Journal of Soft Computing in Civil Engineering 6-1 (2022) 29-45

Contents lists available at SCCE

Journal of Soft Computing in Civil Engineering

Journal homepage: www.jsoftcivil.com

Identifying and Ranking of Mechanized Tunneling Project's Risks by Using A Fuzzy Multi-Criteria Decision Making Technique

Sina Shaffiee Haghshenas[1*], Sami Shaffiee Haghshenas[2], Mohammed Adel Abduelrhman[2], Shervin Zare[3], Reza Mikaei[4]

1. Ph.D. Candidate, Department of Civil Engineering, University of Calabria, 87036 Rende, Italy
2. M.Sc., Department of Civil Engineering, University of Calabria, 87036 Rende, Italy
3. M.Sc., Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende, Italy
4. Associate Professor, Department of Mining and Engineering, Faculty of Environment, Urmia University of Technology, Urmia, Iran

Corresponding author: *sina.shaffieehaghshenas@unical.it*

https://doi.org/10.22115/SCCE.2022.305718.1366

ARTICLE INFO

Article history:
Received: 20 September 2021
Revised: 03 December 2021
Accepted: 01 January 2022

Keywords:
Risk assessment;
Risk management;
Tunneling project;
FAHP;
FMCDM.

ABSTRACT

A tunneling project is one of the most significant infrastructure projects. Its implementation requires access to adequate data and use of unique proceedings; hence it has a special position among civil engineering projects. Unexpected and uncertain conditions in tunneling projects lead to an increase of potential risks during project implementation. Identifying and evaluating risks in tunneling projects are considered one of the significant challenges among civil engineers, which can cause proper risk management during tunnel construction. Therefore, this study aims to evaluate and rank the risks of the second part of the Emamzadeh Hashem tunnel in the north of Iran which was considered as a case study. For this purpose, twelve potential risks were identified by using geological studies and experts. Then, they were evaluated and ranked using effective fuzzy multi-criteria decision-making (FMCDM) techniques, namely fuzzy analytical hierarchical process (FAHP). The three decision variables were considered, including repeat chance, occurrence possibility, and efficacy. The results obtained indicated that the occurrence possibility was the most effective among the decision variables in this case study. In addition, Instability of the wall and lack of contractor's experiences had the highest and lowest ranks with 0.103 and 0.052, respectively.

How to cite this article: Shaffiee Haghshenas S, Shaffiee Haghshenas S, Abduelrhman M, Zare S, Mikaeil R. Identifying and Ranking of Mechanized Tunneling Project's Risks by Using a Fuzzy Multi-Criteria Decision Making technique. J Soft Comput Civ Eng 2022;6(1):29–45. https://doi.org/10.22115/scce.2022.305718.1366

1. Introduction

Infrastructures are the principal foundation for the planning of communities, not only in current time but also through history. Through the past up to now, the implementation and operation of infrastructure projects have played a vital role in developing societies, cities and the improvement of the level of service [1–4]. Planning and constructing infrastructures are very complex and unpredictable in a cooperative system; that is, why one defect or a mistake is considered as an obstacle for the whole functions of the project. Hence, identifying, evaluating, and managing hazards and risks of infrastructures have a fundamental role in the correct implementation of infrastructure projects [5]. The project's risk assessment is considered for both design and implementation phases [6,7]. The tunneling project's risk assessment, among other infrastructure projects, is conspicuously essential due to its unpredicted nature. Extensive and comprehensive studies addressed the risk assessment regarding tunneling projects [8,9,18,10–17].

You et al. (2005) carried out a risk assessment of the twin tunneling project. They selected a convenient coverage for maintaining twin tunnels. In their research, the sum of lost expenses caused by hazards and tunnel coverage's construction expenses per meter are reported as risk [19]. Rehbock-Sander and Boissonnas (2012) evaluated hazards' Damaging through the 30-km path of Gotthard tunnel. They considered some parameters such as investment, rules, geology, construction licenses, project management, and strategies to transact hazards. The results demonstrated that complete coordination between executive agents and the employer had a high effect for overcoming geological risks and prevented high project expenses [20]. Sousa & Einstein (2011) investigated the risk analysis of Poro Metro (Portugal) with the possibility of encountering geological conditions, underground water, and possible damage to the ground surface. They applied the Bayesian networks approach in their studies. They selected the closed-form due to the pressure control of the tunnel face to deal with geological circumstances [21]. Geological risks assessment regarding Ardabil-Mianeh Railway Tunnel is studied by Mikaeil et al. (2016). They divided the tunnel into 24 portions and explored four significant risks, which are tunnel instability, squeezing, water flow, and swelling, according to geological proprieties. Results are compared to actual investigations, which had an excellent matching [22]. A risk assessment is carried out by Haghshenas et al (2016) for the Ghomrud tunnel. They used three mechanical and physical parameters and applied Fuzzy C-means (FCM) technique as one of the most efficient and essential clustering methods. The results obtained had good agreement with the data observed from the project [23]. In another study, Haghshenas et al. (2017) investigated and ranked tunneling projects risks using a fuzzy analytical hierarchy process approach. They considered 11 potential risks of the Toyserkan Doolayi tunnel. Based on their study, the swelling of rock's risk gained the highest rank among eleven risks [24]. Risk assessment for a case study (Yelongmen tunnel in China) was addressed by Xiong et al. (2018). Their study used a multi-scale 3d modeling method for the evaluation of the risk assessment regarding the dynamic evaluation at the early stages of construction due to the challenging geological nature and difficulty of installation, for boreholes and section data collection, as one model data would not be sufficient as different condition evaluations affect each other. A group of sub-models is introduced by them (regional scale for preliminary evaluation, project scale for pre-evaluation, and outcrop scale for dynamic evaluation). Their results were significantly harmonic and

