Safety risk factors of metro tunnel construction in China: An integrated study with EFA and SEM

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Abstract

In this work, we proposed a systematic method by integrating exploratory factor analysis (EFA) and structural equation modeling (SEM) to examine the risk factors for the safety of metro construction. We collected 514 valid questionnaire responses from metro construction personnel in five cities, from which nine common risk factors out of 65 questionnaire items were extracted. The relationships between the individual factors were examined by SEM, and the established model was validated by hypothesis testing and goodness-of-fit tests. The influence of individual factors for the safety in metro construction was characterized by the path coefficient in the model. Real tunnel accident cases in the Wuhan Metro of China were utilized to demonstrate the feasibility and applicability of the proposed EFA-SEM approach. It was found that safety was profoundly influenced by the risks associated with the launching and arrival of tunnel boring machine (TBM) and the risks during tunnel excavation that involved special procedures and conditions. In contrast, the risks pertaining to shaft construction did not have a statistically significant impact on safety. The developed method clarified the causal relationships within a complex project and allowed finding the predominant risk factors, thus providing a guideline to improve safety management for metro construction.

1. Introduction

Underground construction, especially for subways in urban rapid transit systems, is flourishing around the world as civil infrastructural projects (Qian and Lin, 2016; Zhong et al., 2003). Tunnel boring machine (TBM) has become an indispensable machinery in tunnel construction because it is highly mechanized, allows fast progression of tunneling works, and has fewer environmental impacts (Li and Chen, 2012; Lin et al., 2013; Maeda and Kushiyama, 2005; Min et al., 2015; Shang et al., 2004). Mechanical excavation with TBM is carried out in large scale over a long-time, and involves many complicated technical problems. The complex environments in metro construction inherently face many uncertainties and hence a myriad of risk factors, which may lead to accidents (Ding et al., 2014). For instance, in Brazil, the access tunnel at the Pinheiros Station of São Paulo’s Metro Line Four collapsed partly on January 12, 2007, and claimed the lives of seven people (Mei and Zhimin, 2007). In Poland, water flooded into the tunnel at the planned power station at Warsaw on August 23, 2012, which caused considerable trouble to the city traffic (Waltz, 2012). In China, the occurrence of metro construction accidents has been rising over the past years as well. One of the notorious accidents happened on November 15, 2008, in Hangzhou, where a road cave-in accident killed 21 people (AFP, 2008). More recently, on January 1, 2015, two people were killed in a fatal tunnel explosion in Wuhan (Yang and Rongfeng, 2015). As a type of engineering project, mechanical tunnel excavation is highly complicated and involves many potential risks that can seriously threaten public safety. Therefore, it is extremely important to thoroughly evaluate the risk factors for safety in such construction projects.

Regarding mechanical tunnel excavation, the general public is concerned with the possible ground deformations that may endanger surface buildings and disrupt road traffic. According to statistics, risk management in mechanical tunnel excavation improved very little from 2008 to 2016. Accident records have shown that the majority of accidents in civil engineering resulted from human faults, and the cause varied from project to project (Abdelhamid and Everett, 2001). With regard to mechanical tunnel excavation, it was found that only 10% of the accidents could be completely attributed to natural causes, whereas 30% of accidents resulted purely from human errors and 60% of accidents occurred because of the combination of human mistakes and natural mishap. Human errors have recurrent patterns and typically include poor technology, slack management, and inadequate hazard handling. Natural causes of accidents in mechanical tunnel excavation include adverse hydrogeological conditions, groundwater, heavy rainfall, soft soil layers, etc. Collapse is the most frequent type of accidents,
accounting for 60% of the total. The explosion, pipeline damage, and rock burst are other common natural causes. The injury and death rates vary among different types of accidents.

Since mechanical tunnel excavation involves numerous risks, construction organizations can improve the overall safety performance by thoroughly understanding the general distribution and the key determinants (i.e., enablers) of the risk factors (Lee et al., 2012). Nevertheless, existing research publications rarely reported on the correlation of key enablers in empirical validation studies, and researchers are still yet to properly understand the interactions between the risk factors for tunneling safety. Furthermore, the causal links between external goals and internal enablers have not been soundly established (Chinda and Mohamed, 2008). Two statistical methods, exploratory factor analysis (EFA) and structural equation modeling (SEM), have been proposed and exploited in recent years to reveal and test the interactions in hypothetical models. Specifically, EFA allows identifying the structure among questionnaire items without prior knowledge of both the factors and the patterns of the measured variables (Finch and West, 1997). The SEM method can handle complex relationships among variables to simultaneously estimate all coefficients in the model (Xiong et al., 2015). In the current work, we present a systematic approach that combines EFA and SEM to identify, test, and verify risk factors for the safety in the mechanical excavation of the metro construction projects in China. We demonstrate the internal causal relationships and the interactions between enablers, and we generalize the overall distribution of risk factors. The results help to pinpoint important risk factors and strengthen safety by improving the decision-making in the Chinese metro construction industry.

