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Bayesian-network-based safety risk analysis in construction projects

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ABSTRACT

This paper presents a systemic decision support approach for safety risk analysis under uncertainty in tunnel construction. Fuzzy Bayesian Networks (FBN) is used to investigate causal relationships between tunnel-induced damage and its influential variables based upon the risk/hazard mechanism analysis. Aiming to overcome limitations on the current probability estimation, an expert confidence indicator is proposed to ensure the reliability of the surveyed data for fuzzy probability assessment of basic risk factors. A detailed fuzzy-based inference procedure is developed, which has a capacity of implementing deductive reasoning, sensitivity analysis and abductive reasoning. The "3σ criterion" is adopted to calculate the characteristic values of a triangular fuzzy number in the probability fuzzification process, and the α-weighted valuation method is adopted for defuzzification. The construction safety analysis progress is extended to the entire life cycle of risk-prone events, including the pre-accident, during-construction continuous and post-accident control. A typical hazard concerning the tunnel leakage in the construction of Wuhan Yangtze Metro Tunnel in China is presented as a case study, in order to verify the applicability of the proposed approach. The results demonstrate the feasibility of the proposed approach and its application potential. A comparison of advantages and disadvantages between FBN and fuzzy fault tree analysis (FFTA) as risk analysis tools is also conducted. The proposed approach can be used to provide guidelines for safety analysis and management in construction projects, and thus increase the likelihood of a successful project in a complex environment.

1. Introduction

Construction is one of the most dangerous industries in the world [1]. The ramifications of construction accidents are growing with trends toward larger-scale and more complex construction projects [2], especially in developing countries, like China. With the exploitation of urban underground space, underground construction has presented a powerful momentum for the development of a rapid economy worldwide in the past ten years. Due to various risk factors in complex project environments, safety violations occur frequently in metro construction. On January 12, 2007, the Pinheiros Station on Metro Line Four at Sao Paulo's Aquarium in Brazil collapsed, causing the death of seven people [3]. On July 6, 2010, a tunnel collapse also took place in Prague, Czech Republic, causing a 15-meter-wide sunken pit [4]. On August 23, 2012, a metro line leak caused chaos in Warsaw, Poland. Water flooded into the tunnel at the planned Powisle station, causing considerable transportation problems in the already gridlocked city [5]. In China, the number of construction accidents shows a rising trend in metro construction projects. On November 15, 2008, 21 people were killed as a result of a road cave-in above a metro tunnel under construction in Hangzhou [6]. Also, on December 25, 2012, eight people were killed and five others hurt in a fatal tunnel explosion in north China's Shanxi province [7]. Tunnel construction entails to be a highly complicated project with large potential risks, which can bring enormous dangers to public safety [8]. Therefore, it is necessary to investigate the causal relationship and safety risk mechanism of construction failures in tunnel construction by considering the accident scenario and real-time safety analysis, aiming to provide decision support for assuring the safety of tunnel construction.

To avoid heavy casualties and property losses caused by safety violations, innumerable studies have introduced risk-based analysis into safety management practice. Risk analysis can be divided into qualitative and quantitative risk analysis [9]. The former includes fault tree analysis (FTA), comprehensive fuzzy evaluation method (CFEM), check list, and others; while the latter includes job risk analysis method (LEC), influence diagrams, Neural Networks (NN), support vector machines, decision trees, and others. The above risk-based analysis methods make a significant contribution to safety risk

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analysis and management in complex engineering projects [10,11], however, they are confined to static control management [12]. Khakzad [10] indicated FTA unsuitable for complex problems with its limitation in explicitly representing dependencies of events, updating probabilities, and coping with uncertainties. Yang et al. [13] regarded LEC unsuitable in complex dynamic environments, resulting from the insufficiency in timely diagnosing and dealing with various problems. When associated parameters, such as geological, design and construction parameters are changed, the aforementioned methods cannot accurately illustrate the updated features of dynamic environments as the construction progress evolves. Nor can professional supports or suggestions be provided in real time as the parameters are updated. Recently, Bayesian networks (BN) has been proposed to model the complexity in man-machine systems [14]. BN can describe dependencies between variables both qualitatively and quantitatively, and is suitable for knowledge representation and reasoning [15]. Also, BN is powerful in dealing with uncertainty information, and can be used for reliability and failure analysis in complex environments [16,17].

In conventional BN analysis, the occurrence probability of root nodes is always regarded as a crisp value [18]. However, in the construction engineering fields, it is difficult or nearly impossible to obtain exact values of probability due to a lack of sufficient data [19]. Thus, a group decision-making technique is generally employed to assess the occurrence probability of root nodes. Hanss [20] indicated that the fuzzy set theory (FST) provided a successful tool to solve engineering problems under uncertainty. The uncertainty can be taken into account in terms of intervals or fuzzy numbers [21]. Currently, FST and BN have both emerged as powerful and effective tools for knowledge reasoning in uncertainty environments [22]. Thus, it is certainly quite appropriate to investigate the amalgamation of FST and BN, which may well prove to provide an indispensable means of incorporating uncertain factors/elements in a probabilistic risk analysis model domain [23]. This paper therefore investigates the possibility of merging BN and FST, which is Fuzzy Bayesian Networks (FBN), to provide an alternative means to facilitate the construction failure analysis in tunnel construction. Currently, a universally accepted standard regarding the safety risk analysis procedure has not been reached in tunnel construction. A systemic decision approach based upon FBN is developed with step-by-step procedures in detail, aiming to provide guidelines for safety management in tunnel construction throughout the entire life cycle, with the pre-accident, during-construction continuous and post-accident control included. A typical hazard concerning the tunnel leakage in the construction of Wuhan Yangtze Metro Tunnel in China is presented as a case study. Results demonstrate the feasibility of the proposed fuzzy decision approach and its application potential.