Compatible for engineering application for both theory and practice [25]. The multi-factor comprehensive risk assessment method was used for risk investigation for karst tunnels by Li and Wu (2019). In their research, they used twelve effective parameters regarding hydrological and geological conditions and construction techniques. They considered the Yichang-Wanzhou Railway Dazhiping tunnel as a case study to apply their method, which revealed high coordination with the in-situ construction conditions [26]. Mountain Tunnels' risk assessment regarding collapse hazards for Hongyansi Tunnel and Shimenya Tunnel was addressed by Wang et al. (2020). In their research, they used an artificial assigned model for creating a new dynamic risk assessment method by adapting data records for many collapse cases regarding many factors such as water table, depth, rock integrity for mass and bounded rock levels. They also used Mountain Tunnel Collapse Risk Assessment System for considering Real-Time evaluation for collapse. Their research results agreed with actual construction in a exemplary manner [27]. Wu et al. (2021) proposed a risk assessment method for spalling damage in a deep hard-rock tunnel. They evaluated three critical tasks, including risk probability estimation, loss estimation and risk level determination. Then, they proposed a theoretical and analytical equation for the spalling damage expected cost proportion. Finally, the proposed method was applied for a case study. The obtained results indicate that the proposed method could be effective and valuable for accurate risk assessment of spalling damage [28].

By studying the previous literature, the importance of examining the risk of complete tunneling projects becomes clear. Identification of risks affecting the projects of tunneling and ranking of these risks are significantly crucial in the correct implementation of tunneling projects and project management. Therefore, twelve potential risks (machinery failure, lack of machinery, design mistakes, lack of contractor's experience, squeezing, instability of wall, water inflow, face tunnel instability, swelling of rock, gas emission, construction delay, and changes of price) for the second part of Emamzadeh Hashem tunnel (one of the most significant tunneling projects in the north of Iran) are evaluated. Indeed, since mechanized tunneling project's risks have an implicit and uncertain nature, the strength of this research work is to use the FAHP approach for the analysis and assessment of tunneling project's risks.

2. Methodology

In tunneling projects as one of the most significant infrastructure projects, risks assessment has a unique position and significance due to heavy and irreparable financial and human losses. Assessment and ranking of risks are some of the most critical sections in tunneling projects' risk management. Therefore, the primary purpose of this research is to evaluate and rank the risk of tunneling projects for one of the most vital tunneling projects in the north of Iran. In addition, uncertain and unpredicted conditions in risk assessment and its full compliance with the concepts of fuzzy logic is another goal of this research. For this purpose, after collecting data from the case study, the eleven potential risks were considered for this case. Then, after receiving the opinion of experts, the data were evaluated and ranked by fuzzy hierarchical analysis.

2.1. Fuzzy analytical hierarchy process (FAHP)

In recent decades, Soft Computing (SC) approaches are considered an effective applied technique in engineering problems. A wide range of soft computing methods has been used successfully by numerous researchers [29,30,39–44,31–38]. Soft Computing, by focusing on the human mind in solving complex problems, provides the ability to respond appropriately with great flexibility. Unlike rigid computing methods, soft computing is based on the tolerance of inaccuracies and uncertainty and is widely used in many industries and sciences [45–48]. One of the significant features of these methods is to achieve the best answer at the lowest possible cost. In addition, another feature of these methods, the capability to solve uncertain and complex problems [49,50,59–61,51–58]. The fuzzy analytical hierarchy process (FAHP) is one of the multi-criteria decision-making techniques that has been applied in the engineering and academic sectors. Several researchers developed and introduced their FAHP techniques. Different research and methods about the Fuzzy Analytical Hierarchy Process were addressed by Chang (1996) [62–64]. In a fuzzy multi-criteria decision making of Chang's fuzzy analytical hierarchy process with m items and n criteria for fuzzy triangular numbers, several steps have been defined as follows:

-First step: Determining hierarchical graph

In this step, the hierarchical graph is considered for three levels according to the number of criteria and alternatives under study and the desired objective [65].

