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A fuzzy logic-based method for risk assessment of bridges during construction

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ABSTRACT

There are many possible risk factors which may lead to bridge failures and cause numerous economic and human losses during the construction of bridges. Therefore, risk assessment for bridges during construction should be performed very carefully to avoid bridge failures and casualties. This article presents a fuzzy logic-based method which synthesizes fuzzy analytical hierarchy process (FAHP) method based on a 3-point scale, fuzzy set theory and fuzzy logic into a single integrated approach. In this approach, the FAHP method based on a 3-point scale is used to structure and prioritize diverse risk factors, and the fuzzy set theory and fuzzy logic is used to handle imprecise data sets including information featuring non-statistical uncertainties. After the concept and procedure of the FAHP method based on a 3-point scale are demonstrated, the proposed fuzzy logic-based method is used to perform risk assessment of a suspension bridge. The example suspension bridge is the Aizhai Bridge with a main span length of 1176m built in China. The results show that risk assessment of bridges during construction could be more efficiently analyzed using the proposed method.

1. INTRODUCTION

Bridges represent essential parts of transportation network. Failures of bridge structures may bring about numerous economic and social losses as well as indirect losses. Thus, it is necessary to perform risk assessment carefully to avoid bridge failures. Risk assessment can be defined as a process of evaluating the risks associated with a specific situation. The aim of risk assessment for bridges during construction is to enable decision-makers to propose: (1) optimal safety measures; (2)

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appropriate organization plans (Andric and Lu 2016). The construction stage of bridges, perhaps more than others, has been plagued by various risks which have their origins from construction techniques, sudden accidents, natural disasters and human factors, often resulting in poor performance with increasing costs and time delay, even project failure (An and Zeng 2005). Nevertheless, literature indicates that risk analysis of bridges during construction has not been considered equally with that of bridges in design, operation or maintenance phases (Hashemi et al. 2011).

Risk identification, the first step of risk assessment of bridges during construction, is an extremely complex issue and has a significant impact on the efficiency of the following risk analysis and control. And as a matter of fact, finding out some more possible risk factors among many risk ones is a multi-criteria decision making (MCDM) problem, wherein the criteria should satisfy multiple conditions. The analytical hierarchy process (AHP) method has become one of the most commonly used approaches to solve various decision-making problems over the past several decades. The main idea of this method is to help the analysts to organize the critical aspects of the kind of multi-criteria decision-making problem into a hierarchical structure similar to a family tree. By reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, the analysts can arrive at the best decision. Therefore, the AHP method can be used for bridge risk identification. Since Saaty proposed the AHP method in the mid-1970s (Saaty 1980), several efforts have been made to improve this method and enlarge its applicable range. So far, the AHP method has made rapid progress in different fields such as planning, best alternative selecting, optimization, etc. (Vaidya and Kumar 2006; Mahdi and Alreshaid 2005; Bertolini and Bevilacqua 2006; Abudayyeh et al. 2007; Lin et al. 2008; Al-Harbi 2001; Cheung et al. 2001; Yang and Lee 1997; Chang et al. 2007; Shapira and Goldenberg 2005). However, the AHP method is incapable of handling the inherent subjectivity and ambiguity associated with the mapping of one's perception to an exact number. To defeat this problem, FAHP methods have been developed recently. For instance, Kuo proposed an effective fuzzy multi-criteria analysis method based on incorporated grey relations and pairwise comparisons to solve fuzzy MCDM problems (Kuo 2006); Pan presented a FAHP model which employs triangular and trapezoidal fuzzy numbers and the α-cut concept to deal with the imprecision inhere to the process of subjective judgments (Pan 2008).

However, most approaches of the existing AHP and FAHP methods for solving MCDM problems are based on a 9-point scale. Despite its wide range of applications, the conventional AHP and FAHP methods have the following disadvantages: (1) using a 9-point scale of relative importance is hard for fuzzy comparison matrices to have an absolute consistency in the risk identification process. Thus, it is required to repeat pairwise comparisons process, which may consume a large amount of time; (2) in practice, decision makers usually find it extremely difficult to perform exact pairwise comparison judgments by using a 9-point scale.

In order to circumvent these disadvantages, we propose a risk assessment method which combines FAHP method based on a 3-point scale, fuzzy set theory and fuzzy logic in this paper. In this method, fuzzy set theory and fuzzy logic can handle imprecise data sets including information featuring non-statistical uncertainties. Besides, the main advantage of fuzzy set theory compared to other methods is the ability to operate with linguistic variables since some events cannot be described numerically

(Ivezić et al. 2008; Petrović et al. 2014). According to the author's best knowledge, the application of this approach for risk assessment of bridges during construction has not been studied before. Further, the concepts of combining FAHP method based on a 3-point scale, fuzzy set theory and fuzzy logic could be more widely available to simplify the process of risk assessment in other engineering fields.

The rest of this paper is organized as follows: fuzzy logic-based framework for risk assessment of bridges during construction is first presented in Section 2. Section 3 introduces the proposed fuzzy logic-based method for risk assessment of bridges during construction, in which the FAHP method based on 3-point scale is described firstly and further, primary steps of the proposed fuzzy logic-based method for risk assessment of bridges during construction are briefly presented. Section 4 investigates a numerical example of bridge risk assessment to show the applicability of the proposed method. Finally, some conclusions are drawn in Section 5.