The remainder of the paper is structured as follows. Section 2 reviews related studies on the safety risk of tunnel construction and underground projects. Section 3 develops a systematic methodology by combining EFA and SEM to test the causal relationships and interactions between the risk factors for tunneling safety. Section 4 demonstrates the applicability of the developed approach by using the reports of 214 real tunnel accident cases from the Wuhan Metro of China. Section 5 discusses the findings, and Section 6 concludes.

2. Previous studies

The research on the safety risk of tunnel construction and underground projects dates back to the early 1990s (Einstein, 1996). According to the International Tunneling Association (ITA), the risk is defined as “a combination of the frequency of occurrence of a defined hazard and the consequences of the occurrence” (Eskesen et al., 2004). When it comes to metro construction, the risk is defined as “the potential uncertainty causing economic loss, human injury, and damage to the environment, delay to project completion or durability reduction in the metro construction process” (Ding et al., 2012). Construction projects that make use of tunnel boring machine (TBM) require engineering operations at a large scale with high complexity, which makes it challenging to manage the associated risks. The international common risk management theory divides risk into technical risk and planning risk. The former likely culminates in substandard project performance, and the latter includes but is not limited to cost overruns and delayed schedule (Chapman, 2001). The safety risk in mechanical tunnel excavation, which is the sole topic of the current work, belongs to technical risk. In fact, many accidents occur because of the negligence of the risk characteristics in the mechanical excavation. Studying the overall distribution of risks in this context provides a solid theoretical foundation for the safety management of such projects.

Many international organizations have published guidelines on how to identify and evaluate risks in mechanical tunnel excavation. In 2004, the working group of ITA proposed its guidelines for tunneling risk management (Eskesen et al., 2004). In 2006, the International Tunneling Insurance Group published a recommended code of practice for risk management in tunnel works (ITIG, 2006). The Chinese government also dedicated efforts to the risk management of underground constructions. Since 2003, various laws and regulations have been formulated by the Ministry of Housing and Urban-Rural Development of China, including the “Guideline of risk management for construction of subway and underground works” (China, 2007), “Code for risk management of underground works in urban rail transit” (China, 2011), “Standard for construction safety assessment of metro engineering” (China, 2012), etc. These guidelines have elaborated on the theories and evaluation methods for the safety risk management of urban underground metro construction (including open cut method, undercut method, and TBM tunneling). However, since they do not include detailed studied on the safety risks in TBM tunneling, these guidelines cannot effectively instruct the on-site personnel to fully appreciate and actively address the safety risks in different processes of TBM tunneling construction.

International researchers are also actively studying the risk management in underground constructions. Sejohna et al. (2009) utilized fault tree analysis (FTA) and event tree analysis (ETA) to quantitatively assess the risks for a tunneling excavation project in the Czech Republic, in particular targeting four types of failures: (1) cave-in, (2) excessive deformation of the tunnel tube, (3) excessive subsidence of rough, and (4) disturbance of water regime in the surrounding area. Ma et al. (2013) utilized a double Gaussian model to analyze the safety risks related to surface subsidence that resulted from the construction works of the Wuhan Metro after building a safety-oriented geotechnical instrumentation data warehouse. It was found that the surface subsidence could be characterized by a logistic curve, and the first derivative of the surface subsidence was thus applied to represent the evolution of safety risk. Ding et al. (2014) developed a decision-making approach based on “overall process safety management” (OPSM) for risk analysis in tunnel construction, and they made a detailed assessment regarding the safety risks that led to tunnel leakage in the construction of the Wuhan Yangtze Metro Tunnel in China. Nevertheless, these literature reports only addressed a given accident in some particular construction process during TBM tunneling for metro construction. Studies that target the entire construction process in TBM tunneling for metro construction are still lacking.

The ISO 31,000 standard on risk management assigns a pivotal role to knowledge by defining risk as “the effect of uncertainty on objectives.” Throughout the analysis of safety risk, the risk picture must be constantly and progressively updated to eliminate uncertainty when new evidence and information become available (Scarpioni and Paltrinieri, 2016). To date, there is still no well-founded theoretical framework regarding the distribution of risk factors for tunneling safety, and only very few studies have examined the causal relationships and interactions between the risk factors for the tunneling safety. Kletz (2012) indicated that “if a hazard and operability study had been carried out for the entire process of batch and all operating conditions, the runaway would not have occurred”. Following this argument, Villa et al. (2016) and Paltrinieri and Reniers (2017) proposed a systematic methodology for identifying individual risk factors and quantifying their contributions to the overall risk in the production process of the chemical and petroleum industry. Zhao et al. (2016) associated the analysis of risk factors with the multiple steps of the entire production process, put forward the safety requirements of the whole engineering process, emphasized the integration of safety and production, and verified the feasibility of the method in combination with an actual construction project. Hence, with regard to TBM tunneling for metro construction, it is necessary to establish a theoretical framework to evaluate the distribution of safety risks throughout the entire construction process of mechanical tunneling, so as to provide authorities and stakeholders a sound basis for assessing existing hazards and risks. In this work, we propose an analysis of safety risks that integrates the viewpoint of all parties involved in mechanical tunneling. By reviewing the distribution and interaction of risk factors, we report on the analysis results that may be used to introduce potential measures to attenuate risk.
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