-Second step: Defining fuzzy numbers for pairwise comparisons

Fuzzy numbers are defined for conducting pairwise comparisons. These numbers can be considered as fuzzy triangular numbers or fuzzy trapezoidal numbers. It should be noted that in this study, the fuzzy triangular numbers were applied.

-Third step: Forming pairwise comparison (A) matrix with fuzzy numbers

Using experts' opinion, the pairwise comparison matrix will be formed, and the fuzzy numbers of the matrix are as follows [65]:

$$\tilde{A} = \begin{pmatrix} 1 & \tilde{a}_{12} \; \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 \; \cdots & \tilde{a}_{2n} \\ \vdots & \vdots \quad \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} \; \cdots & 1 \end{pmatrix}$$

$$\tilde{a}_{ij} = \begin{cases} 1 & \text{i=j} \\ \tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9} \text{ or } \tilde{1}^{-3},\tilde{3}^{-1},\tilde{5}^{-1},\tilde{7}^{-1},\tilde{9}^{-1} & \text{i} \neq \text{j} \end{cases}$$

-Fourth step: Calculation of Si for each row of pairwise comparison matrix

Si represents a fuzzy triangular number that is calculated based on Eq (1) [65].

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes [\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}]^{-1} \tag{1}$$

Where M_{gi}^{j} is the fuzzy triangular number of pairwise comparison matrix. i and j are the row number and column number, respectively. Then, the values of $\sum_{j-1}^{m} M_{gi}^{j}$, $\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} =$ and $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$ are calculated based on Eqs 2 and 4 [65].

$$\sum_{j-1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{2}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{3}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{m} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{4}$$

-Fifth step: Calculating the degree of possibility between two fuzzy triangular numbers (Si)

If S_1 and S_2 are the two fuzzy triangular numbers, the degree of possibility between them is computing based on Eq 5. Figure 1 represents Eq 5 that d indicates the ordinate of the highest intersection point between μs_1 and μs_2. Hence, the values of $V(S_1 \geq S_2)$ and $V(S_2 \geq S_1)$ should be calculated. Then, the degree of possibility for a fuzzy triangular number to be greater than k fuzzy triangular numbers is computed based on Eq 6 [65].

$$V(S_2 \geq S_1) = hgt(S_1 \cap S_2) = \mu s_2(d) = \begin{cases} 1 & \text{if } m_2 \geq m_2 \\ 0 & \text{if } l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & \text{otherwise} \end{cases} \tag{5}$$

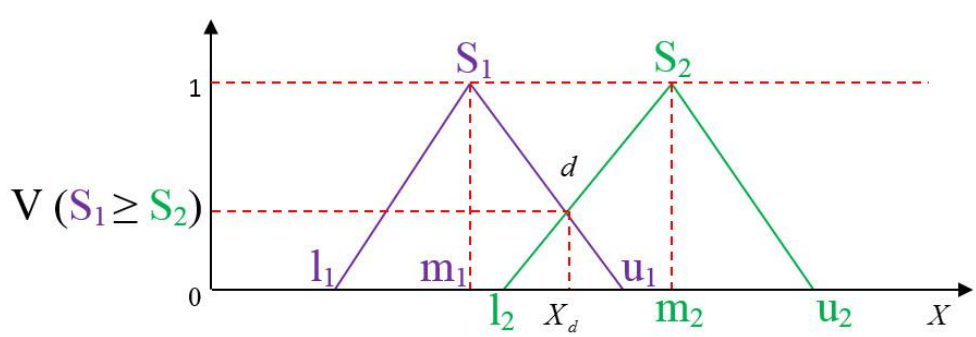


Fig. 1. The degree of possibility between two fuzzy triangular numbers (S1, S2) relative to each other.

$$V(S \geq S_1, S_2, ..., S_k) = V\left[(S \geq S_1) \text{and} (S \geq S_2) \text{and} .... \text{and} (S \geq S_k)\right] = \text{Min} V(S \geq S_i), \quad i=1,2,3,...,k \tag{6}$$

-Sixth step: Calculating Weight of Each Criterion and alternative in the pairwise comparison matrix

For determining the weight of criteria and alternatives in a pairwise comparison matrix, by assuming $d'(A_i)=\text{Min}V(S_i \geq S_k)$ for $k=1,2,...,n$, $k \neq i$, the weight vector is determined based on Eq 7 [65].

$$w'(d'(A_i),d'(A_2),...,d'(A_n))^T \tag{7}$$

-Seventh step: Computing the final weight vector

In the last step, the final normalized weight vector is computed by normalizing the weight vector based on Eq 8.