2. FUZZY LOGIC-BASED FRAMEWORK FOR RISK ASSESSMENT OF BRIDGES DURING CONSTRUCTION

Fig. 1 shows the hierarchically structured framework of the proposed fuzzy logic-based method to risk assessment of bridges during construction, which is based on current codes in China (Ministry of Transport of the People's Republic of China 2011). The framework includes：(1) risk identification; (2) risk ranking; (3) risk analysis; (4) risk assessment. Risk identification is the first step to identify all potential risks and their specifics that could influence structural safety in construction stage. According to their importance, risk factors identified previously should be prioritized. Risk ranking plays an important role in risk assessment and it is implemented based on subjective judgments of experts. The next step is risk analysis, which is the key step in the overall process of risk assessment to evaluate effects of identified risks and it embraces two parts: (1) probability of occurrence (probability analysis); (2) risk losses (loss analysis). The probability of risk occurrence during bridge construction can be obtained by probability analysis, and loss analysis is estimated according to effects of risks on communities, environment and people. In general, parameters of risk factors, including probability of occurrence and risk losses, can be assessed by qualitative or quantitative methods. Qualitative methods estimate risks based on subjective judgments of experts depending on their experience and expertise, such as Delphi technique (Linstone and Turoff 1975). Quantitative methods employ mathematical models to identify potential risks and their specifics that could influence the project. Risk analysis in this paper is carried out based on subjective judgments of experts. The last step of the process is risk assessment, which can be denoted by a multiplication formula. Mathematically, the final risk value of a bridge during construction can be derived by following equation:

$$R = P \cdot L \tag{1}$$

Where, *P*-probability of risk occurrence, *L*-risk losses.

Moreover, fuzzy risk factors have been computed through the fuzzification and aggregation process, as illustrated in Fig. 1. Finally, the risk of the bridge is calculated by aggregation and defuzzification process.

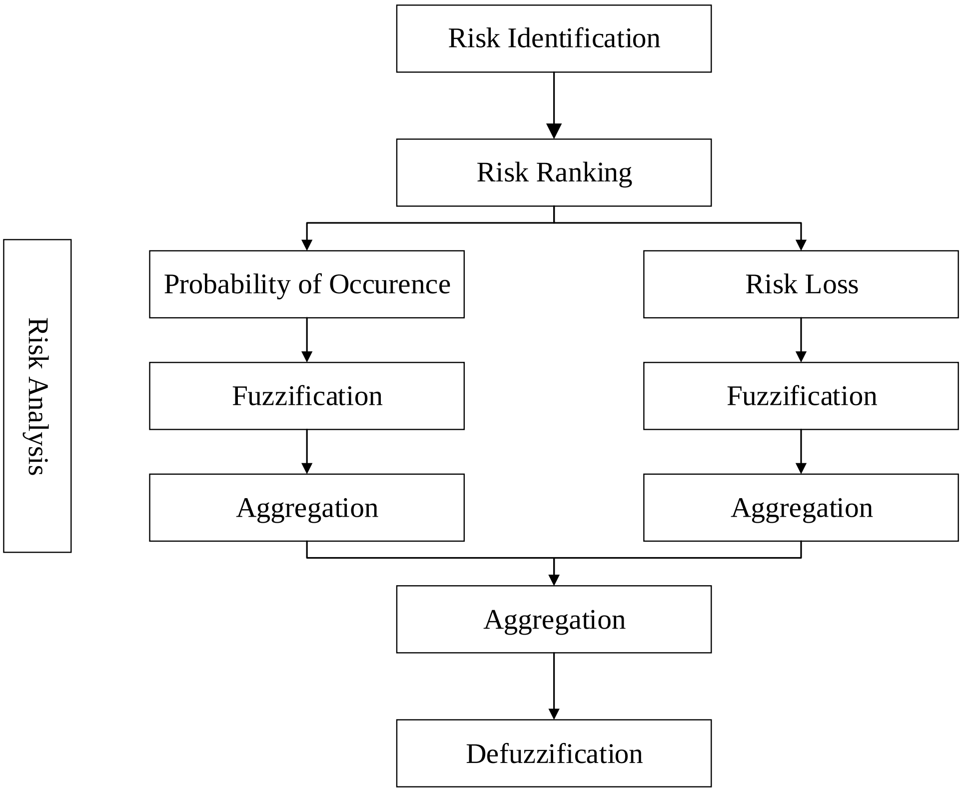


Fig. 1 Conceptual fuzzy logic-based framework for risk assessment

3. PROPOSED FUZZY LOGIC-BASED METHOD FOR RISK ASSESSMENT OF BRIDGES DURING CONSTRUCTION

The proposed fuzzy logic-based method combines FAHP method based on a 3-point scale，fuzzy set theory and fuzzy logic and uses the same basic concept of the aforementioned framework for risk assessment. In this approach, the FAHP method based on a 3-point scale is used to structure and prioritize diverse risk factors of a bridge during construction firstly, and the final risk level of this bridge is then derived by using the proposed fuzzy logic-based theory.

