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Probabilistic risk assessment of tunneling-induced damage to existing properties

Fan Wang [a,b], L.Y. Ding [a,*], H.B. Luo [a], Peter E.D. Love [c]

[a] Department of Civil Engineering & Mechanics, Huazhong University of Science & Technology, 1037 Luoyu Road, Wuhan 430074, PR China
[b] Hongshan Construction Bureau, 4 Hongluo Country, Wuhan 430070, PR China
[c] School of Built Environment, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

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ABSTRACT

There is an intrinsic risk associated with tunnel construction, particularly in urban areas where a number of third party persons and properties are involved. Due to the limited availability of data for accidents and the complexity associated with their causation, it is therefore necessary to combine available historical data and expert judgment to consider all relevant factors to undertake a realistic risk analysis. Thus, this paper presents a hybrid approach that can be used to undertake a probabilistic risk assessment of the risks associated with tunneling and its likelihood to damage to existing properties using the techniques of Bayesian Networks (BN) and a Relevance Vector Machine (RVM). A causal framework that integrates the techniques is also proposed to facilitate the development of the proposed model. The developed risk model is applied to a real tunnel construction project in Wuhan, China. The results derived from the project demonstrated the model's ability to accurately assess risks during tunneling, specifically the identification of accident scenarios and the quantification of the probability and severity of possible accidents. The potential of this risk model to be used as a decision-making support tool was also explored.

1. Introduction

The International Association of Engineering Insurers (IAEI) reported that economic losses of more than 570 million euro were incurred in 18 worldwide tunneling projects during the period of 1994–2005 due to underground construction accidents (Landrin, Blückert, Perrin, Stacey, & Stolfa, 2006). The involvement of a number of third party persons and properties during tunneling, particularly in urban areas can increase the likelihood of accidents. Due to the limited *a priori* knowledge of geotechnical uncertainties, it is a challenge to maintain safety throughout a tunneling project without delays or cost overruns being incurred. For example, in the case of the Wuhan Metro Project, tight control over settlement was required as the tunnel needed to be excavated in a densely populated area. However, most field measurements indicated that this requirement was not fulfilled. If the standards of settlement were strictly adhered to, then the project would be too difficult to accomplish. However, no obvious damage was found even though the settlement was greater than the standard that was required. Therefore, systematic risk assessment, rather than simply controlling the settlement, is needed to appropriately address safety weaknesses in such complex systems and also to support decision making.

Over the past decade, it has been widely recognized that risk management rather than a technical solution is a step forward in improving safety (Trbojevic & Carr, 2000; Goh, Love, Spickett, & Brown, 2012). However, the practice of performing risk management requires a vast range of practical experience as well as sound theoretical knowledge (Eskesen, Tengborg, Kampmann, & Veicherts, 2004), and therefore the determination of risk levels relies heavily on experts' opinions.

Risk is generally defined as a combination of the frequency of occurrence of a defined hazard and the consequences of the occurrence (Eskesen et al., 2004). A scenario has been further added to form a set of triplets (Kaplan & Garrick, 1981). This has become the formal decomposition of risk. Risk management, according to Eskesen et al. (2004), is "the overall term which includes risk identification, risk assessment, risk analysis, risk elimination and risk mitigation and control" (p. 237). Eskesen et al. (2004) also has provided some guidelines for risk management in different stages. However, risk assessment, the core of risk management, which can be undertaken qualitatively or quantitatively to depict the three elements of risk, has not been examined in detail. While some methods are available to represent risks, these approaches are difficult to use due to the restricted or limited availability of data (Cárdenas, Al-Jibouri, Halman, & van Tol, 2012). For this

* Corresponding author. Tel./fax: +86 27 87557824.
E-mail address: dingly_wuhan@yahoo.com.cn (L.Y. Ding).

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reason, expert judgments are often used as a complement to the 'source' data. Moreover, there are many interrelated factors that can influence risks and their relationships with one another. Most risk methods do not fully consider all the influencing factors, which can result in an incomplete understanding of accident causality. Thus, the integration of historical data and expert judgments and the quantification of all the interactive relationships are critical to implement a reasonable risk analysis.

Using the Wuhan Metro Project (China) as a case example, the level of risk for each tunnel section was released per day to indicate if safety control actions were needed. To determine a reasonable risk level, experts were invited to examine relevant information, discuss the safety weakness and provide conclusions. There was a need for a structured and explicit method to integrate relevant information and assess the associated risks. With this in mind, this paper proposed a new methodology that incorporated a Relevance Vector Machine (RVM) and a Bayesian network (BN) to assess the risks associated with the tunnel construction process. The aims of developing such a risk model were twofold: (1) to predict the risks (i.e. scenario, probability and consequences) during tunneling; and (2) to explore the potential for identifying the effects of safety improvement strategies.

2. Risk analysis and techniques

There are a plethora of methods available to conduct risk analysis. However, among the various methods, four techniques and their combinations, as shown in Fig. 1, are commonly used.

Probabilistic risk assessment (PRA) is widely used as it not only estimates the likelihood and consequences of accidents, but also categorizes their potential scenarios (Mohaghegh & Mosleh, 2009). PRA was initially introduced in the nuclear industry and later adapted to other complex systems such as chemical processing, aviation management and aerospace missions. The basic tools usually used to model risks are Fault Tree Analysis (FTA) and Event Tree Analysis (ETA). FTA is a deductive method that enables an investigation of causal relations between basic events or factors and an undesired event. In contrast, ETA is an inductive method that describes accident scenarios through a sequence of events. The major difference between FTA and ETA lies in that the FTA is applicable for the identification of the causes of a top event while the ETA is applicable for the analysis of initiating events that could result in a variety of effects on the project risks. Eskesen et al. (2004) summarized how these techniques can be used to assess and manage risk in tunneling projects. The specific examples of applying FTA/ETA to tunnels can be found in Sturk, Olsson, and Johansson (1996) and Hong, Lee, Shin, Nam, and Kong (2009). Moreover, as the features of FTA and ETA are quite different, a combination of these two techniques can offer more powerful capability in risk modeling. For example, a 'bow-tie' model, with the left and right hand sides respectively corresponding to fault and event trees, is usually used to identify the causes of a critical event and to evaluate the reliability of subsequent safety functions that prevent accident occurrence (Trbojevic & Carr, 2000; Jacinto & Silva, 2010). Another combination approach named 'cause-consequence diagram' can be found in Nývlt, Prívara, and Ferkl (2011) and Beugin, Renaux, and Cauffriez (2007), where each event (including the initiating and subsequent events) in an event tree is associated with a fault tree.

FTA/ETA requires assessment of single probability values for events so that the probability of occurrence of a failure accident can be calculated through the logical or functional relationships that predefined in the diagram. However, it is difficult to obtain such data in tunneling projects so extensive experience as well as practical and theoretical knowledge are required for effective risk management (Eskesen et al., 2004). Expert judgment, as a complement to objective data, is often used in risk analysis. Fuzzy set theory, as the only mathematical tool to handle linguistic variables, is therefore used to capture experts' opinions. Cho, Choi, and Kim (2002) designed a new form of fuzzy membership curves to represent subjective judgments with an uncertainty range. This new methodology has been successfully applied in the construction risk assessment of a subway (Choi, Cho, & Seo, 2004) and a cable-stayed bridge (Choi & Mahadevan, 2008). Pinto, Ribeiro, and Nunes (2012) also proposed several membership functions to estimate the occupational accident severity in the construction industry. The fuzzy set theory can be combined with traditional FTA/ETA, which forms fuzzy FTA (Singer, 1990) or fuzzy ETA (Huang, Chen, & Wang, 2001). Some fuzzy systems are also designed to estimate the risk level or index, which is dependent on several factors or indicators (Gürcanli & Müngen, 2009; Wang & Elhag, 2007; Zeng, An, & Smith, 2007). Human knowledge is used to form the fuzzy rule base that aggregates the effects of multiple risk factors.

The fuzzy system needs to define 'if-then' rules for each possible combination of the states of different input variables. Thus the number of rules will increase exponentially as more factors or more states are included. Although there are some methods to relieve the situation (Hadjimichael, 2009), the number of rules remains substantial, if too many factors are considered. Some researchers use machine learning techniques, such as artificial neural networks (ANNs) (Elhag & Wang, 2007), support vector machines (SVMs) (Li, Liu, Wang, & Xu, 2012), or classification and regression trees (CARTs) (Cheng, Leu, Cheng, Wu, & Lin, 2012) to model the complex relationships between multiple factors and corresponding risk. Since such models can 'learn' the relationships from data or cases, the modeling effort is considerably reduced.

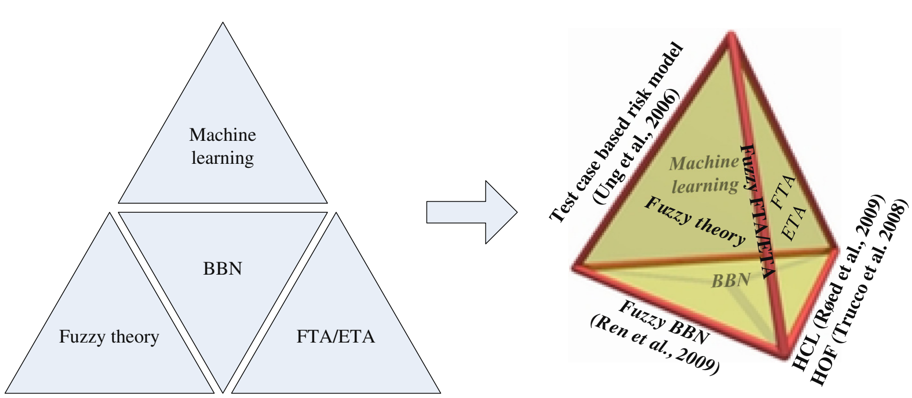

Fig. 1. Candidate techniques used for risk assessment.