Tunnelling and Underground Space Technology 83 (2019) 165–174

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Fuzzy fault tree analysis for coal burst occurrence probability in underground coal mining

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ARTICLE INFO

Keywords:
Coal burst
Rock burst
Underground mining
Seismic event
FTA

ABSTRACT

Coal burst is one of the hazardous events that mining engineers have been struggling with it since past decades. This phenomenon has sudden and violent nature and almost occurs without warning. In coal burst events, a high volume of coal pieces ejected violently into the working space. Consequently, coal burst can lead to casualties and severe damages. The interaction between causing factors of coal burst can lead to different triggering mechanisms. In this paper, coal burst was classified based its mechanisms into self-initiated and remotely triggered. Due to the sever coal burst consequences, its occurrence probability analysis is very essential. In this study, combination of fuzzy theory and fault tree analysis have been used for coal burst occurrence probability analysis. Therefore, occurrence of coal burst as a top event in fault tree has been analyzed using fuzzy fault tree analysis. According to the results, occurrence probability values of coal burst with self-initiated and remotely triggered mechanisms are 0.9% and 11.6%, respectively in coal mines. In addition, the critical paths that lead to coal burst are indicated in this study. These paths are composed of important causing factors that known as basic events in fault tree. Therefore, high mining depth along with local mine stiffness lower than coal stiffness make a more critical path for self-initiated coal burst; and the seismic energy release due to the slippage of discontinuities nearby the coal mines make also a more critical path for remotely triggered coal burst. The result can be inspiring for mining engineers which have conflicted with coal burst.

1. Introduction

One of the hazardous events, which occur in some coal mines, is a sudden and violent failure of highly stressed rock resulting in the release of large amounts of accumulated energy that is called coal burst. Coal burst is described as rock burst of coal and this terminology used in many countries (Calleja and Nemcik, 2016). While coal burst occur, coal or rock pieces that ejected violently into the mine working space, jeopardized both miners and mine equipment (Fig. 1). The nature of coal and rock failure during bursting process is quite different with the normal failure of rocks. In bursting process, during plastic deformation and fracturing, small part of stored strain energy in coal consumed, but large part of this energy released violently and coal seems to be exploded. Therefore, ground vibration and loud noise usually go along with coal burst. Interaction between many fundamental factors influence on converting normal coal failure to the coal burst such as presence of geological structure, mining depth, coal and local mine stiffness, coal strength, mining or excavation rate, and pillar design.

Here are some examples of coal burst events that occurred in the past years to show some of disastrous coal burst consequences. These consequences reveal the severity of coal burst and also necessity of having controlling and mitigating plans against this phenomena in coal mines. In 1982, coal burst of Taozhuang coal mine in China, resulting in five deaths, six injuries, and permanent loss of 500,000 tons of high-grade coal (Cai, 2013). Another event occurred in 2005 at the Sunjiawan coal mine in China and coal burst caused a serious gas explosion and killed 214 people (Wang et al., 2016a). In 2007, coal burst occurred at the Crandall Canyon coal mine in USA. In an extensive pillar failure that resulted in violent coal bursts, six miners with three rescue workers killed (Christopher, 2016). On 3 November 2011, coal burst of Qianqiu coal mine killed ten miners (Wang et al., 2016b). Four miners killed in the Junde coal mine disaster and coal burst caused to closure of 200 m gateway in 2013 (Li et al., 2015). In 2014, two miners killed at the West Virginia coal mine in USA by coal burst (Christopher, 2016). In 2014 and 2016, coal bursts of Austar coal mine in Australia in addition to damage the mine equipment, caused the death of two miners (NSW Mine Safety Investigation Unit, 2015; Hebblewhite and Galvin, 2017). Coal burst occurrence on 14 April 2015 in Xuzhuang coal mine in China led to destroying of up to 73 m ahead of the coal face in the tailgate (Cao et al., 2016). Based on the mentioned events, coal burst ensuing

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https://doi.org/10.1016/j.tust.2018.09.029
Received 22 November 2017; Received in revised form 17 September 2018; Accepted 30 September 2018

Fig. 1. Results of coal burst in longwall working face (Lu et al., 2015).

Fig. 2. Coal burst effects on mine working space (Wang et al., 2016a; Christopher, 2016).

consequences are very critical and disastrous; keep in mind that coal burst anticipation is not also easy. Hence, coal burst occurrence probability analysis is one of the useful ways to decrease coal burst negative effects. However, exact coal burst occurrence time cannot be determined in this way, but the hazard potential of this phenomenon can be recognized. Therefore, engineers can deploy appropriate coal burst controlling and mitigating techniques. Fig. 2 shows effects of coal burst on mine working space.