3.1 FAHP method based on a 3-point scale for risk identification and risk ranking

In order to perform risk identification and work out the priority weights of risk factors, a FAHP method based on a 3-point scale was developed in a previous paper (Cheng and Xiao 2009) which is a hybrid method consisting of AHP and fuzzy consistent matrix method (FCMM). A distinctive feature of this FAHP method is to construct a fuzzy consistent matrix instead of customary pair-wise comparison matrix by using a 3-point scale. As the fuzzy comparison matrix is consistent all the time, consistency checking is no longer required. Hence, computing time of the whole process can be saved greatly. Another advantage of this method is that only “1”, “0.5” and “0” are used to describe the scale of significance in FCMM whereas conventional AHP relies on a 9-point scale, thus, it can overcome difficulties of making judgment and comparison caused by uncertainty that jeopardizes accuracy of the results. For completeness, FCMM is briefly described as follows. A more detailed description may be found in Yao (1998).

3.1.1 Fuzzy consistent matrix method

The FCMM has two major steps. Firstly, a pair-wise comparison matrix based on a 3-point scale (shown in Table 1) is created to take the place of the comparison matrix based on a 9-point scale (shown in Table 2) in AHP (Yao 1998). The comparison matrix based on the 3-point scale is obviously superior to that of AHP by adopting a “logical checking” which only consists of three options: (1) “C_{ij}” is equally important as “C_{ij}'”; (2) “C_{ij}” is more important than “C_{ij}'” and (3) “C_{ij}” is less important than “C_{ij}'”. So the 9-point scale of comparison in AHP can be greatly simplified by using this comparison matrix based on the 3-point scale. Secondly, the structured pair-wise comparison matrix is converted to a fuzzy consistent matrix C' by means of the following definition and theorem.

Table 1 Pair-wise comparison scale in the FAHP method based on a 3-point scale

Comparative judgment	Gradation scale
C_i is more important than C_j	1
C_i and C_j are equally important	0.5
C_i is less important than C_j	0

Table 2 Pair-wise comparison scale in conventional AHP

Comparative judgment	Gradation scale
C_i and C_j are equally important	1
	2
C_i is moderately more important than C_j	3
	4
C_i is strongly more important than C_j	5
	6
C_i is very strongly more important than C_j	7
	8
C_i is extremely strongly more important than C_j	9

Yao (1998) gave the following definition of fuzzy consistent matrix.

Definition. Let $C' = [c_{ij}']$ be an N×N comparison matrix. If $c'_{ij} + c'_{ji} = 1$ and $c'_{ij} = c'_{ik} - c'_{jk} + 0.5$, then the comparison matrix C' is a fuzzy consistent matrix.

Theorem. Let $C' = [c_{ij}']$ be an N×N comparison matrix. When matrix C' satisfies the following equation, it is said to be a fuzzy consistent matrix.

$$C'_{ij} = \frac{C_i - C_j}{2N} + 0.5 \tag{2}$$

Where, C_i-sum of the i-th row's elements; C_j-sum of the j-th row's elements.
Proof. (1)

$$c'_{ij} + c'_{ji} = \frac{C_i - C_j}{2N} + 0.5 + \frac{C_j - C_i}{2N} + 0.5 = 1 \tag{3}$$

Proof. (2)

$$\begin{aligned} c'_{ij} &= \frac{C_i - C_j}{2N} + 0.5 = \frac{(C_i - C_k) - (C_j - C_k)}{2N} + 0.5 \\ &= \left(\frac{C_i - C_k}{2N} + 0.5\right) - \left(\frac{C_j - C_k}{2N} + 0.5\right) + 0.5 = c'_{ik} - c'_{jk} + 0.5 \end{aligned} \tag{4}$$

From Eqs. (3) and (4) and the above definition, it can be confirmed that the comparison matrix C' is a fuzzy consistent matrix.

3.1.2 Procedure for the FAHP method based on a 3-point scale

The procedure of risk identification and ranking using the FAHP method based on a 3-point scale is:

1) Construct a hierarchical structure of identification criteria from the top through the intermediate level to the lowest level which usually contains a list of alternatives;

2) Establish a pair-wise fuzzy comparison matrix C' for each of the lower levels using Eq. (2);

3) With the comparison matrix C', construct and solve the eigenvector equation $C' \cdot W = \lambda \cdot W$, where the normalized eigenvector $W^T = [w_1, w_2, \dots, w_N]$, corresponding to the maximum eigenvalue λmax, gives the relative importance of each criterion (relative weighting of each criterion);

4) Aggregate the weighted scores of each criterion and rank the decision alternatives.

In order to use the above proposed method, a MATLAB based program is developed.

3.2 Fuzzy logic-based theory for risk analysis and risk assessment

In the proposed fuzzy logic-based method, risk analysis and risk assessment are performed by using the fuzzy set theory and fuzzy logic, which can handle imprecise data sets including information featuring non-statistical uncertainties. In this section, the procedure of risk analysis and risk assessment is outlined below, and more details can be found in Andric and Lu (2016).

Step 1: Selection of linguistic scale: The linguistic scale is defined as the set of linguistic variables. Mathematically, linguistic variable represents a fuzzy number. A fuzzy number is a convex fuzzy set, characterized by a given interval of real numbers, each with a grade of membership between 0 and 1. The most commonly used fuzzy numbers are triangular and trapezoidal fuzzy numbers, whose membership functions are respectively defined as:

$$\mu_{\tilde{A}_1}(x)=\begin{cases}(x-a)/(b-a), & a\le x\le b,\\ (d-x)/(d-b), & b\le x\le d,\\ 0, & otherwise,\end{cases} \tag{5}$$

$$\mu_{\tilde{A}_2}(x)=\begin{cases}(x-a)/(b-a), & a\le x\le b,\\ 1, & b\le x\le c,\\ (d-x)/(d-c), & c\le x\le d,\\ 0, & otherwise,\end{cases} \tag{6}$$

For brevity, triangular and trapezoidal fuzzy numbers are often denoted as (a, b, d) and (a, b, c, d) (Wang and Elhag 2006). The linguistic scale is chosen according to the type of the fuzzy numbers which is suitable to describe and present particular linguistic variables for a certain problem.

