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# Risk assessment of construction projects for water conveyance tunnels using fuzzy fault tree analysis

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***Abstract***

*In the water industry, tunnels can be used to transfer water from a basin to other areas over varying distances. Construction of such tunnels is inherently risky and can result in unpredicted events and incidents. It is therefore necessary that thorough risk assessments be carried out as a priority of the owner, contractor, and consultant organization. This is so that, through a systematic and logical plan, they can evaluate risk posed by these unforeseen events and incidents. In this paper, the risks and their main causes, which are often encountered in such projects, are identified and assessed. A fault tree method is applied in order to identify the main causes of events and incidents. By its nature, a risk assessment cannot be defined by absolute values, and so fuzzy data can be used in order to calculate the possibility of incidence and the severity of the risk. This is done on the four main criteria of time, cost, quality, and safety. Analytic Hierarchy Process (AHP) is applied in order to estimate the significance of each criterion and to calculate the significance of the total influence of risk. In this paper, the case study of Dasht-e Zahab water conveyance tunnel has been selected for discussion as it was subjected to severe and multiple hazards. Results obtained using the method was validated by conducting different interviews with field experts. It was concluded that by applying the proposed methodology on the case study, the risks of the project could be evaluated in a more methodical and accurate way than what could be done without using the method. This approach is therefore recommended for similar types of projects where there are complicated risks that should be thoroughly investigated and understood.*

***Keywords:*** *Risk assessment, Water transfer tunnels, Fault tree, Fuzzy logic, Analytical hierarchy process.*

## 1. Introduction

Due to high water demand, the transfer of water from the mountainous regions of Iran to agricultural zones is a priority. The average annual rainfall in Iran is 250 mm and approximately 90% of the country is arid or semiarid. Overall, about two-thirds of the country receives less than 250 mm of rainfall per year [1], with the remaining areas receiving much more.

Problems arising from water shortages in the central plateau of Iran, driven by high demand from industry, agriculture, and supplying potable water, have led government officials to contemplate transferring water from the remote wetter areas to the more populated dryer areas. Water shortages have become such an issue that these schemes are being considered despite high operational and construction costs. Considering the existing population and its growth rate, new water sources are required to satisfy the demand for water. One approach that is currently carried out in Iran is to construct a dam in a mountainous area to store the water and transfer the stored water to the areas with higher demand. In some cases, ([2-4]) very long tunnels are used to shorten the distance of transmission through difficult terrain.

The process of constructing tunnels imposes risks on all parties involved in such projects [5]. These risks may have a significant impact on tunneling operations requiring additional work resulting in major cost and time overruns. To reduce the impact of such problems, managers should manage risks. Risk management involves identification, evaluation, and control of identified risks. Risk assessment can help managers rank and reduce the existing risks [6]. There are various techniques for analyzing risks. These include fuzzy set [7–28], fault trees [29–36], event trees [37–41], failure mode and effect analysis [42–48], game theory [49,50], Monte Carlo simulation [51–59], multi criteria verbal analysis [60], and grey systems [61,62].

Due to the importance of investigating risks in underground construction, numerous researches have been performed for risk evaluation and assessment in this unique environment. Many of these researches used a

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conventional risk analysis approach in which a risk factor is calculated based on generic probability and severity of each risk item [63-70]. In some studies, earth movement estimation and the damage to adjacent buildings and utilities were investigated using complex models and softwares [71-76]. In addition to this, some researchers proposed specific indices such as the standard safety level for risk assessment of tunneling projects [77-80]. Decision tree analysis and event tree analysis have also been used in some projects [40, 81].

Each of these methods has advantages over other methods; however, none of them can investigate the root causes of risks. Conducting root cause analysis can assist managers to find critical points and prepare proactive risk response strategies in order to minimize critical root causes. Fault Tree Analysis (FTA) was therefore applied in risk assessments for tunneling projects [32, 36]. Application of conventional FTA has some shortcomings. These include vagueness, absence of accurate data, and uncertainty. When accurate data is not available, the experiences of field experts provide an effective database to support the rough estimation of the required data (failure rate and probability). Human judgment by linguistic variables becomes an essential part of the process. For this reason, the use of fuzzy set theory has been proposed by many researchers to overcome the limitation of conventional FTA [82].

In this paper, FFTA is applied to identify the main causes of risk incidence, and display them. Due to existing uncertainty of linguistic terms, risk assessment is of a fuzzy nature, so fuzzy data are used to calculate the probability of incidence, and severity of the risk on the criteria of time, cost, quality, and safety. In order to calculate the degree of significance of each criterion and to calculate the significance of the total influence of risk, the severity of risk of each factor must be combined. This was carried out using Analytic Hierarchy Process (AHP). At the end of this paper, a case study of water conveyance tunnel drilled by a tunnel-boring machine was used to illustrate the approach.

The remainder of this paper is organized as follows: The methodology used and tools applied in the work (such as fault tree analysis and fuzzy calculations of it, AHP etc.) are explained in Section 2. In Section 3, a case study (Dasht-e Zahab Water Conveyance Tunnel) is described and the proposed methodology is summarized. A real world case study using the proposed model is implemented in order to illustrate its potential applications in water conveyance tunneling projects. Finally, results and conclusions are discussed in Section 4.

## 2. Methodology

In this paper, a risk assessment model based on Fuzzy Fault Tree Analysis (FFTA) and Analytic Hierarchy Process (AHP) is proposed. Fig. (1) shows the proposed methodology for carrying out risk assessments in construction projects. It consists of the following stages:

