dfrac{1+\sin\phi}{1-\sin\phi}\right)\cdot\left(\dfrac{2x}{R_0}+1\right)^{\frac{2\sin\phi}{1-\sin\phi}}-1\right], & x \le H \\ \sigma_0\cdot\left[1+\dfrac{4H^2}{(2x+R_0)^2}\right]-\dfrac{4H^2}{(2x+R_0)^2}\cdot C\cdot\cot\phi\left[\left(\dfrac{2H}{R_0}\right)^{\frac{2\sin\phi}{1-\sin\phi}}-1\right], & x > H \end{cases} \quad (2)$$