$$W=(d(A_1),d(A_2),...,d(A_n))^T \tag{8}$$

2.2. Case study

The mechanized tunneling projects are considered to be important infrastructures; hence the efficiency in projects' planning and implementation can be increased by evaluating these projects' risks. The second part of the Emamzadeh Hashem tunnel was considered a case study in this research work that is one of the most strategic tunneling projects in the north of Iran. The purpose of this tunnel is to reduce the number of road accidents and traffic. This tunnel is constructed in the northeast of Tehran, and at the boundary of Mazandaran in an entirely rocky environment, which belongs to the mountainous region of the Alborz mountain range. The total length of the tunnel is about 5.6 (km). The second part of the Emamzadeh Hashem tunnel has approximately 3.2 (km) length. The highest and lowest overburden thicknesses of the tunnel crest include 450 m and 50 m, respectively. Also, the tunnel is a circular cross-section with a 2.5 % longitudinal slope characterized by an excavation radius of approximately 12.27 m [66,67]. The location and the lithologies of the region under study are shown in Figure 2. There are seven formations from the beginning of excavation to the end of the tunnel, including the Durood Formation (H-3), the Mobarak Formation (H-16), the Ruth Formation (H-16), the Shear Tuff and Lava Eocene (H-4), the Dacite tuff of Eocene (H-1), the Elika Formation (H-11), and the Baroot Formation (H-15). The results obtained from field and laboratory tests for properties of rock and lithology types are indicated in Table 1 [68].

Table 1
Types of lithology and characteristics of rock.

Section Name	Lithology	Length (m)	UCS (Mpa)	RMR	Q	Density (gr/cm^3)	Average Groundwater Table (m)
H-4	Shear Tuff and Lava Eocene	130	35	19	0.02	2.6	35
H-1	Dacite Tuff of Eocene	600	55	43	0.49	2.6	125
H-3	Durood Formation	520	120	63	9	2.6	265
H-16	Mobarak Formation	140	75	55	1.95	2.6	270
H-2	Ruteh Formation	1020	110	59	8	2.6	195
H-11	Elika Formation	180	40	44	2.52	2.6	70
H-15	Baroot Formation	130	30	50	2	2.6	25