Step 2: Linguistic data collection: In this step, subjective judgments of different experts are provided in linguistic variables that have been defined in the previous step. The probability of risk occurrence and risk losses are estimated by experts in bridge engineering through surveys and questionnaires about risk indicators for every risk factor.

Step 3: Fuzzification: Fuzzification is a process which transforms values of linguistic variables into corresponding fuzzy sets using linguistic scale. In this step, the collected data about the risk factors is converted into corresponding fuzzy sets.

Step 4: Fuzzy aggregation of expert opinions: Aggregation is a process to synthetize expert judgments and individual opinions on risk factors to a single combined preference fuzzy set. In this study, expert judgments are weighted equally.

This process can be expressed as following equations:

$$FP_i = \frac{1}{n}\sum_{j=1}^{n} FP_{ij} \tag{7}$$

$$FL_i = \frac{1}{n}\sum_{j=1}^{n} FL_{ij} \tag{8}$$

Where, i-th risk factor; j-th expert; and n-the number of experts; FP_i-the fuzzy probability of occurrence of i-th risk factor; FL_i-the fuzzy risk loss of i-th risk factor.

Step 5: Calculate fuzzy risk factor: The i-th fuzzy risk factor (FRF_i) corresponding to i-th risk factor is obtained through multiplying FP_i by FL_i:

$$FRF_i = FP_i \times FL_i \tag{9}$$

Step 6: Compute fuzzy risk index: The overall fuzzy risk index FR is computed by:

$$FR = \sum_{i=1}^{m} W_i \times FRF_i \tag{10}$$

Where, W_i-the weight of i-th risk factor calculated by using FAHP method presented in Section 3, and m-the number of total identified risk sub-factors, FR-fuzzy risk and it is a fuzzy triangular number.

Step 7: Defuzzification: In the process of defuzzification, the aggregated fuzzy risk is converted into a crisp risk value. The most commonly used defuzzification method is 'Center-of-Gravity'. Mathematically, it is specified by:

$$R = \frac{\sum_{i=1}^{k} Y_i \times \mu(y_i)}{\sum_{i=1}^{k} \mu(y_i)} \tag{11}$$

Where, k-the total number of fuzzy sets in linguistic scale, Y_i-the center of i-th fuzzy set, and $\mu(y_i)$-the membership function of i-th matching fuzzy set.

Step 8: Classification of bridge risk: The bridge risk can be classified into different risk categories and it is carried out based on crisp risk values which have been derived by defuzzification process.

4. AN ILLUSTRATIVE EXAMPLE: A BRIDGE IN HUNAN, CHINA

Aizhai Suspension Bridge, with an 1176 m central span length, which is built in Hunan, China, is investigated for an example here. Span arrangements of this bridge are (242+1176+116) m. The deck cross-section is a steel truss girder which is 27 m in width and 7.5 m in height. The distance between two cables is 27 m and the hanger spacing is 14.5 m. The elevation view of this bridge is shown in Fig. 2.

