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Analysis 320 coal mine accidents using structural equation modeling with unsafe conditions of the rules and regulations as exogenous variables

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ABSTRACT

Mining has been historically considered as a naturally high-risk industry worldwide. Deaths caused by coal mine accidents are more than the sum of all other accidents in China. Statistics of 320 coal mine accidents in Shandong province show that all accidents contain indicators of "unsafe conditions of the rules and regulations" with a frequency of 1590, accounting for 74.3% of the total frequency of 2140. "Unsafe behaviors of the operator" is another important contributory factor, which mainly includes "operator error" and "venturing into dangerous places." A systems analysis approach was applied by using structural equation modeling (SEM) to examine the interactions between the contributory factors of coal mine accidents. The analysis of results leads to three conclusions. (i) "Unsafe conditions of the rules and regulations," affect the "unsafe behaviors of the operator," "unsafe conditions of the equipment," and "unsafe conditions of the environment." (ii) The three influencing factors of coal mine accidents (with the frequency of effect relation in descending order) are "lack of safety education and training," "rules and regulations of safety production responsibility," and "rules and regulations of supervision and inspection." (iii) The three influenced factors (with the frequency in descending order) of coal mine accidents are "venturing into dangerous places," "poor workplace environment," and "operator error."

1. Introduction

As China's major energy supply, coal plays a crucial role in sustaining the country's energy requirements (Burgherr and Hirschberg, 2007; Wang et al., 2014), offering up to 70% of the country's energy supply over the past six decades (Geng and Saleh, 2015; He and Song, 2012). China is the largest country both in coal production and consumption worldwide (Liu et al., 2015a; Niu, 2014). China produced an estimated 3.70 billion tons and 3.87 billion tons of coal output in 2013 and 2014 respectively, and consumed 3.61 billion tons and 3.51 billion tons of coal in 2013 and 2014 respectively.[1] According to China's *National Energy Development Strategy Plan* (2014–2020), coal will continue to control the energy strategy, contributing more than 60% of the country's energy.

Mining has been historically considered as a naturally high-risk industry worldwide (Patterson and Shappell, 2010; Geng and Saleh, 2015). Mining operators are confronted with a relatively dangerous working circumstance compared with operators in other fields (Lenné et al., 2012). China's coal mining industry has the severest casualties of accidents in the production section (Chen, 2006; Wang et al., 2014). Deaths caused by coal mine accidents are more than the sum of all other accidents in China. Although the death rate per million tons (DRPMT) has steadily decreased (Lu and Li, 2011), the deaths caused by coal mine accidents are more than 2000 people every year from 1993 to 2010; the deaths was less than 2000 people for the first time, reaching 1973 people until 2011.[2] This number is much higher than that in other large coal-producing countries, such as the US, Russia, South Africa, and India (Chen et al., 2007; He and Song, 2012; Liu et al., 2015a; Lu and Li, 2011; Wang et al., 2014; Wei, 2009; Xiao and Li, 2006). The high frequency of coal mine accidents has long been regarded as one of the most serious problems in China

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[1] http://chinasafety.gov.cn/newpage/mkaj/index.htm.

[2] http://chinanews.com/gn/2012/01-14/3605009.shtml

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(Liu et al., 2015b). Coal mine accidents significantly affect the sustainable development of mining production, the whole economy, and the society. Safety situation in China's coal mining industry remains grim (Lu and Li, 2011). China's economic development is not and should not be based on a large number of accidents (Geng and Saleh, 2015). Hence, identifying contributory factors impacting coal mine accidents in China is of great importance.

Numerous studies have been proposed in the coal mining domain to explain the happening of incident/accident and the factors or elements affecting such occurrences (Lee et al., 2008; Paul and Maiti, 2007). Researchers have attempted to conduct different approaches, which have underpinned the development of some methods of incident/accident investigation and analysis (Lenné et al., 2012). Traditional accident causation models consider that the accidents are the results of events, such as equipment failure or unsafe behaviors of the operator (Underwood and Waterson, 2014). Among the causes of China's 1900 accidents from 2001 to 2011, human factors accounted for 94.09%, of which intentional violation, mismanagement, and defective design accounted for 35.43%, 55.12%, and 3.54%, respectively (Chen et al., 2012). A total of 5669 mine-year observations were included in Asfaw et al.'s (2013) analysis, where results showed that the incident rate of injuries was inversely related to that of U.S. underground coal mines. Chen et al. (2009) indicated that loopholes in management and the lack of a safety culture were the main causes of major coal mine accidents. Interestingly, Yu and Chen (2013) found a strong causal relationship that the pressure of seasonal production output directly led to seasonal fatalities in coal mine accidents in China. Based on the number of deaths in special major coal accidents from 1981 to 2010 in China, Zhao and Nie (2011) found that gas explosion and gas-related accidents accounted for the largest ratio at 71%, while flood accidents were at second place, accounting for 12%. Applying a binomial regression approach, Page (2009) found that larger coal mines were safer than the smaller ones, and that coal mines with less task pressure were safer than those with more task pressure. The results also considered that at the company level, task pressure decreased coal mine accidents. By using the historical data of coal mine DRPMT, Chen et al. (2015) constructed an unbiased grey Markov model to investigate the effect of the policy of constructing a vertical-management coal mine safety supervision system in China. In addition, Liu et al. (2015a,b) provided a theoretical framework by building an evolutionary game model between the coal mining industry and governmental supervision institutions.

