Tunnelling and Underground Space Technology 74 (2018) 107–118

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Outburst mechanism of tunnelling through coal seams and the safety strategy by using "strong-weak" coupling circle-layers

Wei Yang[a,b,c,*], Hao Wang[a], Baiquan Lin[a,b], Yankai Wang[c], Xianbiao Mao[d], Jianguo Zhang[e], Youchang Lyu[e], Man Wang[e]

[a] Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology. Xuzhou, Jiangsu 221116, China
[b] School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China
[c] Lu'an Mining (Group) Co., Ltd., Changzhi, Shanxi 046299, China
[d] School of Mechanics and Civil Engineering, China University of Mining and Technology. Xuzhou, Jiangsu 221116, China
[e] State Key Laboratory of Coking Coal Exploitation and Comprehensive Utilization, China Pingmei Shenma Group, Pingdingshan 467000, China

ARTICLE INFO

Keywords:
Gas outburst mechanism
Uncovering coal seam
Stress
Tunnelling through coal seams
"Strong-weak" coupling structure

ABSTRACT

The gas outburst potential is typically high when roadways uncover the gassy coal seams associated with outburst hazards. This paper describes the complex stress and displacement evolution that occurs in roadway tunnelling through coal seams under different original stress conditions, which is helpful for better understanding how the stress leads to an outburst accident, and proposing some relevant control measures.

The stress concentration is primarily resulted from the strength difference between coal and rock, and the abutment stress increases gradually as the forward residual rock thickness decreases when the roadway excavation enters a coal seam from rock stratum. When the abutment stress is sufficiently high, the forward residual rock will suddenly be broken after the next cycle, and the stress will decrease rapidly to release elastic energy and generate new fractures. Meanwhile, the coal and rock in front of the heading face will move rapidly towards the free space. Therefore, an outburst accident may occur immediately when the gas pressure in front of the heading face is high enough. Once the outburst accident is triggered, the gas expansion energy and elastic energy distant from the heading face will contribute to developing the accident. The stress perpendicular to the roadway is the primary factor causing such outbursts. The abutment stress concentration will be higher when the maximum original stress is perpendicular to the roadway, which will increase the outburst potential. Therefore, it is suggested that arranging roadways parallel to the maximum original stress, if possible, can also reduce the outburst threat.

Outbursts are triggered by the elastic energy near the heading face and developed by the gas expansion energy and elastic energy distant from the heading face. In this study, the method of "strong-weak" coupling circle-layers was proposed to reduce the outburst hazard when roadways excavated through gassy coal seams. This method was proven to be valid by the comparative experiment. The weak circle can be realized by boreholes and hydraulic cutting. It could not only reduce the elastic energy near the heading face but also prevent the distant energy from contributing to the outburst accident. In addition, the strong circle can be made by injecting water slurry and applying anchors. It could help to reduce the strength difference between coal and rock, thereby decreasing the local stress concentration, resisting the residual outburst energy near the heading face, and preventing the outburst from being triggered. The "strong-weak" coupling structure was successfully applied in Bailongshan coal mine when uncovering the #7,8 coal seam. This structure can effectively promote gas drainage, reduce the coal and gas outburst risk. As a result, the mining efficiency improves a lot, and the uncovering time greatly decreases from the expected 2 years to 5 months.

1. Introduction

Human activity is gradually extending to the deep underground for purposes of gaining access to energy resources, achieving water conservancy, and developing transportation. Large amount of new roadways are being constructed worldwide. In the underground tunnelling engineering activities, tunnelling in coal mine is undoubtedly the most common. Coal occupies an important position in the global

* Corresponding author.
E-mail address: ywcumt@163.com (W. Yang).

https://doi.org/10.1016/j.tust.2018.01.013
Received 25 August 2015; Received in revised form 7 January 2018; Accepted 9 January 2018
0886-7798/

energy structure. Roadways must first be constructed to mine the coal resource, so the tunnelling speed is the key factor for coal output. Meanwhile, the mining depth increases each year because of the depletion of shallow coal resources, and the ground stress increases with the depth (Hu, 2017; Cheng et al., 2016). Rock outbursts have been demonstrated to be primarily affected by the ground stress, material properties and the pore pressure, so the increasing ground stress with the depth will also increase the outburst hazard of tunnelling (Li et al., 2007). For example, gas outburst is known to be mainly affected by the ground stress, gas pressure and coal strength (Karacan et al., 2011; Moore et al., 2005; Moore, 2012). Underground outburst accidents have occurred in many countries worldwide, including China, Russia, India, America, and Australia, and they cause enormous casualties and property loss. There will also be gas outburst hazards when driving the railway or roadway tunnel, e.g., many railway and roadway tunnelling through high gassy coal seams in Guizhou and Yunnan Province in China.

Experiences in China suggest that more than 70% of gas outburst accidents happen during the tunnelling in coal seam. The gas pressure and abutment stress greatly affect the gas outburst hazard, and the outburst hazard increases when the high gas pressure and abutment stress peak are near the roadway face (Lan et al., 2012). An outburst is more likely to occur when tunnelling through a geologic structure, primarily because of the complex stress evolution and the high gas pressure (Cheng et al., 2014; Dong, 2013; Wang et al., 2010; Xu et al., 2006; Zhang et al., 2014). Statistics on the coal and gas outburst accident shows that severe accidents usually occur when a rock roadway is traversing a highly gassy coal seam. Most roadways cannot follow a single layer of the rock stratum. Instead, they usually tunnelling through rock strata with different hardness. The substantial differences in the properties of the rock and coal seam will cause the surrounding stress to undergo a complex evolution. Thus, the difference in mechanical properties between rock strata and coal seams plays a significant role in coal and gas outburst.