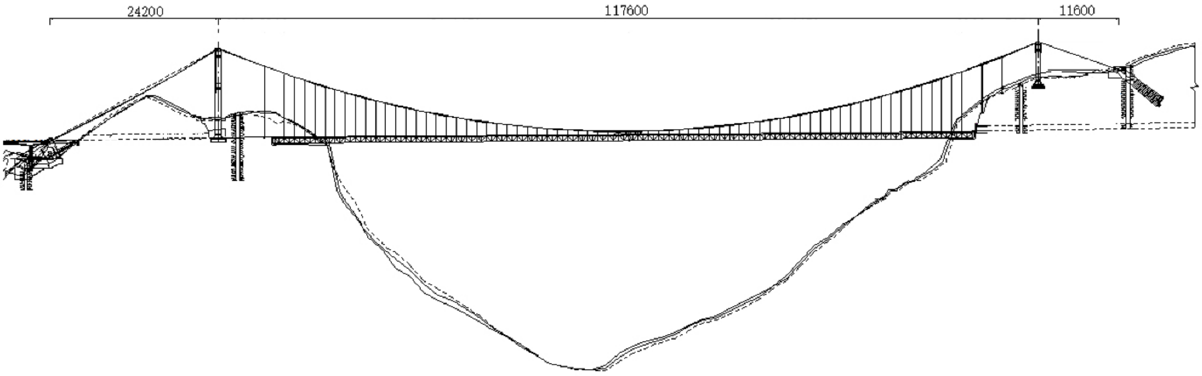
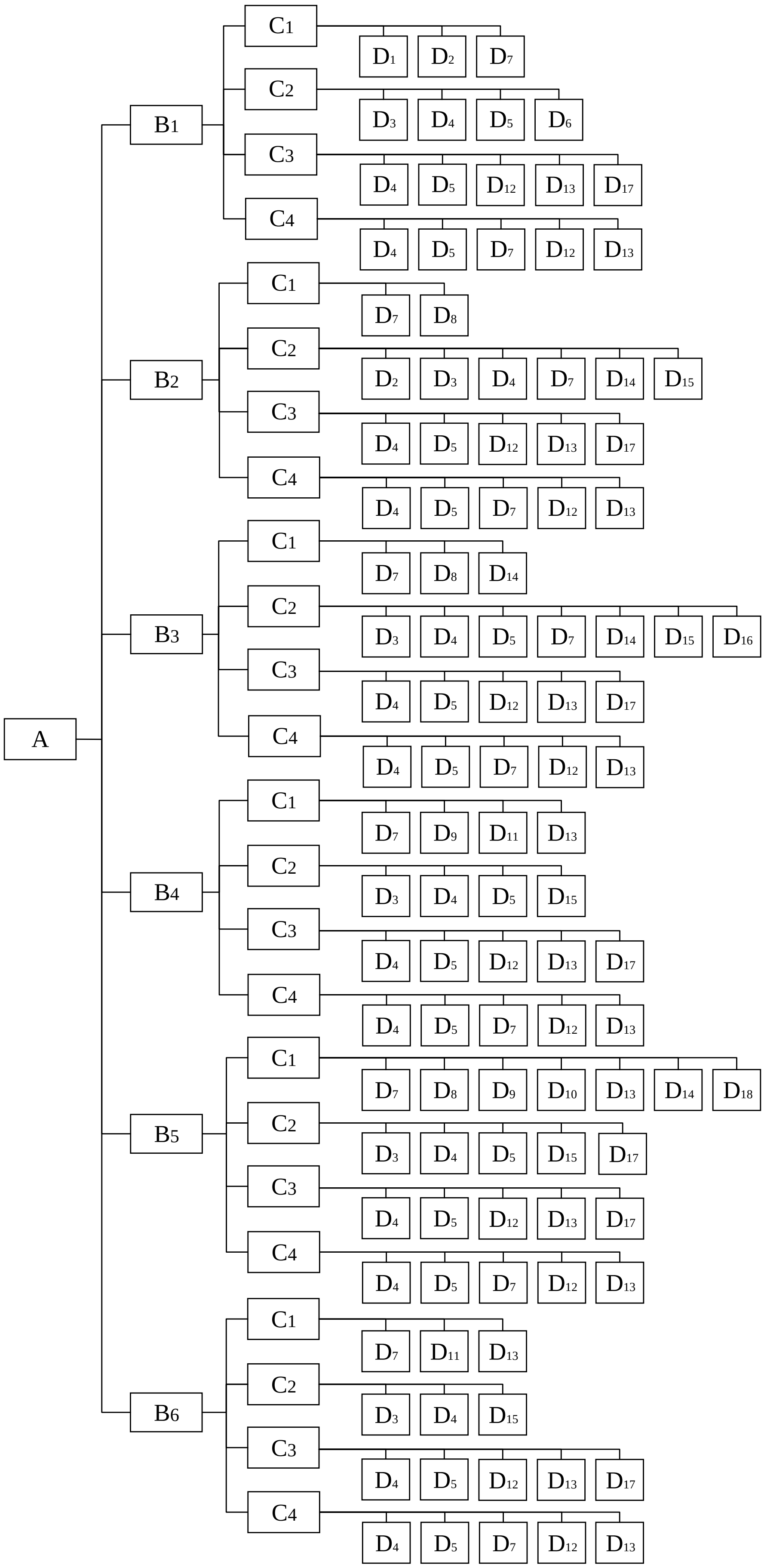


Fig. 2 Elevation of Aizhai Suspension Bridge (unit: cm)

4.1 Risk identification and risk ranking for Aizhai suspension bridge

The hierarchical structure for identification of risk factors is established for Aizhai Suspension Bridge based on the experts' suggestions derived by using Delphi approach. The constructed hierarchical structure, as shown in Fig. 3, divides all identified criteria into four levels. The top level and the lowest level of the hierarchical structure denote the overall objective and the sub-risk factors respectively. The construction sequence of Aizhai Suspension Bridge consists of road excavation and slope protection construction, anchor construction, tower construction, cable construction, girder construction, deck pavement and ancillary facilities construction, is included at the second level. Four main criteria including quality, safety, schedule, and finance are in the third level. Further, the four main criteria are decomposed into various sub-criteria.

Then the FAHP method based on a 3-point scale described in Section 3 is used to perform risk identification and risk ranking of this bridge. The details are no longer displayed here due to length limitations. The results shown in Tables 3-5 present the weight vectors and ranking of risk factors. It can be seen from Tables 3-5 that: (1) anchor construction risk is the most important risk factor in risk group B and quality risk is the most important risk factor in risk group C and drainage measures has the highest priority value in group D. (2) the 3-point scale in the adopted FAHP method is practical to complete the comprehensive risk identification and ranking of bridges during construction.