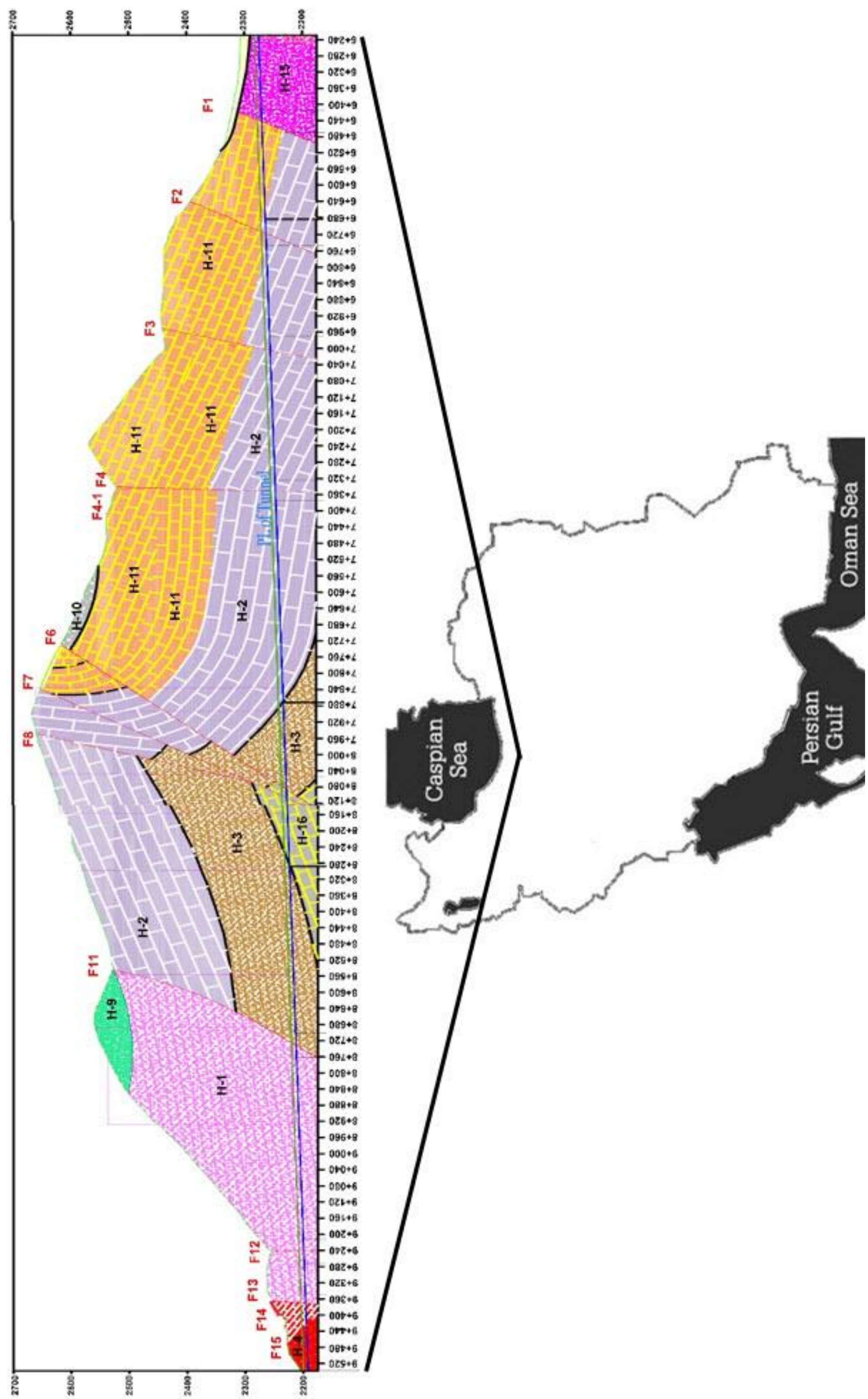


Fig. 2. The location and longitudinal profile of the Tunnel.

3. Modelling and discussion

To assess the risks of the tunneling project, a set of more than thirty possible risks was considered by a team of experts. Then, considering the initial investigation of the project's conditions, the twelve potential risks were assigned for the second part of Emamzadeh Hashem tunnel in the north of Iran based on experts' opinions. The potential risks and sources of risks for this tunneling project are shown in Table 2. Also, three decision variables including repeat chance (C1), occurrence possibility (C2), and efficacy (C3) were considered in this study. Figure 3 shows the hierarchical structure of the problem.

Table 2
Potential risks and risks' sources of the second part of Emamzadeh Hashem tunnel.

Sources of Risks	**Potential risks**	**Number of Risks**
Technical and Accidental Risks	Machinery failure	R_1
	Lack of machinery	R_2
	Design mistakes	R_3
	Lack of contractor experiences	R_4
Geological Risks	Squeezing	R_5
	Instability of wall	R_6
	Water inflow	R_7
	Face tunnel instability	R_8
	Swelling of rock	R_9
	Gas emission	R_{10}
Project Estimations	Construction delay	R_{11}
	Changes of price	R_{12}