The experiences in the Pingdingshan mining region suggest that almost all the large-scale outburst accidents occurred when a rock roadway uncovered coal seams with outburst potential. Tunnelling through a high gassy coal seam usually takes more than half a year (Zhai et al., 2016). To determine the reason and investigate fast tunnelling method, the outburst features have been widely studied. By analysing the physical features of coal and rock mass in front of a heading face when tunnelling through a coal seam, the equations of solid elastic energy and gas expansion energy were set up and compared (Yu et al., 2015).

Currently, it is generally believed that reducing the ground stress and gas pressure while increasing the strength of the coal seam can effectively prevent coal and gas outburst accident. High gas pressure is considered the most important factor of a coal and gas outburst, and high gas pressure is closely related to large outburst accidents. Except for the gas pressure, the initial volume of gas emission from the borehole is also proposed to validate the outburst risk in the process of tunnelling through coal seams (Tian et al., 2016; Zhao et al., 2016). Most recent studies examine why gas can cause coal and gas outburst accidents, with less emphasis on ground stress. Differences in rock mechanical properties will cause complex stress evolution and distribution (Li et al., 2016; Yu et al., 2015), and the stress evolution character is likely to be very important for triggering outburst accidents. The stability of a tunnel is studied when it get through inclined alternating strata of sandstone, mudstone and coal seam. Results show that the coal strata are much more prone over stressed than the mudstone strata (Gong et al., 2015; Sun et al., 2017). In the process of tunnelling through a coal seam, due to the difference in strength between coal and rock, how exactly does the stress in the coal seam in front of the roadway change? How does the gas outburst accident happen? Studies in these areas are still lacking. In addition, the original stresses in different directions have been demonstrated to be substantially different (Li et al., 2016; Rigane and Gourmelen, 2011; Wang and Deng, 2012), and the maximum and minimum principle stresses tend to be oriented along the horizontal direction (An and Cheng, 2014; Guo et al., 2012; Kang et al., 2010; Kang et al., 2009; Krumbholz et al., 2014; Wang et al., 2014). The stress evolution around the roadway also depends on whether differs when the maximum stress is parallel or perpendicular to the roadway (Yang et al., 2014; Yang et al., 2012; Li et al., 2017).

Both the ground stress direction and the mechanical property differences of coal seam and rock strata cause complex stress evolution. However, traditional research has paid less attention to these factors. In this paper, firstly we analyses the outburst mechanism of tunnelling through coal seam. Then we investigate the abutment stress evolution in different original ground stress fields when rock roadways tunnelling through coal seams. Meanwhile, we analyse how the elastic energy changes and how an outburst accident is triggered. Finally, we propose solutions according to the research results. These investigations will help to increase the tunnelling safety and increase the tunnelling speed.

2. Outburst mechanism of tunnelling through coal seams

A rock outburst will catapult rock only, while a gas outburst can erupt both coal and gas in a short time. Rock and gas outbursts have different underlying mechanisms, but both are related to the ground stress (Beamish and Crosdale, 1998; Cai, 2013; Verma et al., 2018). A high ground stress concentration will contribute to the occurrence of an outburst accident. In underground coal mines, statistics have shown that severe gas outburst accidents are most likely to occur when a rock roadway passes through gassy coal seams (Lin et al., 2010). Disturbed ground stress concentration is a key factor, and it can control whether an accident occurs or not (Han et al., 2012).

There are four stages in the outburst process: the accumulation stage, the triggering stage, the development stage and the stop stage. The outburst can be eliminated if we can control the accumulation or triggering stage, and the outburst-caused damage can be reduced if we can control the development stage. To minimize the outburst hazard, we must first know where the stages occur. The four stages of the outburst can be described as follows.

During the accumulation stage, the abutment stress peak increases gradually when the heading face nears the coal seam, as a result, a substantial amount of elastic energy accumulates in the residual forward rock (Fig. 1). The abutment stress is applied to the forward rock and coal seam, and the coal is much more deformable than the rock. Most of the stress is applied to the rock when the heading face is distant from the coal seam, and when the heading face approaches the coal seam, the stress that should have been borne by the coal seam will be transferred to the residual forward rock. The transferred stress will lead to the increase in stress peak and movement towards the heading face, and the elastic energy density in the residual forward rock will also increase. When the abutment stress is high and reaches the critical level, the rock will yield immediately after one cycle, leading to the triggering stage. The rock strength will decrease after this yielding, and the residual forward rock may not be able to withstand the gas pressure in the coal seam. The gas outburst occurs at this point.

During the development stage (Fig. 2), the abutment stress decreases rapidly, and the non-uniform displacement will break the coal and generate new fractures. Then, the absorbed high-pressure gas in the coal seam will desorb rapidly and flow into the new fractures. When the gas pressure in the new fractures becomes high enough, it can further break and blowout the coal. After the coal near the heading face is ejected, the distant elastic energy and gas expansion energy will be involved in the outburst accident, keeping the outburst development. When there is a sufficient amount of coal and rock in the gas outburst gallery, the outburst resistance will gradually stop the gas outburst.

The mechanism of coal and gas outburst is very complex, so far, it still stays in the hypothesis stage just like the earthquake. There is not a