A
B1
C1
D1 D2 D7
C2
D3 D4 D5 D6
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13
B2
C1
D7 D8
C2
D2 D3 D4 D7 D14 D15
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13
B3
C1
D7 D8 D14
C2
D3 D4 D5 D7 D14 D15 D16
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13
B4
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D7 D9 D11 D13
C2
D3 D4 D5 D15
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13
B5
C1
D7 D8 D9 D10 D13 D14 D18
C2
D3 D4 D5 D15 D17
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13
B6
C1
D7 D11 D13
C2
D3 D4 D15
C3
D4 D5 D12 D13 D17
C4
D4 D5 D7 D12 D13

A: Goal;

B_1: Road excavation and slope protection construction risk;

B_2: Anchor construction risk;

B_3: Tower construction risk;

B_4: Cable construction risk;

B_5: Girder construction risk;

B_6: Deck pavement and ancillary facilities construction risk;

C_1: Quality risk;

C_2: Safety risk;

C_3: Schedule risk;

C_4: Finance risk;

D_1: Drainage measures;

D_2: Foundation improvement;

D_3: Personnel security;

D_4: Severe weather;

D_5: Mechanical equipment;

D_6: Blasting work;

D_7: The quality of structural members;

D_8: Construction positioning;

D_9: Alignment quality;

D_{10}: Pushing of cable saddle;

D_{11}: Effect of temperature;

D_{12}: Design changes;

D_{13}: Structural material;

D_{14}: Hoisting procedure;

D_{15}: High altitude operation;

D_{16}: Electricity safety;

D_{17}: Construction organization management;

D_{18}: Construction load.

Fig. 3 Hierarchical structure for identification and ranking of risk factors during construction of Aizhai Suspension Bridge

Table 3 The weight vectors and ranking of pair-wise comparison matrixes for risk group B based on the proposed method

Risk factors	Weight vector	Ranking
B_1	0.1209	5
B_2	0.2429	1
B_3	0.1819	3
B_4	0.2124	2
B_5	0.1514	4
B_6	0.0904	6

Table 4 The weight vectors and ranking of pair-wise comparison matrixes for risk group C based on the proposed method

Risk factors	Weight vector	Ranking
C_1	0.3289	1
C_2	0.3064	2
C_3	0.1824	3
C_4	0.1824	3

Table 5 The weight vectors and ranking of pair-wise comparison matrixes for risk group D based on the proposed method

Risk factors	Weight vector	Ranking	Risk factors	Weight vector	Ranking
D_1	0.0114	14	D_{10}	0.0082	16
D_2	0.0323	10	D_{11}	0.0199	13
D_3	0.0504	8	D_{12}	0.0726	5
D_4	0.1362	2	D_{13}	0.0987	4
D_5	0.1264	3	D_{14}	0.0302	11
D_6	0.0078	17	D_{15}	0.0661	6
D_7	0.1921	1	D_{16}	0.0045	18
D_8	0.0584	7	D_{17}	0.0456	9
D_9	0.0294	12	D_{18}	0.0100	15

4.2 Risk analysis and risk assessment for Aizhai suspension bridge

The computational procedure is summarized as follows:

Step 1: Selection of linguistic scale: A group of triangular fuzzy numbers are selected to characterize linguistic variables, as shown in Table 6. The probability of risk occurrence is ranked by linguistic variables: Very Rare (VR), Rare (R), Moderate (M), Frequent (F), and Very Frequent (VF). Similarly, linguistic variables: Very Small (VS), Small (S), Moderate (M), Big (B), Very Big (VB) are utilized to risk losses.

Step 2: Linguistic data collection: Two linguistic data sets about the probability of risk occurrence and risk losses have been collected from five experienced experts by questionnaires. Tables 7-8 indicates the collected data.

Step 3: Fuzzification: The linguistic data sets in Tables 7-8 are converted into fuzzy sets by using linguistic scale in Fig. 4 and Table 6.

Step 4: Fuzzy aggregation of expert opinions: The fuzzy sets obtained from the previous process are aggregated by Eqs. (7) and (8) in this step. The second and third columns in Table 9 present the results.

Step 5: Calculate fuzzy risk factor: Fuzzy risk factor can be derived by Eq. (9) and results of fuzzy degree of risk factors are summarized in the last column of Table 9.

Step 6: Compute fuzzy risk index: The overall fuzzy risk of bridge is calculated by following Eq. (10):

$FR = \sum_{i=1}^{m} W_i \times FRF_i = (0.0330, 0.1232, 0.3479)$

Step 7: Defuzzification: The aggregated fuzzy risk is converted into crisp risk value by defuzzification procedure. The matching fuzzy sets from linguistic scale and the membership degree of bridge fuzzy risk belonging to these fuzzy sets are:

Very low: $\mu = 0.6843$

Low: $\mu = 0.7329$

Moderate: $\mu = 0.1128$

The procedure is illustrated in Fig. 5. The bridge fuzzy risk is converted into crisp risk value by 'Center-of-gravity' method according to Eq. (11):

$$R = \frac{0.1 \times 0.6843 + 0.25 \times 0.7329 + 0.5 \times 0.1128}{0.6843 + 0.7329 + 0.1128} = 0.2013$$

Step 8: Classification of bridge risk: The bridge risk can be categorized into different risk categories according to the risk ratings ranges. In Table 10, crisp risk ratings for linguistic risk parametric scale are obtained with reference to Table 6. Five different crisp risk values have been computed by defuzzification process using 'Center-of-Gravity' method and corresponding to such crisp values, four possible risk categories (Risk Category 1~4) are defined with a range of (0.13–0.80). The highest risk rating is 0.80 assigned to risk factors and the lowest risk rating is 0.13. Further, risk categories describe four risk levels: Low Risk (LR), Moderate Risk (MR), High Risk (HR), and Very High Risk (VHR) as it is presented in Table 11.