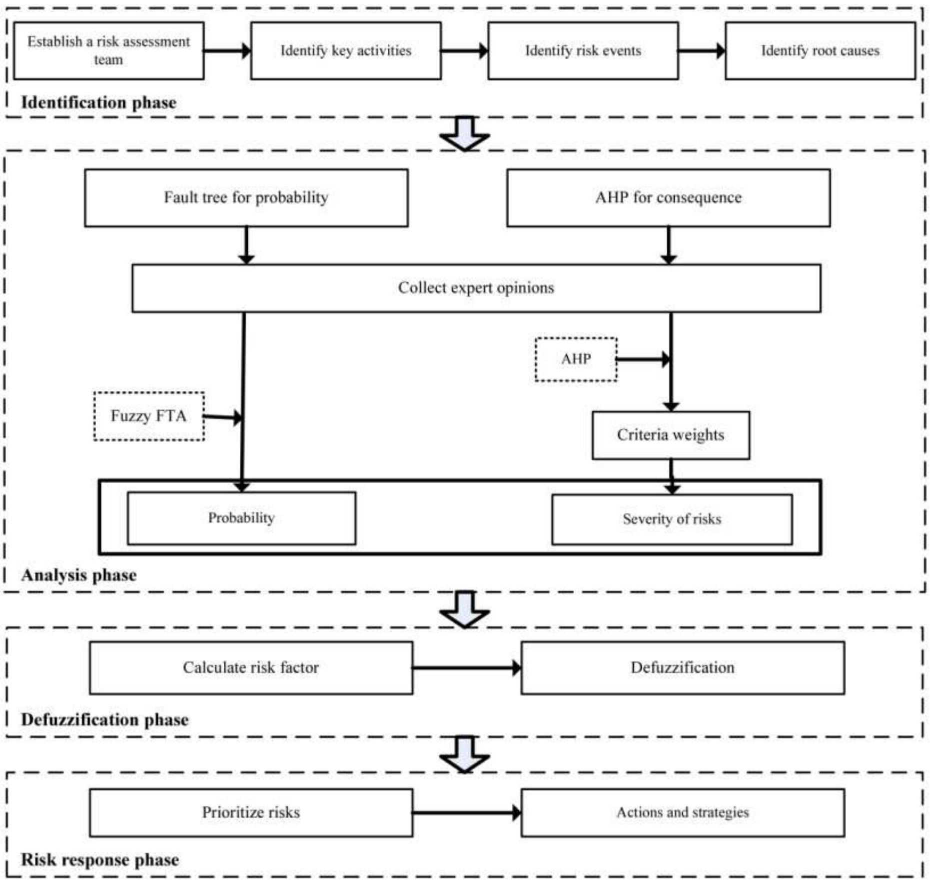



**Fig. 1** Flowchart of the proposed approach

First, a risk assessment group composed of experts, consultants, and supervising engineers of water conveyance tunnel construction projects should be formed. The main tasks of the projects and their risks are identified and validated. Thereafter, the events of each risk, original causes of the events, and the impact of each risk are identified and discussed by the group. At the end of this stage, a list of risks and their causes can be drawn up in the form of fault trees.

The risks identified in the first stage are then analyzed according to the fuzzy FTA method. First, a hierarchical structure is established for risks, criteria and the causes of undesirable events. Then, a questionnaire is prepared for fault trees and the impact of each of the risks in terms of linguistic variables (very low, low, medium, high, and very high). These are then completed by experts, supervisors, and contractors. The occurrence probabilities of different risk items can then be calculated using FFTA. The impact of each risk together with the accumulative impact of risk on four criteria including time, cost, quality, and safety will also be calculated using AHP.

By using α-cut method, risk factors will be obtained. The final stage is to defuzzify these risk factors. Finally, the risks are prioritized according to risk factors. Actions for those risks that have a greater priority will be taken, and preventive course of actions will be suggested.

In the following subsections, the tools used in the methodology detailed above are described.

### *2.1. Fault tree analysis*

This method was initially developed in Bell's telephone laboratory in 1960-1961, and it was adapted to be used in the assessment of risks by the Boeing Company. Fault Tree Analysis has been used in different industries such as aerospace, nuclear, and chemical industries since 1965. It has been widely used for analysis of reliability and the safety of systems. This method has been frequently used for analysis of events and the distinction of the relationship between the cause of events and their logic [83]. Fault tree analysis is particularly useful in functional paths of high complexity in which the outcome of one or more combinations of noncritical events may produce an undesirable critical event. Typical candidates for fault tree analysis are functional paths or interfaces, which could have critical impact on flight safety, munitions handling safety, safety of operating, and maintenance personnel. The fault tree provides a concise and orderly description of the various combinations of possible occurrences within the system, which can result in a predetermined critical output event. Performance of the fault tree analysis does require considerable engineering time, but it is important to note that the quality of results is only as good as the validity of input data and accuracy of the fault tree logic [84].

Fault tree analysis can provide valuable information to decision-makers. Some of its advantages are as follows [85]:

(1) Fault trees provide visual representation to communicate the logic behind the occurrence of top events (i.e. risk events). This information can be used more effectively by the project team as a way to communicate risk.

(2) Fault trees can be utilized as a proactive tool to help create proactive response strategies. By understanding the logic behind each risk event, proactive response strategies can be designed to control those root causes at early stages before occurrence of risk events.

(3) Fault tree analysis and importance analysis provide valuable information to risk analysts by allowing prioritization of the contribution of events to the occurrence of the top event. Using such an approach, the project team can work on establishing proactive risk response strategies to minimize critical root causes.

(4) Fault trees can be used to conduct root cause investigation after the realization of any risk event. By analyzing the logic between different root causes, decision-makers can understand why a risk event is realized.

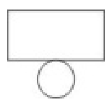
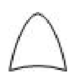
(5) Fault trees are sufficiently flexible to model any system and to help analyze the effect of change of one or more basic events on the probability of failure of the top event.

Based on previous works ([86-88]), different steps in a fault tree analysis are described as follows [89]:

1. Knowledge accumulation about the process system and process operation using process block diagram;
2. Identification of system hazard or undesired top-event by analyzing hazard scenarios for a process;
3. Fault tree construction for a process facility;
4. Estimating or collecting failure probability data for all basic events;
5. Qualitative and quantitative evaluation of a developed fault tree;
6. Sensitivity analysis or importance analysis of a fault tree, and
7. Re-evaluation of the fault tree for corresponding changes in the tree.

Special symbols are used when risks are analyzed using Fault Tree Analysis. The symbols used in this paper are shown in Table 1.

**Table 1** Symbols used in Fault Tree Analysis [90]

| | | |
|---|---|---|
| The event is placed in the most top of the fault and the related causes are identified and analyzed | Top event |  |
| A basic initiating fault requiring no further development | Basic event |  |
| Output fault occurs if at least one of the input faults occurs | OR gate |  |

In the present study, a list of risks and their causes are identified with the help of the risk assessment group. Then, a fault tree is drawn for each of the identified risks, and the occurrence probabilities of basic events are obtained using a questionnaire survey in terms of linguistic variables. The probability of each top event is then obtained based on fuzzy calculations of fault tree described in the following subsection.