In the last years, many researchers attempted to evaluate coal burst hazard. Christopher and Gauna (2015) used a framework for coal burst risk assessment in coal pillar recovery and longwall mining. In this framework, the level of coal burst risk factor like depth of cover, panel width, pillar design, etc. can be rated as low, moderate, or high grade. However, in their assessment an overall coal burst risk value was not introduced. It is because a universal rating scale that be quantitative does not exist yet. Li et al. (2015) for evaluate coal burst risk in the underground coal mine used a static and dynamic stresses superposition-based risk evaluation method. In this method, static stress in the coal and dynamic stresses that are induced by seismic events aggregated (total stress). Then, coal burst risk can be judged by closeness of critical stress (coal uniaxial compressive strength) with total stress. Based on their report, due to the difficulties in dynamic stress measurement, they only used static stress that decreases capability of proposed method. Cao et al. (2016) have used the relationship between microseismicity and rock bursting to develop a rock burst pre-warning system in Xuzhuang coal mine. In their study, high seismic zones that are hazardous areas for bursting were located by combining seismic monitoring and tomographic imagery. Wang et al. (2016a) based on relationship between seismic wave velocity and stress distribution, used seismic velocity tomography (SVT) to infer high-static stress distribution locations at the Xingan coal mine in China. They concluded that high-velocity regions correlated with regions of high stress and these locations are might be potential rock burst risk areas. Wang et al. (2016b) have established a rock burst risk evaluation system for mining in thick coal seam with rock parting. They combined analytical fuzzy method with bursting liability indices (e.g. bursting energy index) and maximum value of the shear forces to shear strength ratio near the mining face, and define rock burst risk degrees. These degrees are divided from 'none' which means no potential for rock burst to 'powerful' which means high rock burst potential.

In this paper, coal burst hazard in coal mining is evaluated by fuzzy fault tree analysis (FFTA), a quantitative risk assessment method, which considers most of the influencing factors (basic events) that contribute in coal burst occurrence (top event). In this analysis, major causing factors that may have contribution into coal burst occurrences in the most of the coal mines around the world are considered. The present paper is arranged as follows. In Sections 2, 3 and 4, coal burst phenomenon and its triggering mechanism are described respectively. Section 5, explains FFTA. In Section 5, coal burst occurrence probability estimation process is presented. In Sections 6 and 7 results and study conclusion are described.

2. The difference between coal burst and coal failure

Whyatt et al. (2002) define rock burst as a sudden and violent failure of overstressed rock resulting in the instantaneous release of large amounts of accumulated energy. As mentioned in first section, the nature of coal failure during bursting process is quite different with the normal failure process. In normal failure, when loading pressure exceed coal peak strength (peak stress point) due to the plastic deformation and fracturing, large part of stored strain energy in coal, which accumulated during loading process, consumed and coal broke in a controlled manner (Fig. 3a). In this condition, post-peak coal stiffness (K_c) plays an important role. When coal stiffness is lower than loading system stiffness (K_m, surrounding rock masses or local mine stiffness), failure process is normal. This kind of failure also called plastic failure. Nevertheless, when surrounding rock mass are softer than coal (Fig. 3b), plastic deformation cannot continue and large part of stored

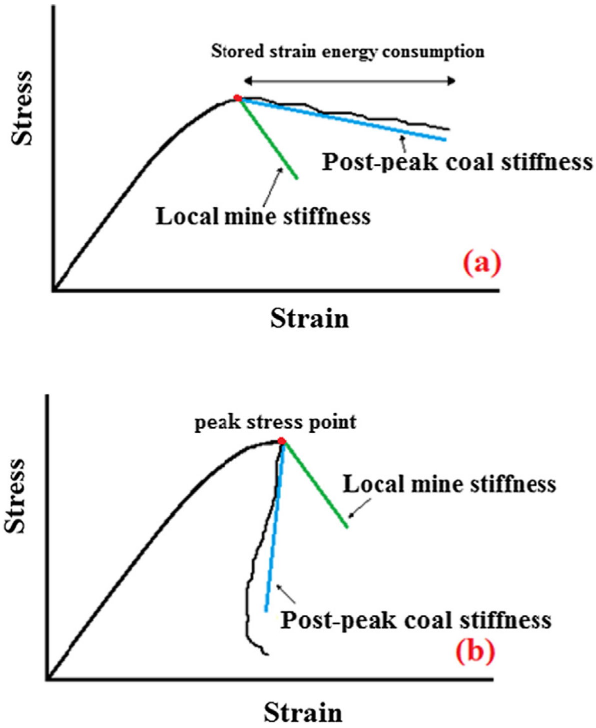

Fig. 3. schematic difference veiew of plastic failure (a) and brittle failure (b).