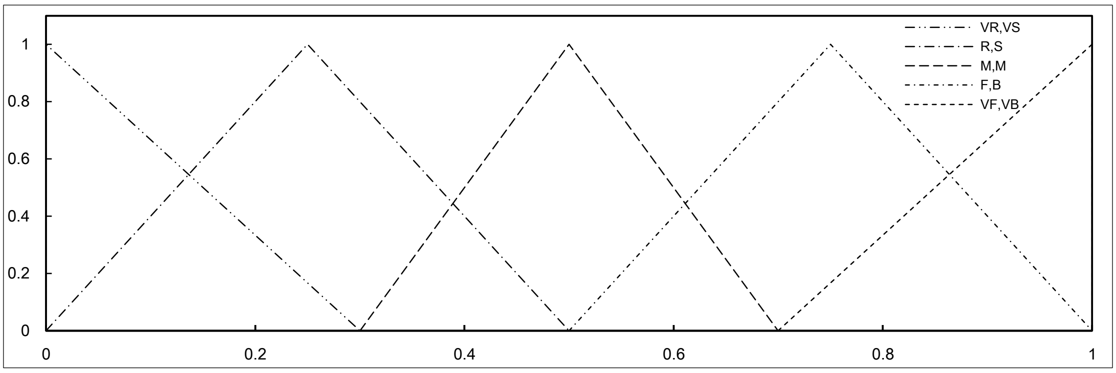

Fig. 4 Five member linguistic scale for evaluation P and L

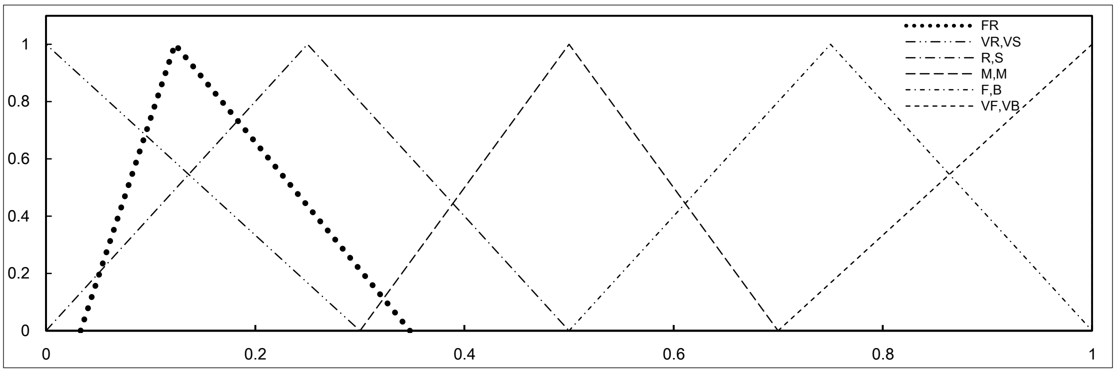

Fig. 5 Matching fuzzy sets of fuzzy risk

It can be seen from Tables 6-11 that: (1) the risk level of Aizhai Suspension Bridge obtained by the proposed method is moderate, which corresponds with the result estimated by Tongji University (2011). (2) fuzzy set theory and fuzzy logic can handle imprecise data sets and have the ability to operate with linguistic variables. These advantages make the proposed fuzzy logic-based method more practical since some events cannot be described numerically.

Table 6 Linguistic classification of grades of risk factors

Probability of occurrence	Risk losses	Triangular fuzzy numbers
Very rare	Very small	(0,0,0.3)
Rare	Small	(0,0.25,0.5)
Moderate	Moderate	(0.3,0.5,0.7)
Frequent	Big	(0.5,0.75,1)
Very frequent	Very big	(0.75,1,1)

Table 7 The probability of risk occurrence assigned by experts in linguistic variables

Risk factors	E1	E2	E3	E4	E5
D_1: Drainage measures	F	M	F	M	F
D_2: Foundation improvement	VR	VR	R	VR	VR
D3: Personnel security	VR	R	VR	R	VR
D4: Severe weather	M	R	M	M	M
D5: Mechanical equipment	F	M	M	R	M
D6: Blasting work	R	M	R	R	R
D7: The quality of structural members	VR	VR	VR	R	VR
D8: Construction positioning	VR	R	VR	VR	VR
D9: Alignment quality	M	R	M	M	M
D10: Pushing of cable saddle	F	F	M	F	M
D11: Effect of temperature	R	M	F	M	M
D12: Design changes	F	F	M	F	M
D13: Structural material	VR	VR	R	VR	R
D14: Hoisting procedure	F	F	M	F	M
D15: High altitude operation	R	VR	VR	R	VR
D16: Electricity safety	R	M	R	VR	R
D17: Construction organization management	VR	R	VR	VR	R
D18: Construction load	R	VR	VR	R	VR

Table 8 The risk losses assigned by experts in linguistic variables

Risk factors	E1	E2	E3	E4	E5
D_1: Drainage measures	B	VB	B	B	M
D_2: Foundation improvement	M	B	M	B	B
D3: Personnel security	VB	B	VB	B	VB
D4: Severe weather	B	M	B	B	B
D5: Mechanical equipment	VS	S	VS	VS	VS
D6: Blasting work	B	VB	VB	B	VB
D7: The quality of structural members	VS	S	VS	VS	VS
D8: Construction positioning	M	S	M	S	M
D9: Alignment quality	M	B	M	S	M
D10: Pushing of cable saddle	M	B	B	M	B
D11: Effect of temperature	M	S	M	S	M
D12: Design changes	M	M	S	M	S
D13: Structural material	M	S	M	S	M
D14: Hoisting procedure	S	S	VS	S	VS
D15: High altitude operation	S	M	M	S	M
D16: Electricity safety	VS	VS	S	VS	S
D17: Construction organization management	S	VS	S	VS	S
D18: Construction load	VS	VS	VS	S	VS