*2.2. Fuzzy calculations of fault tree*

Since an analyzer is forced to think accurately and deeply about the system, therefore, drawing a fault tree is of great importance. However, when the fault tree becomes quantitative, it will be more functional and useful as a decision making tool. Fault Trees can be made quantitative through allocation of a rate of fault or fault probability to each basic event and calculation of the resulting fault rate of the system [85].

In the case of quantitative analysis of fault trees, the incidence probability values for all basic events must be found. In this paper, data relating to water conveyance tunnels was collected by a questionnaire survey. To interpret the data as expressed in terms of very low, low, medium, high, and very high incidence possibilities, it was necessary for these terms to be converted into fuzzy numbers. The conversion was made through attribution of trapezoidal fuzzy numbers as shown in Fig. (2). The fuzzy number counterparts of the linguistic expressions of very low, low, medium, high, and very high can be used for calculations and conducting quantitative analysis. We allow the respondents to our questionnaire to enter their responses using linguistic terms rather than exact occurrence rates as this can be a very difficult task indeed. The risk can be analyzed quantitatively by converting these expressions into fuzzy numbers. Each linguistic term is represented by its alpha-cuts. The α-cut of a fuzzy set is a crisp set containing the members whose membership functions are greater than or equal to α. The α-cut representation of fuzzy sets introduces an important connection between crisp sets and fuzzy sets and allows us to extend the various properties of classical crisp sets to fuzzy sets. Each trapezoidal fuzzy number can be displayed as [a b c d] where a represents the minimum value, b and c represent the most likely values, and d represents the maximum value. These numbers are applied for evaluations [91].

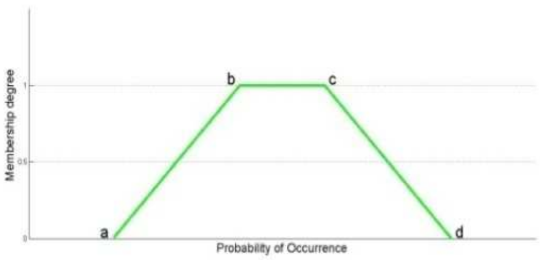



**Fig. 2** A sample of Trapezoidal Fuzzy Number

To make quantitative calculations of the gates and events (described in Table 1), the following equations are applied. The output value of "OR" gate is given by the following equation [92]:

$$\text{FPro}_T\ (\text{top event})^{\alpha} = \{1-\prod_{i=1}^{n} [1-(a_i+(b_i-a_i)\alpha)],\ 1-\prod_{i=1}^{n} [d_i-(d_i-c_i)\alpha]\} \quad (1)$$

where n is the number of cut sets connected by "OR", and FPro is the fuzzy probability.

Output value of "AND" gate is given by the following equation [92].

$$\text{FPro}^T\ (\text{top event})^{\alpha} = \{\prod_{i=1}^{n} [a_i+(b_i-a_i)\alpha],\ \prod_{i=1}^{n} [d_i-(d_i-c_i)\alpha]\} \quad (2)$$

*2.3. Analytical hierarchy process (AHP)*

Analytical Hierarchy Process was initially introduced in 1980 by Thomas EL Saaty [93]. This process is a multi-criterion decision-making approach that uses a method of multiple paired comparisons to rank order alternative solutions to a problem, formulated in hierarchical terms [94].

If n criteria are determined for comparison, AHP performs the following steps to calculate the weight of these criteria [95]:

(a) Create (n×n) pairwise comparison matrix A for n objectives;

(b) Divide each value in column j by the total of the values in column j. The total of the values in each column of the new matrix must be one;

(c) In AHP, the values of $c_i$ are calculated by finding the principal eigenvector of the matrix A. Calculate $c_i$ as the average of the values in row i of the $A_W$ matrix to yield the column vector C where $c_i$ value shows the weight of the ith objective, and (d) Check consistency of the weight values ($c_i$).

## 3. Case Study

The water conveyance tunnel of Dasht-e Zahab is a part of a larger project for transferring water from Dasht-e Zahab to Iran's southwestern regions. The plan aims to bring much needed water for irrigation to Khuzestan's agricultural fields. The overall length of the Dasht-e Zahab water transferring pipeline is approximately 460 Km. Given the high mountains and undulating terrain it is thought necessary to construct a tunnel from the beginning point (Sirvan River) to Dasht-e Ozgoleh as part of the scheme. [96].

The proposed water conveyance tunnel of Dasht-e Zahab has a cross sectional area of 52.35 m2 and length of 48 Km. Once constructed, it will be able to transfer 70 m3/s of water. According to technical and economic studies, the two-shield mechanized drilling method will be applied for drilling the second part of the tunnel with a length of 25,741 m. As we know, cost is often considered to be the most important criteria for accepting or rejecting engineering projects. Cost is in turn a function of any other factors such as labor, materials consumed, and time required for performing the project [97]. In terms of geological classifications of Iran, the site of the project is situated in the fields of high Zagros and folded Zagros mountains. In the area of the tunnel entrance (Leileh river) to a short distance after the Zimkan river, a rough topography, deep valleys, and compressed and reclined folds (faults) are present making the terrain very complicated indeed [98].

In general, two different types of TBMs are used depending on the expected ground conditions for constructing tunnels. These are open type machines, and closed type machines. Open type machines can be used in ground conditions where the face of the excavation is self-standing.

• Gripper TBM

Gripper TBMs are open-type machines, which can be used in rocks where the face of the tunnel is self-standing. The advance rate of a Gripper TBM depends on the time required to install rock support devices such as steel ribs, rock anchors, meshes, and shotcrete.

• Single Shield TBM

Single Shield TBMs are field machines without a closed system for pressure compensation at the tunnel face, and can be used where the breast is self-standing. The support will be obtained via a segment lining. Single Shield TBMs have a very wide range of applications from hard to brittle or soft rock.

• Double Shield TBM

Double Shield TBMs combine the Gripper principle and the installation of the segments in one coordinated process. Therefore, they are technically very sophisticated machines. They can also be adapted to particular ground conditions. Double Shield TBMs are thus ideally suited for drilling long tunnels in hard rock where geological fault zones occur [99].

In this regard, to select the type of boring machine for Dasht-e Zahab tunnel, several factors were considered. These included the geomechanical properties of the tunnel's path, water absorption through the tunnel walls, overburden height of the tunnel, hardness and erosion, single-axle compression strength, single-axle tensile strength, engineering classification, the existence of faults and cracks, and the condition of groundwater in the tunnel route.