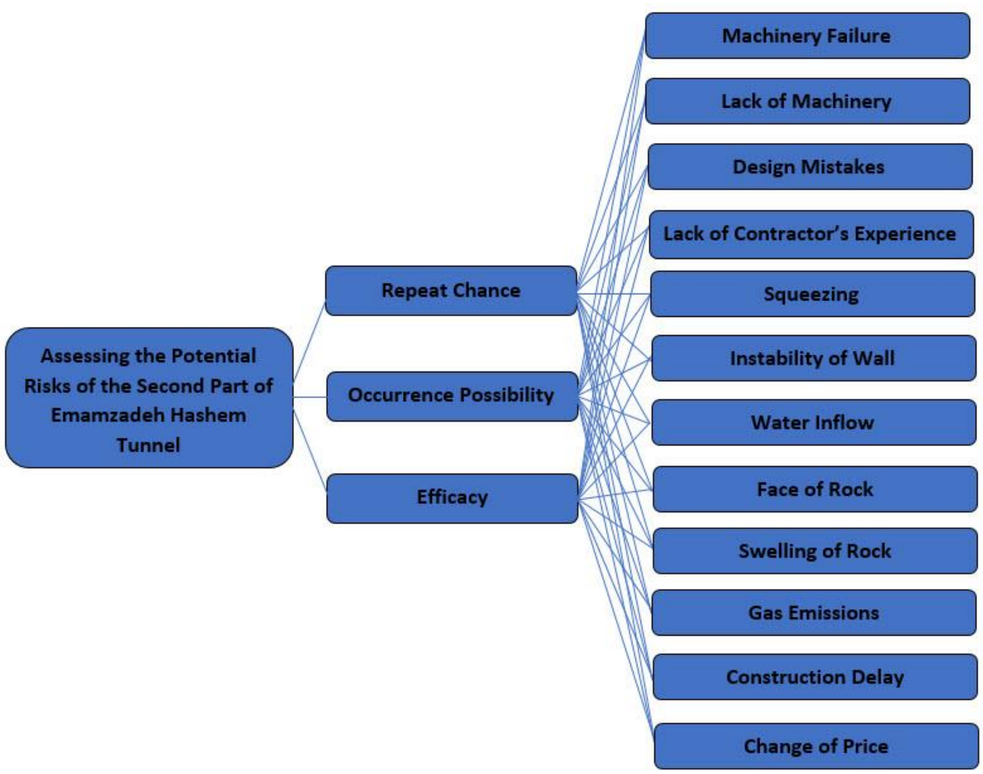


Fig. 3. The hierarchical structure of study**.**

Once the twelve potential risks and three decision variables have been identified, a pairwise comparison matrix for the three decision variables was developed and completed by a team of experts after several meetings and consultations like brainstorming. Also, three pairwise comparison matrices for twelve risks were formed based on three decision variables and completed by experts. It should be noted that the experts used fuzzy triangular numbers based on Table 3 where values are varying in a scale from 1 to 9 in an ascending manner of the importance level for completing the pairwise comparison matrices of decision variables and criteria (twelve potential risks) [69].

Table 3
Fuzzy number and Triangular fuzzy scale for ranking.

Triangular fuzzy scale	Fuzzy number	Triangular fuzzy scale	Fuzzy number
$(1,1,1)$	$\tilde{1}$	$(1,1,1)$	$\tilde{1}^{-1}$
$(1,2,4)$	$\tilde{2}$	$(\frac{1}{4},\frac{1}{2},1)$	$\tilde{2}^{-1}$
$(1,3,5)$	$\tilde{3}$	$(\frac{1}{5},\frac{1}{3},1)$	$\tilde{3}^{-1}$
$(2,4,6)$	$\tilde{4}$	$(\frac{1}{6},\frac{1}{4},\frac{1}{2})$	$\tilde{4}^{-1}$
$(3,5,7)$	$\tilde{5}$	$(\frac{1}{7},\frac{1}{5},\frac{1}{3})$	$\tilde{5}^{-1}$
$(4,6,8)$	$\tilde{6}$	$(\frac{1}{8},\frac{1}{6},\frac{1}{4})$	$\tilde{6}^{-1}$
$(5,7,9)$	$\tilde{7}$	$(\frac{1}{9},\frac{1}{7},\frac{1}{5})$	$\tilde{7}^{-1}$
$(6,8,10)$	$\tilde{8}$	$(\frac{1}{10},\frac{1}{8},\frac{1}{6})$	$\tilde{8}^{-1}$
$(7,9,11)$	$\tilde{9}$	$(\frac{1}{11},\frac{1}{9},\frac{1}{7})$	$\tilde{9}^{-1}$

After forming the pairwise comparison matrices, based on the relationships of 1 to 8, the weight of each decision variable was calculated, and the obtained weights were normalized according to Figure 4.

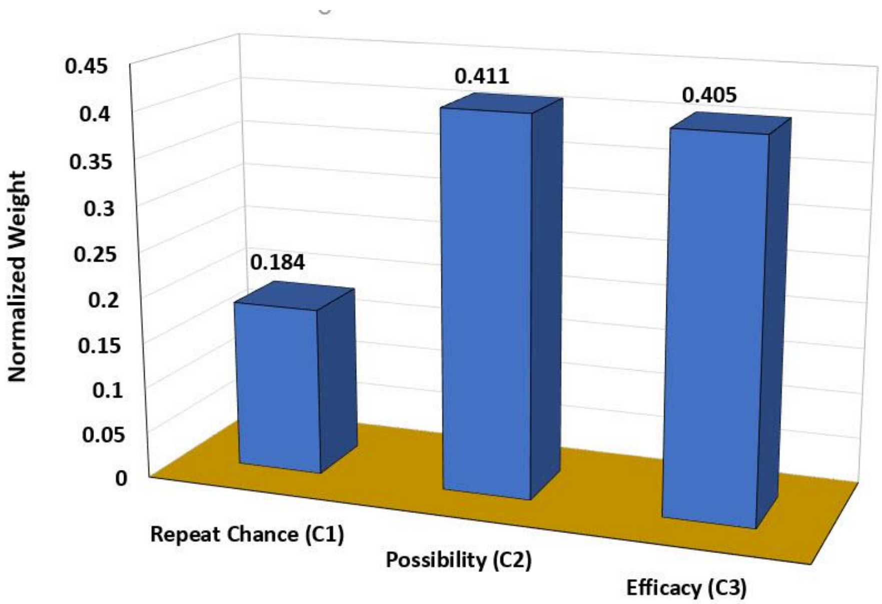
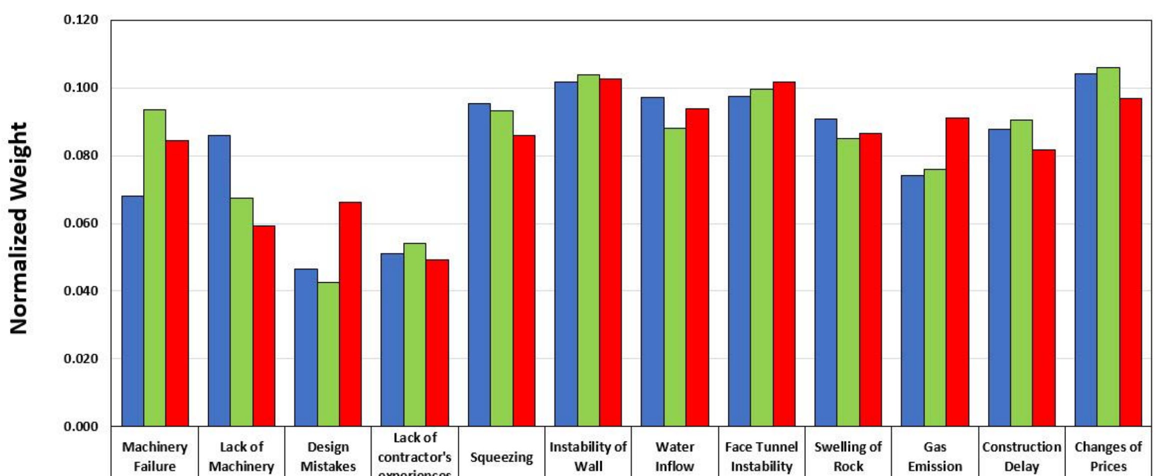


Fig. 4. The normalized values of each decision variable.

Based on the results, occurrence possibility (C2) had the highest weight among the decision variables with a weight of 0.411, then efficacy (C3) with a weight of 0.405 achieved the second position in terms of impact on the examined risks. In the end, repeat chance (C1) has most minor importance in terms of influencing the risks under consideration. Furthermore, all calculations for pairwise comparison matrices formed for 12 risks were performed based on each decision variable, and the results are shown in Figure 5.



	Machinery Failure	Lack of Machinery	Design Mistakes	Lack of contractor's experiences	Squeezing	Instability of Wall	Water Inflow	Face Tunnel Instability	Swelling of Rock	Gas Emission	Construction Delay	Changes of Prices
Repeat Chance (C1)	0.068	0.086	0.047	0.051	0.095	0.102	0.097	0.098	0.091	0.074	0.088	0.104
Occurrence Possibility (C2)	0.094	0.068	0.042	0.054	0.093	0.104	0.088	0.100	0.085	0.076	0.091	0.106
Efficacy (C3)	0.085	0.059	0.066	0.049	0.086	0.102	0.094	0.102	0.087	0.091	0.082	0.097

Fig. 5. The values of the normalized weight of twelve risks based on three decision variables.

In the first category (Technical and Accidental Risks), there are the four risks including Machineries failure, Lack of machinery, Design mistakes, and Lack of contractor's experiences. According to the obtained results, it is clear that these four risks weighed less among the twelve potential risks based on three decision variables, which indicates the low importance of the risks of this category compared to other risks were this research. Overall, given the weights obtained from the calculations, Machinery failure is a more critical risk among these four risks. Machinery failure also gained the highest weight in possibility (C2), equals to 0.094, and it could achieve the following weight in efficacy and repeat chance in descending order, respectively. In addition, the results of the calculations showed that the contractor's experience was able to obtain almost equal weights based on the three decision variables. In the second category (Geological Risks), there were six risks which is the number of risks in this category compared to the number of risks in other categories, geological risks are of great importance in the process of risk management in this project. At first glance, Figure 5 shows that all six risks in this category have relatively high weights in all three decision variables. Among the six risks in this category, Face tunnel instability and Instability of the wall have more weight than the others. According to the type of soil characteristics and formations in the tunnel route using Table 1, the results are in good agreement with the realities of the project. In the last category, R11 and R12 achieved the highest weights based on the probability, and then they gained subsequent weights based on repeat chance and efficacy. It is also clear that Changes in prices gained the most weight based on all three decision variables compared to Construction delay, indicating the importance of this risk in the category of project estimations. This result was quite reasonable given the economic conditions.

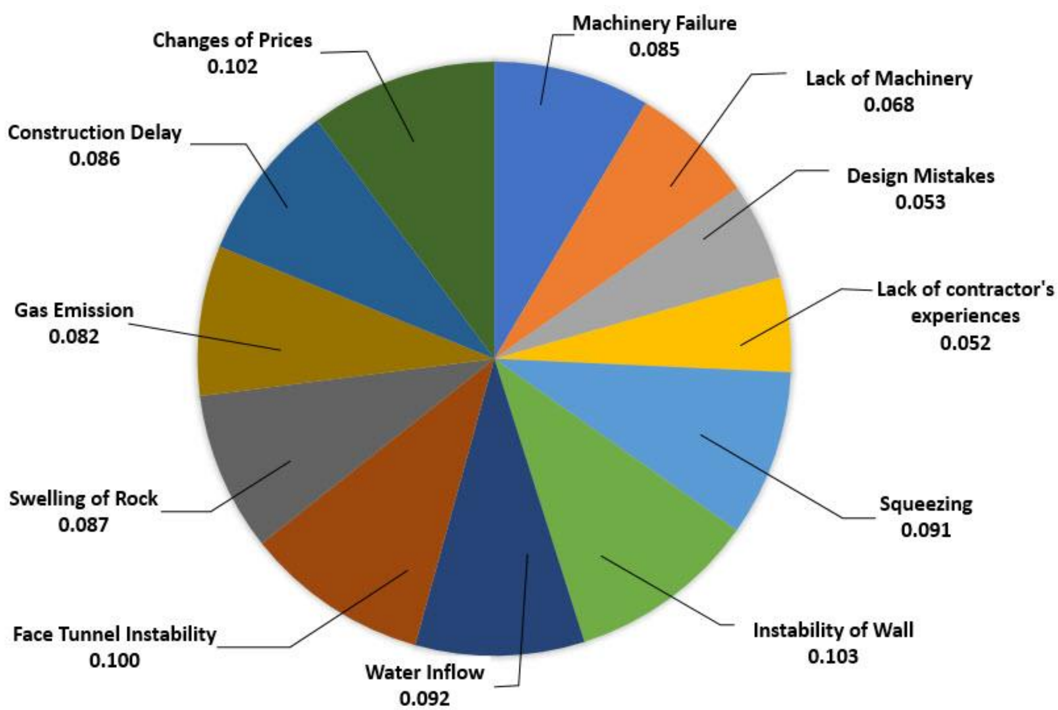


Fig. 6. The final rank of the twelve risks.

A final rank of the twelve risks is illustrated in Figure 6. The value of each risk calculated is normalized due to the total risk summation. The value for each risk is inserted by the weight of its effect on each decision variable from repeat chance (C1), occurrence possibility (C2), and Efficacy (C3). A value of 0.103 is obtained by the Instability of the wall to be ranked as the first potential risk. On the other hand, the lack of contractor-s experiences is the least to be considered in the list of potential risks. The other three potential risks were directly ordered after the wall instability in the list of potential risks, which are changes of prices, Face tunnel instability and water flow with the values of 0.102,0.100 and 0.092 by order.

A good match between the conditions in the project and the results obtained from the calculations and ranking of the risks clearly showed that the FAHP is a reliable system modeling approach for assessing and ranking risks with highly acceptable degrees of precision and robustness. It should be noted that the calculated values for each risk and their ranking are unique, and they are only applicable to this project and cannot be used for other projects. In addition, the most important limitation of this method is choosing the right team of experts who have the necessary experience and ability to diagnose and understand the problems.

4. Conclusions

Risk assessment of infrastructure projects is an imperative part of project management. Tunneling projects are considered substantial infrastructure projects, so the risk assessment of tunneling projects has a special place in the proper project management of tunneling. Therefore, due to the issue’s importance, the FAHP approach was applied to investigate and rank the potential risks of tunnel construction in this study. The second part of the Emamzadeh Hashem tunnel in the north of Iran was considered as a case study, which is one of the most important tunneling projects in the north of Iran. The twelve potential risks, including machinery failure, lack of machinery, design mistakes, lack of experiences of contractor, squeezing, instability of wall, water inflow, face tunnel instability, swelling of rock, gas emission, construction delay, and changes of price, have been considered for this project based on experts' opinions. In addition, repeat chance, occurrence possibility, and efficacy were considered as the three decision variables. After analysis, the results showed that instability of wall and changes of price were the first and second potential risks in this project by 0.103 and 0.102, respectively. Also demonstrated that, lack of contractor experiences had the lowest ranking by 0.52 among the twelve potential risks in this tunneling project. The results obtained had very high compliance concerning the geological conditions of the project and market conditions in Iran. For future work, it is recommended to see the performances of other fuzzy multi-criteria decision-making approaches for evaluation of mechanized tunneling project risks.

Acknowledgments

We would like to express our deepest thanks to Mahdi Ghaem for his excellent advice.

Funding

This research received no external funding.

Conflicts of Interest

All authors have read and agree to the published version of the manuscript. The authors declare no conflict of interest.

Authors Contribution statement

The author's contributions in the paper are as follows: conceptualization, S.S.H., and R.M.; methodology, S.S.H., S.S.H., and S.Z.; formal analysis, S.S.H., S.S.H., S.Z. and M.A.A.; investigation, S.S.H., and M.A.A.; writing—original draft preparation, B.P., and S.S.H.; writing—review and editing, S.S.H., S.S.H., S.Z. and M.A.A.; supervision: S.S.H., and R.M.

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