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Risk assessment of underground coal fire development at regional scale

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ABSTRACT

Underground coal combustion is a phenomenon known worldwide. Coal fire monitoring and risk assessment provide important input data for the delineation of coal fire zones and planning of extinguishing activities. At present, research on coal fire risk focuses mainly on the probability assessment of spontaneous combustion at micro scale, based on laboratory investigations of coal molecular structure and composition, and their impact on the combustion process. Coal fire risk assessment at a larger scale, such as for mines, relies on geological factors and aspects of mining engineering and mine management. These scales, however, are insufficient when considering extinguishing activities in larger areas. In order to fill these gaps, we studied risk assessment of underground coal fire development (UCFD) at a regional scale.

The factors impacting on coal fire development were analyzed under three different aspects: coal composition and structure which can influence the direction of underground coal combustion; topography and geology which determine the burning environment; and climatic conditions and human activities which trigger combustion processes. Based on this analysis, a regional underground coal fire risk assessment (UCF-RA) index system was established; it is predicated on the assumption that all indices contribute equally to coal fire risk. Data layers of 1 km × 1 km spatial resolution for each index were calculated and overlaid. Xinjiang Uygur Autonomous Region was selected as a validation area. In view of local conditions and the availability of relevant data, the index system was modified; the applied method, however, remained unchanged. Assessment results are generally satisfying and can be used for monitoring and extinguishing of underground coal fires (UCFs) in Xinjiang.

1. Introduction

"Underground Coal Fire" (UCF) refers to a series of processes, which are trigged when an underground coal seam, or its outcrop, is exposed to the atmosphere. From oxidation, self-ignition, and smoldering through to a raging fire, the phenomenon consumes large amounts of coal and impacts the environment significantly (Pone et al., 2007; Stracher and Taylor, 2004; Wu et al., 2009). Greenhouse gases such as CO_2 and CH_4, as well as dust particles released from coal fires have been identified as contributing significantly to global warming (O'Keefe, et al., 2010; Voigt et al., 2004). UCFs pose serious obstacles to mining as they threaten mining safety and infrastructure nearby, as well as local residents' health living in nearby communities.

The fingerprints of burning coal fires could be found in almost every corner of the world. But, countries with large coal production and consumption are particularly affected by the phenomenon — the U.S.A., India, and China, for example (DLR, 2005; Sinha and Singh, 2008). Centralia, Pennsylvania, had to be completely evacuated because of coal fires; in India, 37 million tons of coal was devoured by spontaneous combustion, and extraction of another 1.453 billion tons is blocked in the Jharia coalfield (Stracher and Taylor, 2004). As a central area of national coal production, north of China is interspersed with 56 or so UCF zones, distributed over Xinjiang, Ningxia, Shanxi, and Inner Mongolia. According to Guan and Van Genderen (1997), 4.22 billion tons of coal have been destroyed there already by the fires, to which another 20–30 million tons are added every year (Kuenzer, 2005; Voigt et al., 2004).

UCFs impair the development of society as well. It is mainly for this reason that UCFs have attracted increasing attention from politics, science, as well as mining engineering point of view over the past several years (Stracher and Taylor, 2004; Zhang, 2004). More and more funds and resources are allocated at research on coal fire mechanisms (Lu et al., 2004; Schloemer et al., 2005), coal fire detection, monitoring (e.g., Dlamini, 2009; Kim, 2004; Kuenzer et al., 2008; Prakash et al., 1999; Saraf et al., 1995; Zhang et al., 2004a,b), and extinguishing (e.g. Whitehouse and Mulyana, 2004) so that effective coal-fire mitigation techniques can be developed. Risk analysis and assessment of UCF at a regional scale play a crucial role

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in all these efforts. Results can provide a reasonable scientific guide for fire protection engineering, and even for resource allocation, ultimately improving the efficiency of fire extinguishing as a whole. They also can be used as input parameters for UCF monitoring and early warning systems. Yet, the work done so far in UCF area remains relatively premature (Kuenzer, 2005; Prakash and Vekerdy, 2004) since several concepts still need clarification (Bachmann and Allgöwer, 2000). It seems appropriate, hence, to present a summary of the progress in research on regional UCF risk assessment as well as the general terms used in this effort in the following sections.

"Risk" describes the possibility of damage or loss. It contains three distinct aspects: (i) the probability of a hazard to occur, (ii) the vulnerability of the victim, and (iii) the victim's ultimate exposure to the hazard (Shi et al., 2009; Wilhite, 2002) — these are basic to classical risk theory and have been widely applied in many research fields, especially in those related to disasters (Timothy et al., 2009). UCF, however, are different from other disasters and thus "underground coal fire risk" is a newly developed branch of risk theory. UCF contains two main risks that are important from research point of view: (i) the probability of occurrence of underground coal fires (UCFs), and (ii) the expected losses of natural resources and environmental as well as human losses originated by the fires (Kuenzer, 2005; Prakash and Vekerdy, 2004). This paper focuses on the first type of risk; that is, it aims to quantify of the probability of coal combustion in spatial extent and burning intensity.

Based on scale, burning intensity and location, coal fires can be divided roughly into two subtypes: coalfield fires and mine fires (Zhang, 2004). Most research on coal fire risk assessment so far has been focused on coal's spontaneous combustion tendency at laboratory scale (Heffern and Coates, 2004; Kaymakci and Didari, 2002; Singh et al., 2003; Wessling, et al., 2008). At a larger scale, in mine fire risk assessment within a coalfield, for example, there also some work has been done for coal mine fires, dump heap fires (Krishnaswamy et al., 1996; Singh et al., 2007; Smith et al., 1991; Xie et al., 2011), engineering and facility management have been included as factors (Abhishek, 2009). As for methodologies, fuzzy synthetically evaluation, back propagation neural network and LEC (frequency, possibility and severity) have been used (Wu et al., 2009); as well as the knowledge-based methods (Singh et al., 1990). Advancements on the development of a risk assessment index system, particularly for mine fires, were also introduced.

Currently, scientific and technical know-how to evaluate combustion risk for an entire coal mine exist and results can be used for fire monitoring and early warning systems. However, numerical quantification of risk remains complex and the models developed so far are not effective for resource allocation in large-scale fire fighting. Therefore, quantifying coal fire risk at a regional scale is important and is an eminent need.

The objectives of the present paper are threefold: (i) identify the factors impacting on UCF; based on this, (ii) choose appropriate evaluation indices for an index system; and from there, (iii) develop a method for quantifying UCF risk at a regional scale. For the purpose of validation, a case study will be presented.

2. Index system and assessment method

2.1. Analysis of impact factors

The three basic factors that must come together for an UCF to develop include: first, spontaneous combustion tendency in a coal seam; "coal combustion tendency" here refers to the coal characteristics, which determine the mechanisms of combustion, and aggravate burning intensity (Abhishek, 2009; Kaymakci and Didari, 2002; Schmal et al., 1985; Singh et al., 2003; Wang, 1999). Beside the coal as ingredient, geological and tectonic factors such as geological age of overburden rock, the degree of metamorphism in the coal seam, as well as its thickness also affect heat accumulation before and during combustion (Cao et al., 2007). The second component is coal exposure to air for underground coal combustion to sustain. It mainly depends on ventilation pathways or fractures in the surface. It's closely related to coal seam depth, hydrology, topography, and geological conditions such as the distribution of faults and cracks (Abhishek, 2009; Cao et al., 2007; Dlamini, 2009; Zhang et al., 2004a). The third factor is the direct fire cause or trigger, this either being chemical reactions within the fuel material itself, or external natural or anthropogenic sources, which mainly depend on the meteorological and social economic conditions (Guan and Van Genderen, 1997; Wu et al., 2009). A regional risk assessment index system for UCFs based on these constituents can be shown as in Fig. 1.

2.1.1. Factors influencing coal combustion tendency

Different coals have different self-ignition temperatures (SITs) and porosity values, both of which affect the area where coal reacts with oxygen. These factors influence coal combustion tendency. These factors can be investigated on a micro-scale level in the laboratory (Banerjee, 1982; Gijbels and Bruining, 1982). Different factors influencing coal combustion tendency can be summarized as.

Ingredient: coal rank includes mineral-rich coal, vitrain, bright coal, and dull coal. Because of the difference in their oxidation abilities and self-ignition temperatures, the combustion tendency of these coals is different. Generally, mineral rich coal and vitrain, having a lower SIT, display well-developed inside fractures and are easy to burn, while bright coal and dull coal do not catch fire that easily; they have higher density values and SITs (Guan and Van Genderen, 1997, Wu et al., 2009). Coal metamorphic grade: coal of low metamorphic grades (low rank coals) has more macropores, which facilitate oxygen uptake, and always contains many oxygen-enriched combustion groups. Its SIT is low, and it is easy to oxidize and releases more heat. By contrast, coal with a high metamorphic grade contains less oxygen-enriched groups and is difficult to oxidize at low temperatures (Abhishek, 2009; Cao et al., 2007). The geological age of overburden rock has no direct impact on coal combustion, but statistical research suggests that it is closely linked to UCF spatial distribution with northern part of China (Guan and Van Genderen, 1997; Wu et al., 2009). For example, coal fires in northern China are concentrated in Jurassic and Permian coalfields, the former ranking first in extent, scale, and burning intensity, as well as coal loss. The geologic age of overburden rock may also affect the characteristics of rock integrity for heat confinement. Sulfur/pyrite content: heat released from pyrite oxidation at low temperatures intensifies coal

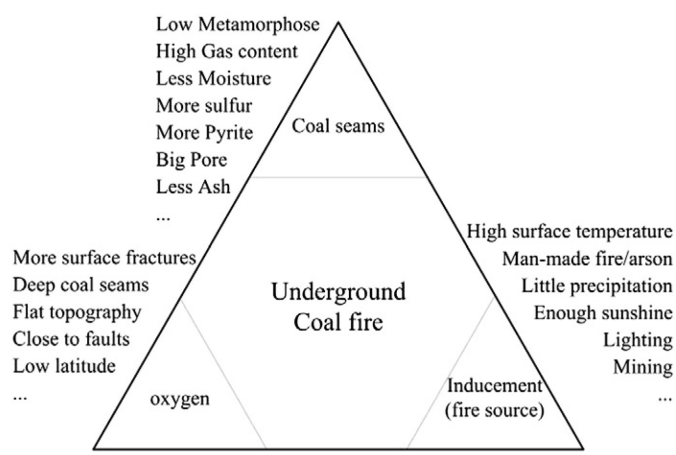

Fig. 1. Constituents model of underground coal fire development. The basic elements of the underground coal fire: the coal seam with the orientation of combustion, the oxygen environment to support coal combustion, the inducement to light or cause the flame, which may concludes the natural and artificial reasons or one from its own chemical reactions. (Edited according to Guan and Van, 1997).