Similar projects include the water tunnel to Kerman, water tunnel from Roozieh spring to Semnan, and water tunnel of Sabzh Kuh. Based on these projects, 18 risks were identified, and different possible fault trees related to the risks of the construction of the water tunnel of Dasht-e Zahab were drawn. In the following section, a sample fault tree related to risk of low advance rate during construction of the tunnel using TBM is provided.

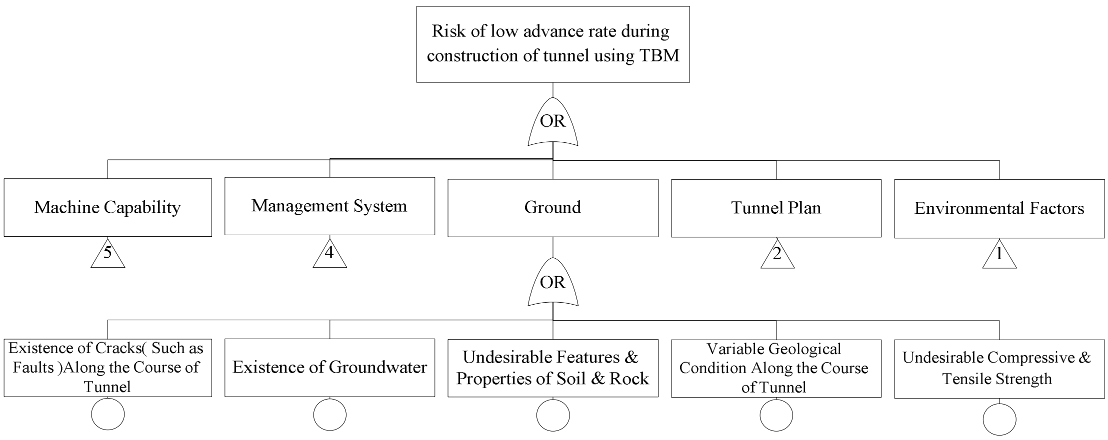



**Fig. 3** a- Fault tree of risk of low advance rate during construction of tunnel using TBM

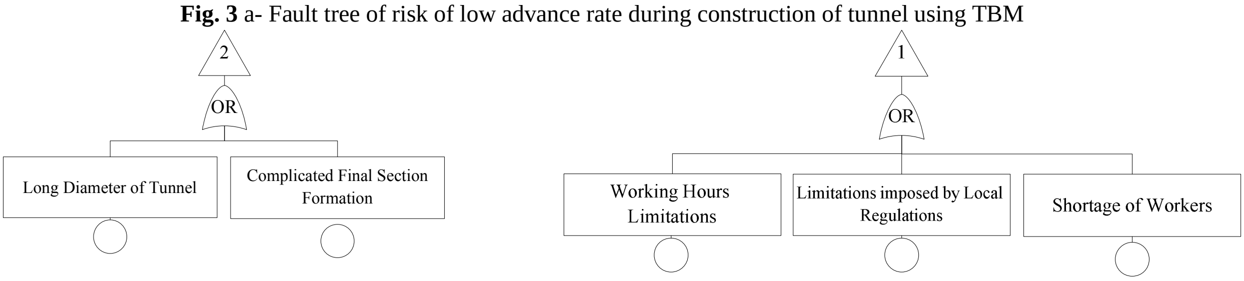



**Fig. 3** b- Subtrees 1 and 2 of fault tree presented in Fig. 3-a

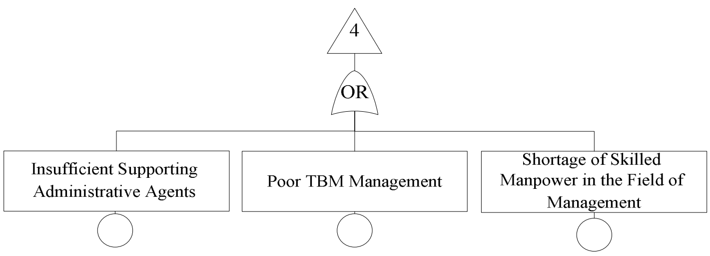



**Fig. 3** -c- Subtree 4 of fault tree presented in Fig. 3-a

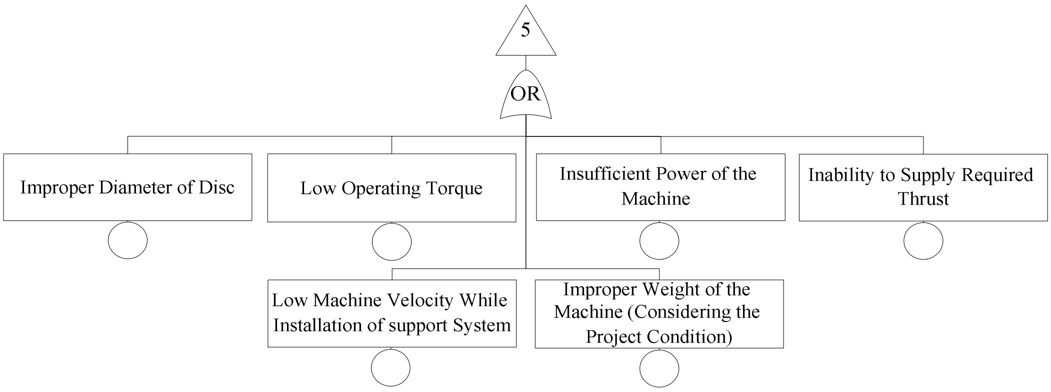



**Fig. 3** -d- Subtree 5 of fault tree presented in Fig. 3-a

To gather the required information, a closed structured non-disguised type of questionnaire in terms of linguistic variables (very low, low, medium, high, and very high) was prepared (a sample can be found in Appendix A). This was distributed among the experts, supervisors, and contractors of Dasht-e Zahab water conveyance tunnel project. In order to carry out our study, 50 questionnaires were distributed, of which, 42 questionnaires were returned, giving a response rate of 84%.

As was described in the methodology section, expressions obtained for incidence probability of each basic event were substituted by their corresponding fuzzy numbers. Following this, the formulas shown earlier in this paper were used in order to quantitatively assess the risk. In this paper, we have calculated a fuzzy number after completion of calculations for the incidence probability of the risk of low advance rate. The incidence probability of risk of low advance rate of TBM is shown in Fig. (4) and the Fuzzy numbers proportional to the severity of the main risks on the criteria of time, cost, quality, and safety are shown in Fig. (5).