Table 9 Aggregated fuzzy risk's parameters and fuzzy degree of risk factors for every risk

Risk factors	Probability of risk occurrence	Risk losses	Fuzzy degree of risk factors
D_1: Drainage measures	(0.42,0.65,0.88)	(0.06,0.1,0.14)	(0.0252,0.065,0.1232)
D_2: Foundation improvement	(0.06,0.15,0.42)	(0.42,0.65,0.88)	(0.0252,0.0975,0.3696)
D3: Personnel security	(0,0.1,0.38)	(0.65,0.9,1)	(0,0.09,0.38)
D4: Severe weather	(0.24,0.45,0.66)	(0.46,0.7,0.94)	(0.1104,0.315,0.6204)
D5: Mechanical equipment	(0.28,0.5,0.72)	(0.06,0.15,0.42)	(0.0168,0.075,0.3024)
D6: Blasting work	(0.06,0.3,0.54)	(0.65,0.9,1)	(0.039,0.27,0.54)
D7: The quality of structural members	(0.06,0.15,0.42)	(0,0.05,0.34)	(0,0.0075,0.1428)
D8: Construction positioning	(0.06,0.15,0.42)	(0.18,0.4,0.62)	(0.0108,0.06,0.2604)
D9: Alignment quality	(0.24,0.45,0.66)	(0.22,0.45,0.68)	(0.0528,0.2025,0.4488)
D10: Pushing of cable saddle	(0.42,0.65,0.88)	(0.36,0.6,0.84)	(0.1512,0.39,0.7392)
D11: Effect of temperature	(0.28,0.5,0.72)	(0.18,0.4,0.62)	(0.0504,0.2,0.4464)
D12: Design changes	(0.42,0.65,0.88)	(0.18,0.4,0.62)	(0.0756,0.26,0.5456)
D13: Structural material	(0.06,0.2,0.46)	(0.12,0.35,0.58)	(0.0072,0.07,0.2668)
D14: Hoisting procedure	(0.42,0.65,0.88)	(0.06,0.2,0.46)	(0.0252,0.13,0.4048)
D15: High altitude operation	(0.06,0.2,0.46)	(0.18,0.4,0.62)	(0.0108,0.08,0.2852)
D16: Electricity safety	(0.06,0.25,0.5)	(0.06,0.2,0.46)	(0.0036,0.05,0.23)
D17: Construction organization management	(0.06,0.2,0.46)	(0.06,0.2,0.46)	(0.0036,0.04,0.2116)
D18: Construction load	(0.06,0.2,0.46)	(0.06,0.15,0.42)	(0.0036,0.03,0.1932)

Table 10 Crisp risk levels

Probability (H)	Risk losses(L)	Fuzzy risk rating (H×L)	Crisp risk (rating)
Very rare	Very small	(0,0,0.09)	0.1314
Rare	Small	(0,0.0625,0.25)	0.1613
Moderate	Moderate	(0.09,0.25,0.49)	0.2709
Frequent	Big	(0.25,0.563,1)	0.5235
Very frequent	Very big	(0.563,1,1)	0.8020

Table 11 Crisp risk ranges and categories

Risk category	Risk range
Risk category 0:	(0-0.12)
Risk category 1: Low Risk	(0.13-0.16)
Risk category 2: Moderate Risk	(0.17-0.27)
Risk category 3: High Risk	(0.28-0.52)
Risk category 4: Very High Risk	(0.53-0.80)
Risk category 5:	(0.81-1.00)

5. CONCLUSIONS

In this paper, a new fuzzy logic-based method is developed in order to perform risk assessment of bridges during construction. The proposed method synthesizes FAHP based on a 3-point scale, fuzzy set theory and fuzzy logic into a single integrated approach. It can be conducted reliably by integrating both qualitative information based on subjective judgments of experts and quantitative method. Firstly, the FAHP based on a 3-point scale is applied to determine weights of various risk factors and perform risk ranking, further, the fuzzy set theory and fuzzy logic are used to calculate the imprecise risk indicators with the linguistic variables.

The following conclusions can be drawn from this study:

(1) The FAHP method based on a 3-point scale is viable for identification and ranking of risk factors. And it is more efficient not only because the pairwise comparison of identified risk factors can be greatly simplified by using a 3-point scale compared with the 9-point scale in the conventional AHP, but also because it does not involve consistency checking during calculation. It should be noted that the conventional AHP requires decision makers to understand well the relationship of various decision alternatives to provide precise pairwise comparison judgments. However, from the current practitioners' point of view, one usually finds it difficult to perform comparison by

using a 9-point scale. This difficulty can be overcome by using a 3-point scale in the FAHP method.

(2) The example illustrated in Section 4 has demonstrated the applicability of the proposed fuzzy logic-based method for risk assessment of bridges during construction. And further, it could be applied for risk assessment in other engineering fields.

(3) This paper provides an efficient method for risk assessment of bridges during construction. However, the results obtained from this study are restricted to special circumstances. In further study it is needed to consider more alternatives of risk factor and establish more comprehensive hierarchical structure for a risk assessment problem.

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