This paper is organized as follows. The fundamental theory and the proposed decision analysis procedure are introduced in Section 2. In Section 3, an expert confidence indicator is proposed for the fuzzification in probability assessment of basic risk factors. In Section 4, a fuzzy-based decision analysis approach, with the capacity of deductive reasoning, sensitivity analysis and abductive reasoning, is developed based on Bayesian inference. In Section 5, the proposed method is applied to fuzzy decision support for safety assurance in a tunnel case. A comparison of advantages and disadvantages between FBN and fuzzy fault tree analysis as risk analysis tools is presented in Section 6. The conclusions are drawn in Section 7.

2. Methodology

2.1. Bayesian networks

Bayesian networks (BNs) are a combination of two different mathematical areas, graph theory and probability theory, which consists of a directed acyclic graph (DAG) and an associated joint probability distribution (JPD). A BN model with n nodes can be represented as B $<G, \Theta>$, where G stands for a DAG with n nodes, and Θ stands for the JPD of the BN model. The nodes $\{X_1,\ldots, X_n\}$ in the graph are labeled by related random variables. The directed edges between nodes represent association relationships among variables. DAG contains conditional independence assumptions, and the relations represented by DAG allow JPD to be specified locally by the conditional probability table (CPT) for each node. Assuming $\pi(X_i)$ is the parent nodes of X_i in DAG, the CPT of X_i is denoted by $P(X_i|\pi(X_i))$. The JPD of $P(X_1,\ldots, X_n)$ can be written as Eq. (1).

$$P(X_1,\ldots,X_n) = \prod_{X_i \in \{X_1,\ldots,X_n\}} P(X_i|\pi(X_i)) \tag{1}$$

2.2. Fuzzy set theory and Fuzzy Bayesian Networks

Fuzzy set theory (FST) is first introduced by Zadeh [24] with an effort to deal with uncertainty due to the imprecision and vagueness. FST provides a basis to generate powerful problem-solving techniques with wide applicability, especially in the field of decision making [25]. A fuzzy set $\tilde{P}$ is usually indicated by a tilde "∼", where X is characterized by a membership function $F_{\tilde{P}}(x)$ with an interval [0, 1]. The function $F_{\tilde{P}}(x)$ represents the membership value of x in $\tilde{P}$. In general, FST uses triangular, trapezoidal or Gaussian fuzzy numbers to convert the uncertain numbers into fuzzy numbers [26]. Without loss of generality, triangular fuzzy numbers are often utilized to provide more precise descriptions and to obtain more accurate results [27]. Thus, in this paper, triangular fuzzy numbers are used for representing probabilities of root nodes in a BN model. A fuzzy number $\tilde{P}=(a, m, \mathrm{b})$ is called a triangular fuzzy number if its membership function is given by Eq. (2). Herein, a, m, and b represent the lower least likely value, the most likely value, and the upper least likely value, respectively. The constants $[a, \mathrm{b}]$ give the lower and upper bounds of the available area, reflecting the fuzziness of the actual data. Assuming two triangular fuzzy numbers, namely $\tilde{A}_1=(a_1, m_1, b_1)$ and $\tilde{A}_2=(a_2, m_2, b_2)$, the operators between $\tilde{A}_1$ and $\tilde{A}_2$ can be defined by Eq. (3), including the addition, subtraction, multiplication, and division (see the work of Mentes and Helvacioglu [19]).

$$F(x) = \begin{cases} 0, & x \le a \\ \frac{x-a}{m-a}, & a \le x \le m \\ 1, & x = m \\ \frac{b-x}{b-m}, & m \le x \le b \\ 0, & x \ge b \end{cases} \tag{2}$$

$$\begin{cases} \tilde{A}_1 \oplus \tilde{A}_2 = (a_1+a_2, m_1+m_2, b_1+b_2) \\ \tilde{A}_1 \,\Theta\, \tilde{A}_2 = (a_1-a_2, m_1-m_2, b_1-b_2) \\ \tilde{A}_1 \otimes \tilde{A}_2 = (a_1a_2, m_1m_2, b_1b_2) \\ \tilde{A}_1 \varnothing \tilde{A}_2 = (a_1/b_2, m_1/m_2, b_1/a_2) \end{cases} \tag{3}$$

When constructing a BN model, analysts are confronted with insufficient data concerning probabilities of root nodes. In the engineering practice, the occurrence of an extremely hazardous event is rare, and therefore, the data would be rare. In the absence of sufficient data, it is necessary to work with rough estimates of probabilities [28]. Under such uncertain circumstances, it is considered inappropriate to use conventional BN for computing the system failure probability. FST offers an analysis frame that can deal with imprecision in input failure probabilities for the estimation of probability of the leaf root, and such analysis is termed fuzzy Bayesian network (FBN). With regard to FBN, it is essential to choose the proper fuzzy probability measure as to conduct the fuzzy Bayesian inference. Based upon the work of Halliwell et al. [29],