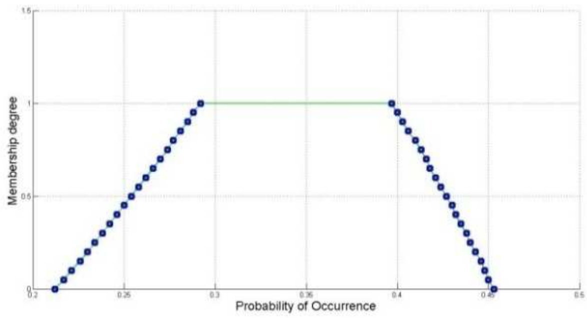



**Fig. 4** Incidence probability of risk of low advance rate of TBM

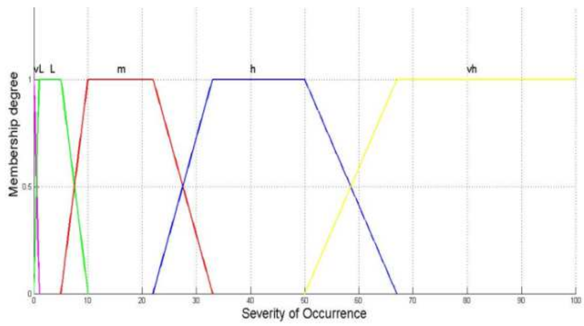



**Fig. 5** Fuzzy numbers proportional to the severity of the main risks on the criteria of time, cost, quality, and safety

At this point, the severity of this risk on the main objects of the project (including time, cost and quality) as well as other important factors such as safety can be considered. To do so, based on the gathered information using questionnaires, the effects of each risk were identified on four parameters as described above. Then, using the Analytical Hierarchy Process (AHP) technique, the weight of each of these factors was calculated. The weights calculated for the criteria of time, cost, safety, and quality were 0.21, 0.28, 0.24, and 0.27, respectively, and the rate of incompatibility was 0.022. Since, the rate of incompatibility was found to be less than 0.1, the numbers as obtained for the criteria can be accepted as correct, and the responses made by the individuals indicate good compatibility with group judgment. These figures can therefore be applied as coefficients for the next stages of the calculations [100]. These weights were therefore used to calculate total severity, which is the product of the integration of the effect of risks on the criteria. The fuzzy numbers proportional to the severity of the main risks on the criteria of time, cost, quality, and safety are shown in Fig. (5). In order to calculate the incidence probability and severity of the risks using data as provided in the questionnaires, the service record of those who have filled them was taken into account. Weight averaging was carried out based on the service record of each respondent. The responses made by the respondents who had longer service records were given higher weightings. Fuzzy numbers proportional to the severity of low advance rate of TBM on cost, time, quality, and safety are shown in Fig. (6) to Fig. (9).

Integration of these two parameters for each of the risks is the last step in risk assessment. In order to find the risk factor, Equation 3 was applied, where P stands for "risk incidence probability" and C is the "consequence of risk" on the objects of the project, respectively [101].

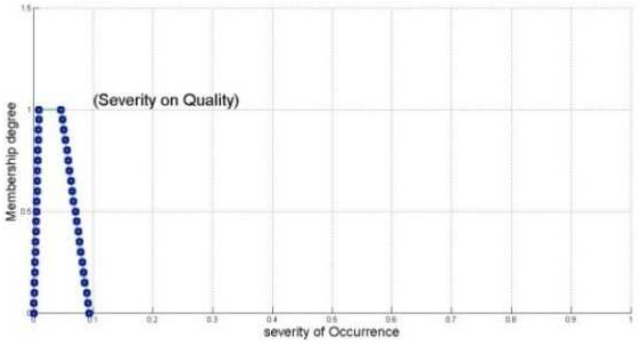



**Fig. 6** Fuzzy number proportional to the severity of low advance rate of TBM on quality

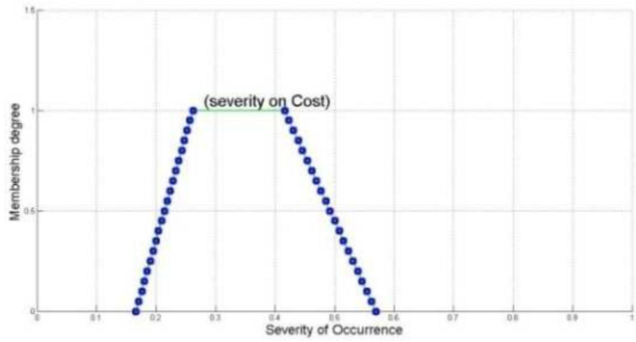



**Fig. 7** Fuzzy number proportional to the severity of low advance rate of TBM on cost

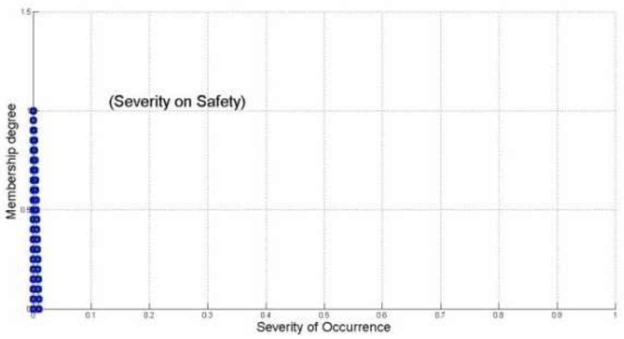



**Fig.** 8 Fuzzy number proportional to the severity of low advance rate of TBM on safety

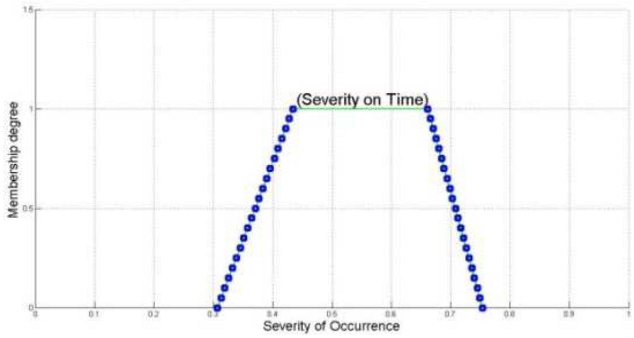



**Fig.** 9 Fuzzy number proportional to the severity of low advance rate of TBM on time

Risk Factor = (P+C)-P×C (3)