Several accident causation methodologies were proposed in the past decades as flexible and combined analytic methods, which stand for the approaches and tools to investigate and analyze industrial incident/accident (Carroll, 1998; Dien et al., 2012; Rooney and Heuvel, 2004). Some of the well-known methodologies are Swiss cheese model (SCM) (Reason, 1990, 1997), Accimap (Rasmussen, 1997), human factors analysis and classification system (HFACS) (Shappell and Wiegmann, 2001), and system theoretic accident modeling and process model (STAMP) (Leveson, 2004). HFACS is one of the widely used methods to investigate and analyze coal mine accidents. Through an analysis of 508 coal mine accidents from Queensland of Australia using a modified version of HFACS, Patterson and Shappell (2010) found that skill-based errors are the most common unsafe behaviors. A sample of 263 significant mining incidents that occurred from 2007 to 2008 in Australia was analyzed using the HFACS. The results of Lenné et al.'s (2012) research showed that several HFACS categories appeared frequently: organizational processes (65%), skill-based errors (64%), violations (57%), and issues with the physical environment (56%). By employing the statistics of 515 coal mine accidents, Song et al. (2011) considered that the lack of a safety management system was the fundamental cause of the occurrence of unsafe behavior.

Structural equation modeling is frequently applied in incident/accident analysis, safety management, and other fields. These studies attempt to examine the complex relationships between exogenous latent variables and endogenous variables. By using structural equation modeling with factors in the individual and organization levels as exogenous variables, Chen et al. (2007) indicated that the biographical characteristics of workers have a direct positive influence on deliberate violation behavior, whereas the characteristics of an organization have an indirect negative influence. With factors of team, firm, and environment as exogenous variables, Liu and Li (2008) considered that the factors of "team safety construction" must be paid more attention, and the factors of "setting of safety management departments" and "regulations and policies" must be improved further in China's coal mine firms. Through path analysis, Paul and Maiti (2007) found that job dissatisfaction and risk-taking behaviors could foresee the number of injuries in India's coal mines. Wong et al. (2010) indicated that risky riding behavior is negatively influenced by an unawareness of traffic conditions and is positively influenced by attitude toward unsafe riding. Seo et al. (2015) applied structural equation modeling to establish relationships between the individual and organizational variables. The results indicated that job stress, safety culture, safety climate, and self-perceived fatigue are associated with safety behavior. To the best of our knowledge, structural equation modeling, which is applied to examine the interactions between the contributory factors of accidents, has yet to be implemented in the field of accident research.

2. Statistics of 320 coal mine accidents

2.1. Accident characteristics

This study collected a total of 320 coal mine accident cases that occurred in Shandong province from *The Assembler of Coal Mine Accidents of Shandong Province* (2005–2010), which was produced by Shandong Coal Mine Safety Supervision Bureau. Table 1 shows the accidents from each year based on the type of occurrence. Overall, from 2005 to 2010, the frequencies of accidents and deaths caused by the accidents decreased, while the frequency and percentage of all types of accidents were not the same. The percentage of roof accidents was the highest, followed by mechanical transport accidents. The number and percentage of deaths caused by all types of accidents were also not the same. The largest number of deaths was caused by roof accidents, followed by gas accidents. The probability of gas accidents and flood accidents is very low. However, once the accidents happen, they result in serious casualties. The frequency of gas accidents and flood accidents are 22 and 17, totaling 7% and 5% of all accidents respectively. However, the number of deaths is 100 and 93, which are 20% and 18% of the total deaths respectively. Thus, great importance should be attached to gas accidents and flood accidents.

2.2. Coding of data

In 1986, the National Standardization Management Committee of the People's Republic of China promulgated two national standards: *The Classification Standard for the Casualty Accidents of Enterprise Staff and Workers* (GB6441-86) and *The Rules for the Investigation and Analysis of Casualty Accidents of Enterprise Staff and Workers* (GB6442-86). According to the two standards, the contributory factors of an accident are classified into several categories, which include "the unsafe conditions of the equipment, materials, and environment," "unsafe behaviors of the operator," "defect of technology and design," "lack of safety education and training," "labor organization unreasonable," "lack of on-site inspection work