This is done through calculation of trapezoidal fuzzy number in which we employ the concept of α-cut. Through the concept of α-cuts derived from fuzzy numbers with membership function of μ (x), a definite subset of $\alpha_A$ is defined in the reference set of X, which is called α section for set A. In other words:

$$\alpha_A = \{ x \in X \mid A(x) \geq \alpha \} \quad (4)$$

For each $\alpha \in [0,1]$, this equation indicates that the α section is belonging to a fuzzy set such as A, and it is a definite set of $\alpha_A$, which includes all elements of A, which are greater or equal to the given value of α. For a trapezoidal fuzzy number [a b c d] we have:

Upper Bound= a+(b-a)* $\alpha$ (5)
Lower Bound= d-(d-c)* $\alpha$ (6)

If A and B are two fuzzy sets represented over the interval $A_\alpha$ = [a1 d1], $B_\alpha$ = [a2 d2], then $A_\alpha + B_\alpha$ ,$A_\alpha - B_\alpha$ and $A_\alpha * B_\alpha$ are defined as shown in Equations 7 to 9 [110].

$$\alpha_{(A+B)} = \alpha_A + \alpha_B = [a1+ a2, d1 + d2] \quad (7)$$

$$\alpha_{(A-B)} = \alpha_A - \alpha_B = [a1 - d2, d1 - a2] \quad (8)$$

$$\alpha_{(A*B)} = \alpha_A * \alpha_B = [\min (a1 * a2, a1 * d2, d1 * a2, d1 * d2), \max (a1 * a2, a1 * d2 ,d1 * a2, d1 * d2)] \quad (9)$$

When a risk factor is calculated using fuzzy data, a final crisp number is given after defuzzification. The Middle of Maximum (MOM) approach was applied for defuzzification. Finally, the value of 0.48 was attributed to risk of low advance rate of TBM from Fig. (10). Risk factors for other risks were similarly calculated. For comparison purposes, we ranked the 18 identified risks based on their calculated risk factors as shown in Table 2. Some comments and subdivisions of each risk were carried out as a result of findings from the literature (referenced comments in Table 2) and interviews and discussion with experts. These are also provided in this table.

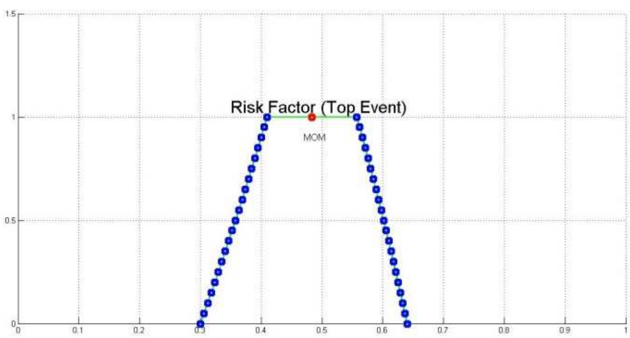



**Fig.** 10 Fuzzy number proportional to the risk factor of low advance rate of TBM

**Table 2** Ranking of the identified risks based on their calculated risk factors, including some comments and subdivisions of each risk

| Risk ranking | Risk factor | Risk | Comments and subdivisions of each risk |
|---|---|---|---|
| 1 | 0.812 | Inrush of great volume of water into the tunnel | Where tunnel of karstic and highly hydrated zones meet underground canals, a flow with high rate and pressure is expected [106]. |
| 2 | 0.8 | Poisonous & dangerous gases | For instance, if a tunnel meets the layers containing oil, gas and or coal, penetration of poisonous gases into the tunnel is not unlikely (refer to [104] for further study). |
| 3 | 0.746 | Meeting the hydrated layers and or drilling underground water table | Lack of identification of hydrated layers and improper selection of TBM may affect the performance of the machine and the schedule as well as operational costs.<br>The existence of water in a tunnel will give rise to instability of tunnel face and its walls and equipment; electrical and mechanical devices will be damaged and carrying drilled material will become more difficult.<br>Basically, open type machine is applicable when the flow of groundwater can be controlled [98]. |
| 4 | 0.725 | Damage and abrasion of cutter head | Primary abrasion refers to an abrasion occurring in drilling tools such as claws, discs, scratchers, and buckets, and it is already expectable for these tools. Therefore, these tools are designed for drilling and shall be exchanged in reasonable intervals. On the other hand, secondary abrasion is an unplanned event and occurs when the initial abrasion of drilling tools goes beyond the allowable limit and results in abrasion of supporter parts of the said tools such as spokes of cutter head or holders of cutting tools and or other surfaces not predicted by the designers and manufacturers of such machines. |
| 5 | 0.534 | TBM’s shield jammed | For instance, highly squeezed rock, higher friction of the shield with crushed and broken materials or falling heavy blocks on the machine may cause jamming of the shield [103]. |
| 6 | 0.526 | Clogging and blockage of cutter head and disc cutter of machine | In case of tunnels where TBM is used for drilling the rocks and argillaceous rocks and sticky clay, cutter heads and disc cutters are at the risk of clogging and blockage. Usually, the adhesiveness of argillaceous ores to metal surfaces of the machine may severely affect the efficiency of the machine.<br>Adhesiveness and clogging give rise to hard controlling, low advance rate, and additional cleaning [107]. |
| 7 | 0.495 | Existence of faults in the course of tunnel | Meeting fault zones in the course of drilling may result in special problems when the earth falls. Meeting such loose layers due to faults may give rise to many problems such as follows [105]:<br>1- Protection limits for intended joint system;<br>2- Friction of the shield and crushes and broken solid materials and even jamming.<br>3- Fall of heavy blocks from the ceiling or the walls on the machine;<br>4- Application of the gripper is limited. |
| 8 | 0.488 | Segments cannot resist the input water | This risk can be attributed to the low quality of produced segments, forced pressure (such as squeezing pressure), improper sealing, inability of seals applied to segments, and or cracking and breaking occurred in the segments. |
| 9 | 0.48 | Low advance rate | The related fault tree is presented in Section 3. |
| 10 | 0.43 | Engagement of cutter head | For instance, meeting argillaceous layers may cause the cutter head of the machine to be engaged and the advance rate to decrease significantly. |
| 11 | 0.385 | Extra abrasion of cutting tools | It may occur owing to meeting layers and material with great hardness and abrasive effect, especially where these layers and material had not been identified during exploration studies, or contacting with sticky material. |
| 12 | 0.381 | Contact with abrasive mineral in the course of drilling | Where the machine contacts abrasive minerals, the disc cutters are severely affected ([108]) and must be replaced at earlier intervals, |

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|---|---|---|---|
| | | | from which a financial burden is imposed on the project. |
| 13 | 0.315 | Delay in mobilization and supporting TBM | TBM shall be supported continuously. For instance, custodian measures and increasing the length of discharging system of the conveyor with advance rate of the machine and timely replacement of disc cutters and fabrication of segments should be applied. |
| 14 | 0.287 | Where the TBM is placed in incorrect path | Introduction of unbalanced pressure in hydraulic jacks and or in case the machine encounters complicated geological conditions or human errors; lack of experience of the personnel may result in deviation of the tunnel. |
| 15 | 0.255 | Occurrence of mechanical problems in TBM | For instance, incapability to service the machine or inability to supply spare parts, and shortage of equipment may result in this type of risk. |
| 16 | 0.243 | Blockage of TBM due to instability of advancing face | For instance, instability of the advancing face may be attributed to joint distance of greater than of 0.2 to 0.6. Where the joint distance is less than 0.2, uncovered TBM may not be applied [98]. |
| 17 | 0.22 | Instability of tunnel's wall and or distortion of segment ring | Factors such as water or squeezing, joint distance or shocks, explosion and operational incidents or damage may result in this type of risk. |
| 18 | 0.214 | Contact with squeezing rocks | Where the TBM is determined and selected without taking into consideration the project conditions, progress of the project may be severely affected by many problems. Some of them are as follows:<br>1- Convergence degree resulting from squeezing is varied from 3% to 5%.<br>Under these conditions, application of a single-shield machine is prioritized over a dual-shield one due to shorter length of the shield. However, installation of a prefabricated segment may result in problems such as sealing and inability to control ground movements.<br>2- Convergence degree resulting from squeezing is greater than 5%.<br>Under these conditions, application of prefabricated segments as a cover is limited and is even impossible. Using the machine under these conditions is generally not feasible ([98],[109]). |

Table 2 demonstrates that the risk of inrush of a great volume of water and the risk of encountering poisonous and dangerous gases during tunnel excavation have been identified as the most significant risks (risk factor 0.812 and 0.8, respectively). The least significant risks are instability of tunnel's wall and distortion of segment ring, and risk of contact with squeezing rocks (risk factor of 0.22 and 0.214, respectively).

A "Face validation" technique was conducted to validate the results. Interviews with field experts were conducted and nearly all of them agreed that the results are meaningful and present the real critical hazards of the project.

As a response to the analysis, considering the root causes of the fault trees of these two major risks, some actions and solutions were recommended. These actions were as follows:

1- To prevent the corrosion of electrical equipment, compressed air should be externally injected by the compressor and special pipes to the control room in which major parts of electrical devices are located. By creating positive pressure in the cabin, the entrance of air contaminated by $H_2S$ is prevented.

2- Given the existence of $H_2S$ and its related corrosion results, the strength and stability of the rails and tracks should be checked in their places to ensure their safety and operability.

3- To decrease groundwater flow rate leakage, cement grouting is applied, and water entering into the tunnel is pumped out.

4- To minimize risks from gas, the ventilation system should be improved by the addition of three 200 KW jet fans.

5- The shut down time of fans for the purpose of repairing and patching the duct should be limited to 10-15 minutes, so the accumulation of hazardous gas at the end of the tunnel is prevented.

6- Training courses and exercises should be undertaken by all personnel in order to improve their readiness to respond to an emergency.

7- A safety team should be set up with continuous responsibility for monitoring the conditions of the work environment.

8- A 16 inch pipe and a number of emulsion (Swamp) pumps should be installed to ensure that the water containing $H_2S$ that leaks from the construction site is collected.

## 4. Conclusion and Discussion

It is necessary to identify and control risks at the earliest stage of project planning for water conveyance projects. If this is not done, the project may be crucially challenged during its operation. The methodology used in this paper offers some advantages as follows: (i) a visual representation of root causes of each risk is provided to communicate the logic behind the occurrence of risk events; (ii) proactive response strategies can be designed to control those root causes at early stages; (iii) by asking the probability of each basic event through questionnaire survey and using fault tree calculations, the probability of each top event can be estimated in a much more accurate manner; (iv) the severity of risk is also estimated more precisely (based on the criteria of time, cost, quality, and safety, and (v) in the absence of accurate data, the experiences of field experts are used in the form of linguistic variables.

A real world case study using the proposed methodology was implemented in order to illustrate its potential applications in water conveyance tunneling projects. The project of Dasht-e Zahab was selected as a case study because it was subjected to severe and multiple hazards. The results obtained from implementing the proposed method on Dashte-e Zahab water conveyance tunnel project demonstrate that the two most significant risks are (i) risk of water inrush into the tunnel, and (ii) risk of encountering poisonous and dangerous gases. The rush of groundwater within the length of 3800 meters challenged the performance of the water conveyance project of Dasht-e Zahab. Water enters the tunnel with a flow rate of 300 liters per second, and this water contains soluble $H_2S$ gas. This gas is poisonous and hazardous and can jeopardize the health of the personnel and halt the project for several months. Due to its corrosive nature, this gas damages electrical and mechanical equipment.

To validate the results of the case study, different interviews with experts were conducted. The majority of them agreed that the results were meaningful and presented the real critical hazards of the project. The recommended actions (at the end of Section 3), if acted upon, could also significantly mitigate the major risks. Hence, it can be concluded that the proposed approach is a useful method for risk assessment, especially where there are complicated risks and those risks require detailed investigation.

Future research can be performed to apply FFTA to other risk analysis methods such as FMEA.

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## Appendix A

Amirkabir University of Technology
Civil and Environmental Engineering Department
Construction Engineering and Management Group

Dear expert,

This questionnaire is developed to gather the required information needed to fulfill the master thesis entitled **Risk Assessment for Tunnel Construction using Fuzzy Approach**.

In this research we aim to evaluate risks of Dasht-e Zahab water conveyance tunnel. Following your accurate answers to these questions, we will benefit greatly from the experience of experts in the field.

To do so, 18 risks are identified as the major risks in mechanized tunnel construction projects using TBM.

Best Regards,
Research Team

| Projects you have worked on since now: | Position: | Name: |
|---|---|---|
| | | |
| Organization: | Academic Degree: | Service record: |
| | | |

Please determine the occurrence probability of basic events of risk #1 (as a sample of 18 main risks).

| Main Risk | Risk Occurrence Probability / Factors Causing Main Risk (Basic Event) | Very Low | Low | Medium | High | Very High |
|---|---|---|---|---|---|---|
| **Risk of Low Advance Rate** | What is the probability that undesirable compressive and tensile strength causes low advance rate of TBM risk? | | | | | |
| | What is the probability that variable geological condition along the course of tunnel causes low advance rate of TBM risk? | | | | | |
| | What is the probability that existence of groundwater causes low advance rate of TBM risk? | | | | | |
| | What is the probability that existence of cracks (such as faults) along the course of tunnel causes low advance rate of TBM risk? | | | | | |
| | What is the probability that undesirable features and properties of soil and rock cause low advance rate of TBM risk? | | | | | |
| | What is the probability that shortage of workers causes low advance rate of TBM risk? | | | | | |
| | What is the probability that limitations imposed by local regulations causes low advance rate of TBM risk? | | | | | |
| | What is the probability that working hour limitations cause low advance rate of TBM risk? | | | | | |
| | What is the probability that working hour limitations cause low advance rate of TBM risk? | | | | | |
| | What is the probability that complicated final section formation causes low advance rate of TBM risk? | | | | | |
| | What is the probability that long diameter of tunnel causes low advance rate of TBM risk? | | | | | |
| | What is the probability that shortage of skilled labor in the field of management causes low advance rate of TBM risk? | | | | | |
| | What is the probability that poor TBM management causes low advance rate of TBM risk? | | | | | |
| | What is the probability that insufficient support of administrative agents causes low advance rate of TBM risk? | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | What is the probability that inability to supply required thrust causes low advance rate of TBM risk? | | | | | |
| | What is the probability that insufficient power of the machine causes low advance rate of TBM risk? | | | | | |
| | What is the probability that low operating torque causes low advance rate of TBM risk? | | | | | |
| | What is the probability that improper diameter of disc causes low advance rate of TBM risk? | | | | | |
| | What is the probability that improper weight of the machine causes low advance rate of TBM risk? | | | | | |
| | What is the probability that low machine velocity while installing the support system causes low advance rate of TBM risk? | | | | | |

The following table presents the definition of linguistic terms for each criterion (time, cost, quality and safety) and it is designed to help respected respondents to complete the following pages of this questionnaire.

| **Definition** | **Linguistic Terms** | **Criteria** |
|---|---|---|
| Inconsiderable delay | Very Low | **Time** |
| Delay is less than 5% of contract duration | Low | |
| Delay is between 5% and 10% of contract duration | Medium | |
| Delay is between 10% and 20% of contract duration | High | |
| Delay is more than 20% of contract duration | Very High | |
| Inconsiderable cost overrun | Very Low | **Cost** |
| Cost overrun is less than 5% of contract duration | Low | |
| Cost overrun is between 5% and 10% of contract duration | Medium | |
| Cost overrun is between 10% and 20% of contract duration | High | |
| Cost overrun is more than 20% of contract duration | Very High | |
| Intangible quality reduction | Very Low | **Quality** |
| Low quality reduction | Low | |
| Quality needs owner's approval | Medium | |
| Quality is unacceptable to owner | High | |
| Product is unusable | Very High | |
| Intangible safety reduction | Very Low | **Safety** |
| Low safety reduction | Low | |
| Safety needs owner's approval | Medium | |
| Safety is unacceptable to owner | High | |
| Poor and unacceptable safety | Very High | |

Please determine the severity of each main risk on the **time** criterion in the following table.

For example, to what extend does existence of faults in the course of tunnel affect the completion time of the project?

Please determine the severity of each main risk on the **cost** criterion in the following table.

For example, to what extend does risk of low advance rate of TBM affect the project cost?

Please determine the severity of each main risk on the **quality** criterion in the following table.

For example, to what extend does instability of tunnel's wall and or distortion of segment ring affect quality of the project?

Please determine the severity of each main risk on the **safety** criterion in the following table.

For example, to what extend does leakage of poisonous and dangerous gases affect safety of the project?

| ID | Main Risks | Severity of the risk on each criterion | | | | |
|---|---|---|---|---|---|---|
| | | Very Low | Low | Medium | High | Very High |
| 1 | Risk of low advance rate of TBM | | | | | |
| 2 | Risk of clogging and blockage of cutter head and disc cutter of machine | | | | | |
| 3 | Risk of damage and abrasion of cutter head | | | | | |
| 4 | Risk of existence of faults in the course of tunnel | | | | | |
| 5 | Risk of contact with squeezing rocks | | | | | |
| 6 | Risk of contact with abrasive mineral in the course of drilling | | | | | |
| 7 | Risk of meeting the hydrated layers and or drilling underground water table | | | | | |
| 8 | Risk of TBM's shield jammed | | | | | |
| 9 | Risk of instability of tunnel's wall and or distortion of segment ring | | | | | |
| 10 | Risk of blockage of TBM due to instability of advancing face | | | | | |
| 11 | Risk of engagement of cutter head | | | | | |
| 12 | Risk of inrush of great volume of water into the tunnel | | | | | |
| 13 | Risk of occurrence of mechanical problems in TBM | | | | | |
| 14 | Risk of poisonous and dangerous gases | | | | | |
| 15 | Risk of extra abrasion of cutting tools | | | | | |
| 16 | Risk of incapability of segments to resist the input water | | | | | |
| 17 | Risk of drilling in incorrect path | | | | | |
| 18 | Risk of delay in mobilization and supporting TBM | | | | | |

To calculate the weight of each criterion, please answer the following questions. Use numerical values as defined in the following table.

| Numerical value | Definition |
|---|---|
| 1 | Equal importance of i and j |
| 3 | Moderate importance of i over j |
| 5 | Strong importance of i over j |
| 7 | Very strong importance of i over j |
| 9 | Extreme importance of i over j |
| 2,4,6,8 | Intermediate values |

Please answer the following questions carefully:

| |
|---|
| Priority of safety over project cost |
| Priority of safety over completion time of project |
| Priority of safety over quality of project |
| Priority of project cost over completion time of project |
| Priority of project cost over quality of project |
| Priority of completion time over quality of project |

Finally, we ask you to notify us of any other risks you may have encountered in similar tunnel construction projects, or you predict might happen in the Dasht-e Zahab project: