

# Flyrock risk assessment in blasting operations of road construction in hard rock using the FFTA-FDAHP method

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## Review Paper

Received:  
12 February 2024  
Revised:  
8 August 2024  
Accepted:  
2 November 2024  
Published online:  
10 April 2025

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## Abstract:

Creating a safe environment is of utmost importance in any project. One crucial aspect of ensuring safety is addressing potential hazards. In the context of road construction projects involving hard rock, one significant risk is flyrock. Flyrock refers to the occurrence of fragments being propelled outside the blast area with high energy and speed during blasting operations. These flying rock fragments have the potential to cause severe and irreversible injuries to both people and equipment. The objective of this research is to identify and assess the risks associated with flyrock in road construction projects involving hard rock. To accomplish this, a collaborative approach was adopted, involving experts, analysis of scientific records, as well as observations and inspections. A thorough examination revealed a total of 54 flyrock events, which were prioritized for further analysis. To quantify the probability of flyrock occurrence, a fuzzy fault tree analysis was employed. This analysis method takes into account various factors and uncertainties to yield a calculated value of 0.4907, indicating the likelihood of flyrock incidents. Additionally, the intensity of flyrock consequences was determined to be 0.2248 using the fuzzy Delphi analytical hierarchical process. These assessments collectively indicate the potential severity of flyrock incidents. Based on the evaluations conducted, the resulting risk number associated with flyrock reached an undesirable level of 12. It highlights the imperative need to recognize and evaluate the risks posed by flyrock during road construction projects. By doing so, appropriate measures can be implemented to mitigate the occurrence of flyrock and minimize potential harm to individuals and equipment. Recognizing and understanding the risks associated with flyrock is a crucial step towards improving safety in road construction projects involving hard rock. Through the insights gained from this research, proactive measures can be taken to prevent flyrock incidents and ensure a safe working environment for all involved.

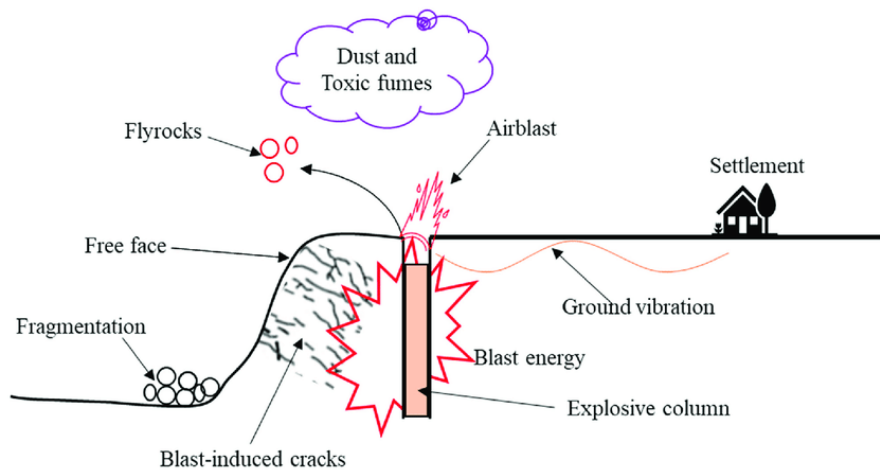
**Keywords:** Blasting; Mining; Road construction; Risk management; Risk identification

## 1. Introduction

The mining industry holds a crucial position in the economic growth of many countries (Kopljenovic and Kecojevic, 2007). Not only does it create employment opportunities, but it also serves as a key supplier of raw materials for various industries (Ma et al., 2020). In both mining and civil engineering projects, blasting is a common technique employed to remove rock mass efficiently. However, this blasting process faces challenges like wasted blasting energy, which can occur due to various factors, leading to several environmental issues. These issues include ground vibrations, backbreak, dust and fumes, air overpressure, and flyrock (Koopalipoor et al., 2018). In mining operations,

blasting is a necessary step to effectively fragment rocks (Yari et al., 2023). By controlling the quality and quantity of the resulting fragmentation, blasting operations can reduce overall costs and mitigate the adverse environmental effects typically associated with blasting, such as backbreak, vibration, dust, flying rocks, and noise (Al-Bakri and Sazid, 2021; Dehghan and Yazdi, 2023). Despite its effectiveness, blasting can have negative consequences, including flyrock, ground vibration, airblast, dust, and toxic fumes (K Raina, 2022). Figure 1 provides an illustration of these undesirable outcomes associated with blasting (Dumakor-Dupey et al., 2021; Shahani et al., 2023).

It is crucial to address these environmental issues and their potential risks in order to enhance the safety and sustainabil-



**Figure 1.** Undesirable consequences of blasting (Dumakor-Dupey et al., 2021; Shahani et al., 2023).

ity of mining and civil engineering projects. By adopting strategies and technologies that minimize the occurrence of flyrock, control ground vibrations, mitigate airblast effects, manage dust emissions, and reduce toxic fumes, mining operations can minimize their impact on the environment and ensure the well-being of workers and nearby communities. Continuous research and development efforts in the field of blast optimization and environmental management are necessary to achieve these goals and promote responsible mining practices.

When considering blasting hazards, particularly flyrock, it is crucial to address them during the design phase (Zhou et al., 2019). It is important to note that only a fraction of the blasting energy, typically ranging from 20% to 30%, is utilized for rock crushing, while the remaining energy contributes to various undesirable outcomes such as flyrock, ground vibration, airblast, dust, toxic fumes, noise, and more (Singh and Singh, 2005; Rezaei et al., 2011; Hajihassani et al., 2014; Sadeghi et al., 2020). The direct and indirect costs associated with these events significantly impact the mining economy (Abbasi, 2018).

Unfortunately, mining operations inherently involve hazards and accidents (Mithal Jiskani et al., 2020). Unsafe conditions within mines can lead to numerous accidents, resulting in casualties, serious and minor injuries, as well as financial losses. Accidents in mines are unplanned events that occur due to the presence of hazards. Therefore, it is of utmost importance to identify and analyze risks to minimize the occurrence of accidents. Inadequate risk management practices contribute to accidents within the mining industry. Examples of such events include falls from heights, slips, rock falls, flyrock incidents, and more (Elenge et al., 2013; Strzalkowski, 2019; Saira et al., 2021).

The measurement and management of risks play a crucial role in assisting mine management in mitigating the impact of identified hazards within the mining environment (Camm and Girard-Dwyer, 2005). While many explosion risk parameters have been identified and listed (Kiani et al., 2019), there is a lack of research investigating risk assessment in blasting operations for road construction in hard rock using methods such as fuzzy fault tree and fuzzy Delphi analytical

hierarchy process. The purpose of this research is to identify and categorize risks, propose effective responses, provide solutions, and prevent risks. In this study, the following main framework was adopted:

1. Identification of risks associated with blasting operations.
2. Creation of a fault tree to visualize the risk factors.
3. Determination of the probability of occurrence for each identified risk.
4. Preparation of a questionnaire and obtaining expert opinions.
5. Quantification of experts' opinions and achieving consensus.
6. De-fuzzification of the collected data.
7. Determination of the probability of top and intermediate events.
8. Assessment of the importance and classification of risks.
9. Determination of the consequence intensity.
10. Calculation of fuzzy numbers and formation of a fuzzy inverse matrix.
11. Estimation of fuzzy weight and its de-fuzzification.
12. Determination of the risk number.
13. Formulation of response strategies to address identified risks.
14. Providing effective solutions to prevent risks.

By implementing a comprehensive risk assessment process in blasting operations and incorporating the findings into proactive risk management practices, the mining industry can minimize accidents, enhance worker safety, and mitigate potential environmental and economic consequences.

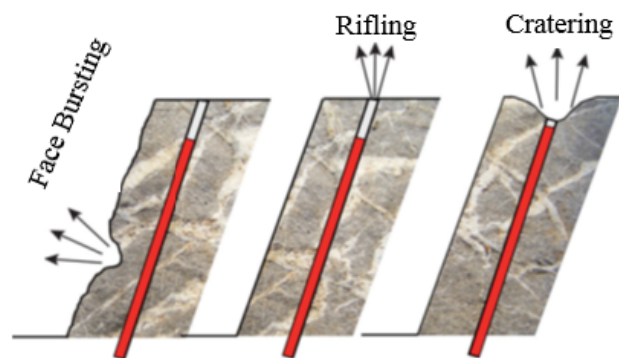
## 2. Flyrock

Flyrock poses a significant concern and is considered a prominent risk in blasting operations, particularly in mining and road construction projects conducted in mountainous regions. Researchers have consistently identified flyrock as a leading cause of human injuries, fatalities, and equipment damage, often surpassing other detrimental environmental effects associated with blasting operations (Dongtao, 2014; Tubis et al., 2020; Matloob et al., 2021; Rikhotso et al., 2022).

Despite significant advancements in blasting control techniques, the occurrence of flyrock continues to pose threats to both human lives and the financial well-being of mining and construction projects (Balakrishnan and Rai, 2021). It is widely recognized as one of the most hazardous consequences arising from blasting operations (Blanchier, 2013). The mechanism of flyrock can be categorized into three forms, as depicted in figure 2 [mention the specific figure if available] (Ghasemi et al., 2012; Hasanipanah et al., 2018; Jinbi et al., 2020; Hasanipanah and Bakhshandeh Amnieh, 2020). These forms include:

1. **Projection Flyrock:** This occurs when fragmented rocks or debris are propelled outward in a ballistic trajectory due to the high energy released during blasting. The projectile nature of flyrock makes it highly dangerous, as it can travel significant distances from the blast site, affecting nearby personnel, structures, and equipment.
2. **Rebound Flyrock:** Rebound flyrock happens when rocks or debris bounce off surfaces such as faces, walls, or floors within the blasting area, further increasing the risk of flyrock propagation. The rebound effect can lead to unpredictable trajectories and potentially extend the reach of flyrock beyond the immediate blast zone.
3. **Rolling Flyrock:** Rolling flyrock refers to the movement of large rock fragments or boulders that are dislodged and displaced by the blast forces.

The mechanism of flyrock can be categorized into three main forms, each with its own distinct characteristics and causes:



**Figure 2.** Three flyrock mechanisms (Ghasemi et al., 2012; Hasanipanah et al., 2018; Jinbi et al., 2020; Hasanipanah and Bakhshandeh Amnieh, 2020).

1. **Rifling:** Rifling occurs when inadequate stemming material is used in a blast. In such cases, blast-induced gases can stream up a blast hole along the path of least resistance, leading to the ejection of stemming material. In more severe cases, this can cause the collar rock to be ejected as damaging flyrock (Hasanipanah and Bakhshandeh Amnieh, 2020). The lack of proper stemming allows the gases to escape in an uncontrolled manner, resulting in the expulsion of rocks with potentially hazardous consequences.
2. **Cratering:** Cratering primarily occurs in the stemming area of a blast pattern where a layer has been weakened by preceding blasts from the bench above. In this weakened area, blast-induced gases simply release pressure into the air, causing cracks to propagate. The gases venting through these cracks contribute to the occurrence of cratering and the subsequent expulsion of flyrock (Hasanipanah and Bakhshandeh Amnieh, 2020). The compromised integrity of the weakened layer allows the gases to escape more forcefully, leading to the creation of craters and the projection of rock fragments.
3. **Face Bursting:** Face bursting happens when explosive charges are placed in proximity to key geological structures or areas of weakness. The high-pressure gases induced by the explosives travel along these paths of lower resistance, resulting in air blasts, noise, and the ejection of flyrock (Hasanipanah and Bakhshandeh Amnieh, 2020). The pressure from the explosive force causes fractures and dislodges rock fragments, which can be projected at high velocities during blasting operations.

Flyrock has a significant impact on airblast, referring to the ejection of rock fragments caused by blasting. It poses risks to both equipment and personnel (Nababan and Kartini, 2022). The high-velocity projection of small and large stones during blasting can lead to injuries, equipment damage, and harm to individuals involved. For a visual representation of incidents involving stone projection, please refer to figure 3, which depicts a schematic illustration (Serowe, 2016).

Understanding the mechanisms behind flyrock formation is crucial in developing effective prevention and control measures. By addressing the causes, such as ensuring proper stemming materials, reinforcing weakened layers, and carefully considering geological structures and areas of weakness, the risk of flyrock incidents can be significantly reduced. Additionally, implementing safety protocols, such as the use of protective barriers, adequate blast design, and proper training for personnel, can further enhance safety and minimize the potential for flyrock-related accidents.

## 3. Risk management

This article focuses on applied research that aims to provide practical solutions for reducing risks in road construction projects involving hard rock drilling and blasting methods. Blasting operations in hard rock road construction projects

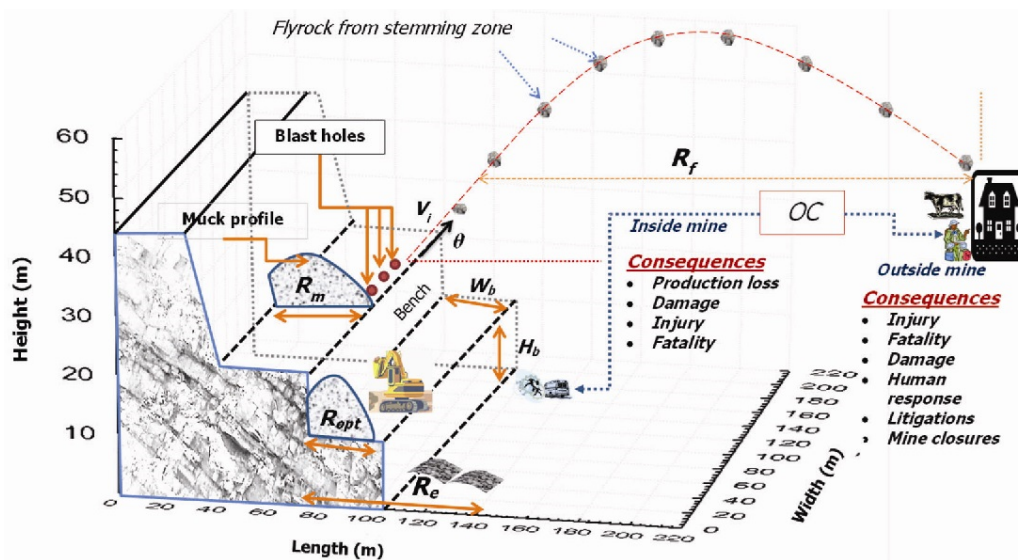


Figure 3. Schematic of flyrock events (Serowe, 2016).

occur in an environment full of uncertainties and various risks. The effective management of project risks can have a direct impact on the success or failure of the projects and can prevent accidents and damages. However, even with a proactive risk management approach, it is essential to have effective response plans and solutions in place in case incidents do occur.

Risk management is a crucial strategic component of any project. By implementing proper risk management practices, project stakeholders can minimize costs, damages, and accidents, ultimately enhancing productivity. The risk management process generally consists of two stages: risk assessment and risk response (Ataei, 2016; K Raina and Bhatawdekar, 2022).

In risk assessment, project teams must identify and evaluate potential risks associated with the drilling and blasting operations in hard rock road construction. This involves understanding the geological conditions, analyzing the characteristics of the rock mass, assessing the environmental impact, considering the presence of nearby structures or communities, and evaluating the existing safety protocols and regulations. By conducting a comprehensive risk assessment, project managers can prioritize risks based on their significance and develop appropriate mitigation strategies. Once the risks have been identified, the next stage involves developing risk response plans. This includes implementing preventive measures, such as improving blast design and execution techniques, reinforcing safety measures, and providing proper training and education for personnel involved in the operations. Additionally, contingency plans should be established to address potential accidents or incidents that may still occur, such as emergency response procedures, evacuation plans, and communication protocols. The general approach to risk management in road construction projects involving hard rock drilling and blasting is depicted in figure 4 (Ataei, 2016; K Raina and Bhatawdekar, 2022).

This visual representation illustrates the systematic and cyclical nature of risk management, emphasizing the ongoing

ing process of risk assessment, response, and continuous improvement in order to ensure the safety, efficiency, and success of the project.

It is crucial for project stakeholders, including contractors, engineers, and regulatory bodies, to work collaboratively in implementing effective risk management strategies. Regular monitoring, evaluation, and feedback mechanisms should also be established to assess the effectiveness of risk response measures and make necessary adjustments throughout the project lifecycle. By prioritizing risk management, road construction projects in hard rock environments can minimize potential hazards, protect the project's integrity, and ensure the safety of workers and surrounding communities.

#### 4. Calculating the probability rate of events using Fuzzy Fault Tree Analysis (FFTA)

There are many risk management approaches as following:

1. Failure Mode and Effects Analysis (FMEA)
2. Bowtie Risk Analysis



Figure 4. The general process of risk management (Ataei, 2016; K Raina and Bhatawdekar, 2022).

3. Root Cause Analysis (RCA)
4. Hazard and Operability Study (HAZOP)
5. Swiss Cheese Model
6. Event Tree Analysis
7. Process Safety Management (PSM)
8. Operational Risk Models (e.g., LDA, EVT)
9. Scenario Analysis
10. Business Continuity Planning (BCP)
11. Key Risk Indicator (KRI) Monitoring
12. Fault tree analysis (FTA)

The concept of safety and the analysis of events have gained increasing importance over time, prompting the use of analytical methods such as fault tree analysis for quantitative evaluation of explosion risks.

Fault Tree Analysis (FTA) is a logical and widely utilized technique in risk management (Lavasani et al., 2011). It has proven to be an effective method for assessing risks (Yaqian et al., 2017), and numerous authors and organizations have extensively employed it (Ericson, 2005; 61025, 2006; Oakley, 2012; Harms-Ringdahl, 2013; Luko, 2013; Koohdarii et al., 2016; Jahanbani et al., 2017). In the context of explosion risk evaluation, fault tree analysis provides a suitable quantitative approach (Ataei, 2016). However, considering the uncertainties inherent in such events, this research adopts fuzzy fault tree analysis as an effective method to account for uncertainty.

When conducting Fault Tree Analysis, the following eight steps are commonly recommended (Giraud and Galy, 2018):

1. Define the Top Event: Identify the undesired event that serves as the starting point for the analysis, in this case, an explosion.
2. Identify Basic Events: Determine the potential contributing factors or events that could lead to the occurrence of the top event. These events should be observable and specific.
3. Construct the Fault Tree: Develop a logical diagram that visually represents the relationships between the basic events and how they lead to the occurrence of the top event. This diagram is structured hierarchically, with logical gates representing the relationships between events.
4. Assign Probabilities: Quantify the probabilities of occurrence for each basic event. These probabilities can be based on historical data, expert opinions, or any other available sources of information.
5. Determine the System Failure Probability: Calculate the overall probability of the top event based on the probabilities assigned to the basic events and the logical relationships defined in the fault tree. This step allows for the assessment of the likelihood of the explosion occurring.

6. Analyze Critical Elements: Identify the critical events or combinations of events that have a significant contribution to the top event. This analysis can help prioritize risk mitigation measures.
7. Assess Risk Mitigation Measures: Evaluate the effectiveness of potential risk mitigation measures in reducing the overall probability of the top event. This step aids in decision-making regarding the implementation of preventive actions.
8. Continuously Improve: Review and update the fault tree analysis periodically to account for new information, changes in the system, or lessons learned from incidents. This ongoing improvement process ensures that the analysis remains relevant and up to date.

By following these steps, fault tree analysis provides a systematic and structured approach to quantitatively evaluate explosion risks. It helps identify critical factors, prioritize mitigation efforts, and continuously improve safety measures to minimize the chances of a catastrophic event occurring. Incorporating fuzzy logic in fault tree analysis enhances its ability to handle uncertainties and make more robust risk assessments.

In fault tree analysis, a comprehensive assessment of failure scenarios is conducted by selecting a detrimental or critical scenario as the top event, and then exploring all possible pathways that could lead to this undesirable situation based on the system's environment and performance (Hetang et al., 2017). These failure causes are organized systematically in a top-down structure, resembling a tree, wherein the fault tree extends until it reaches the smallest components of the system, known as basic events.

The fault tree comprises a single top event and multiple intermediate events. The basic events are interconnected via logical gates, forming logical relationships that trigger the occurrence of the top event. This hierarchical structure allows for a clear representation of the dependencies and relationships among the events.

Once the fault tree is constructed, it becomes possible to identify cut sets and minimum cut sets, which represent combinations of events or causes that, if they occur simultaneously, would lead to the occurrence of the top event. Analyzing these cut sets helps in understanding the critical factors contributing to the occurrence of the undesirable scenario.

However, assigning accurate probabilities to each basic event can be challenging due to factors such as limited information or incomplete estimations. To address this challenge, the fuzzy approach is employed in combination with expert opinions during the probability determination stage. An expert in fault tree analysis refers to an individual who possesses substantial knowledge about the system under evaluation and is familiar with the fault tree analysis method. It's important to consider that the weight or importance of each expert may vary, depending on factors such as their level of responsibility, work experience, education, and age, among others.

To evaluate the significance of each expert, a scoring system, as demonstrated in Table 1, is employed. This scoring sys-

**Table 1.** Scoring based on the characteristics of experts (Renjith et al., 2010).

Row	Condition	Classification	Score
1	Title	Director, Deputy	4
		Inspector, Assistant Manager, Controller	3
		Workshop manager, foreman	2
		Operator	1
2	Experience (Year)	$\geq 30$	4
		20 – 30	3
		10 – 20	2
		5 – 10	1
3	Education	P.H.D	5
		Expert and Master	4
		Diploma	3
		Has a technical degree	2
		High school	1
4	Age (Year)	$\geq 50$	4
		40 – 50	3
		30 – 40	2
		$\leq 30$	1

tem aids in determining the importance coefficient of each expert by dividing their total points by the overall points obtained by all experts (Renjith et al., 2010). This process allows for the consideration of diverse expert opinions and expertise, taking into account their relative significance in the analysis.

Utilizing the fuzzy approach alongside expert opinions ensures a more comprehensive and robust assessment of the probabilities associated with each basic event. By considering multiple perspectives and incorporating expert knowledge, the analysis becomes more reliable and adaptable, addressing the uncertainties and limitations inherent in traditional probabilistic analyses. This approach enhances the overall effectiveness of fault tree analysis in evaluating the risk and identifying suitable risk mitigation measures.

Figure 5 introduces a fuzzy linguistic scale that is used to capture the judgments of experts regarding hazards with unknown failure rates. The scale represents linguistic terms using both triangular and trapezoidal fuzzy numbers.

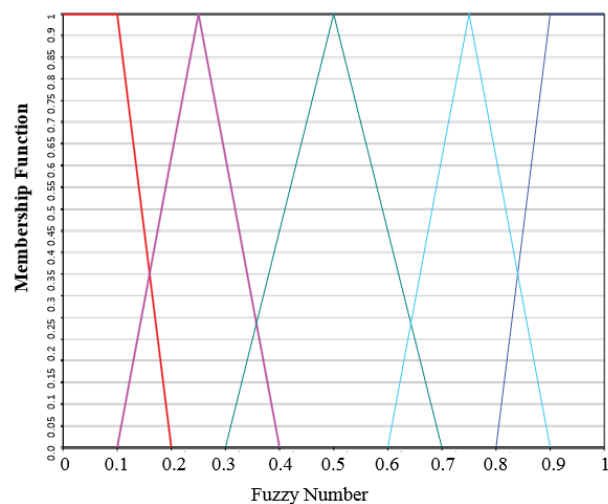
To enhance the ease of analysis, all the triangular fuzzy numbers in the scale can be converted into the corresponding trapezoidal fuzzy numbers.

Table 2 presents the complete set of fuzzy numbers from figure 5 in the form of trapezoidal fuzzy numbers.

This conversion allows for more precise and consistent analysis of the expert judgments. A heterogeneous group of experts is employed to provide judgments for these vague events with unknown failure rates. It's important to note that the weights of these experts are not equal. In order to determine the relative importance of each expert, the scoring system described in Table 1 can be utilized. Table 4

showcases the weights assigned to the ten experts participating in the judgment process. This table is specifically designed for the research project at hand, ensuring a fair representation of the experts' contributions.

Expert judgments regarding the basic events associated with unknown failure rates are documented in Table 5. These judgments are expressed using linguistic variables, such as very low (VL), low (L), medium (M), high (H), and very high (VH). The linguistic variables are represented using trapezoidal fuzzy numbers, as depicted in figure 5 or Table 2.

**Figure 5.** Linguistic variables used by experts (Lavasani et al., 2014).

**Table 2.** The weight of linguistic variables in quantifying the opinion of experts (Lavasani et al., 2014; Shulei et al., 2018).

Language variable	Weight of language terms			
Very low (VL)	0.2	0.1	0	0
Low (L)	0.4	0.25	0.25	0.1
Medium (M)	0.7	0.5	0.5	0.3
High (H)	0.9	0.75	0.75	0.6
Very High (VH)	1	1	0.9	0.8

This linguistic representation allows for the incorporation of experts' qualitative assessments, providing a more holistic understanding of the probabilities associated with the basic events.

By capturing expert opinions through linguistic variables and utilizing trapezoidal fuzzy numbers, the analysis incorporates subjective assessments effectively. This approach enables the consideration of uncertainties and diverse perspectives, enhancing the overall accuracy and comprehen-

siveness of the evaluation process. It empowers decision-makers to devise informed risk management strategies and prioritize mitigation measures based on a more nuanced understanding of the hazards with unknown failure rates.

When there is insufficient available information, the use of expert opinions becomes crucial. An expert is an individual who possesses adequate knowledge and expertise related to the evaluated system. In the context of this research, a diverse panel of 10 experts was carefully selected to provide

**Table 3.** Expert Questionnaire.

			parameters		Nonsignificant (L)	No Importance (VL)	Medium importance (M)	Medium importance (H)	Medium importance (VH)
Factors affecting the parameters after closing the blasting circuit	Fly rock	Design mistake	1	Improper delay time					
			2	Improper arrangement of blasting					
			3	Low Amount of spacing					
			4	Low Amount of burden					
			5	sub drilling					
			6	Large diameter of the hole					
			7	Low Stemming length					
			8	Low Hole length					
			9	Improper selection of explosives					
			10	Improper slope of the hole					
			11	Incorrect estimation of natural effects					
	Operational mistake	Human mistake	12	Spending quality					
			13	Type of drilling machine					
			14	Failure to hold retraining courses					
			15	Lack of effective accountability and monitoring					
			16	Inexperience					
			17	Unmotivated					
		Unpredictable natural effects mistake	18	Long working hours (fatigue)					
			19	Lack of work conscience					
			20	Mental preoccupation					
			21	unpredictable					
			22	time limit					
			23	Lack of access to facilities and equipment					

valuable insights. It is important to note that each expert does not carry an equal weight in the evaluation process. To determine the relative importance of experts, a method proposed by Lavasani et al. (2014) and Shulei et al. (2018) was adopted. This method aids in assigning appropriate weights to the experts based on their expertise and credibility.

Figure 4 illustrates a fuzzy linguistic scale that has been developed to guide the experts' judgments concerning hazards with unknown failure rates. The scale incorporates both triangular and trapezoidal fuzzy numbers as linguistic terms. This combination of fuzzy numbers allows for a more comprehensive representation of expert opinions. Additionally, the triangular fuzzy numbers can be easily transformed into corresponding trapezoidal fuzzy numbers to facilitate analysis and interpretation.

Table 2 provides a comprehensive presentation of all the fuzzy numbers shown in figure 4, representing them in the form of trapezoidal fuzzy numbers. This conversion allows for a standardized and consistent approach to analyzing the expert judgments.

A heterogeneous group of experts with diverse backgrounds and expertise was involved in assessing the vague events under consideration. The utilization of a diverse panel helps capture a wider range of perspectives and knowledge. However, as mentioned earlier, the weights assigned to each expert are not equal. To determine these weights, Table 1 was employed as part of the research methodology.

In this study, ten experts were engaged to evaluate the events, and Table 4 displays the specific weights assigned to each expert. This table has been specifically designed for this research project to ensure fairness and accuracy in representing the relative contributions of the experts.

Expert judgments related to the basic events associated with unknown failure rates are documented in Table 5. This table summarizes the qualitative assessments provided by the experts, permitting a comprehensive understanding of the uncertainties associated with the evaluated events.

Incorporating expert opinions, especially through the use of fuzzy linguistic scales and trapezoidal fuzzy numbers, enhances the decision-making process by considering qualitative insights and subjective assessments. This approach acknowledges the limitations of available data and adds valuable experiential knowledge to the analysis, resulting in more robust evaluations and risk management strategies.

Once a consensus has been reached among the experts regarding the occurrence probabilities of the basic events, which are represented as fuzzy numbers, it becomes necessary to transform these fuzzy numbers into crisp, or definite, values. This conversion is essential to facilitate further analysis, considering the complexity of the variables involved and the extensive calculations required. Several methods for defuzzification can be employed, each with its own characteristics and suitability for different scenarios.

The Center of Gravity method is one commonly used approach for defuzzification. It involves calculating the centroid or average value of the fuzzy number, which represents the center of mass or center of gravity of the fuzzy set. This method provides a single crisp value that summarizes the fuzzy number.

Another method is the Largest Maximum method, which selects the highest value within the fuzzy number as the corresponding crisp value. This approach encapsulates the most optimistic interpretation of the fuzzy number.

The Average Maximum method calculates the average of all the maximum values within the fuzzy number, providing a representative crisp value that balances both optimistic and pessimistic perspectives.

Conversely, the Smallest Maximum method selects the smallest value within the fuzzy number. This approach represents a more cautious or conservative interpretation of the fuzzy number, considering the lowest possible outcome. The Surface Halving method divides the area under the fuzzy set curve into two equal halves. It then identifies the crisp value at the intersection of this dividing line with the

**Table 4.** Scoring based on the characteristics of experts.

Row	Title	Education	Experience	Weighted index	Age	The coefficient of importance of each expert
1	Blasting Expert	Associate Degree	11 – 15	8	30 – 40	0.0833
2	Responsible for the blast team	Associate Degree	21 – 25	10	40 – 50	0.1042
3	Blasting Expert	Associate Degree	16 – 20	8	30 – 40	0.0833
4	Blasting Expert	Associate Degree	11 – 15	8	30 – 40	0.0833
5	Blasting Expert	Associate Degree	16 – 20	9	40 – 50	0.0937
6	Blasting Expert	diploma	21 – 25	9	40 – 50	0.0937
7	Responsible for the blast team	Masters	>30	14	>50	0.1458
8	Technical Office Engineer	MSc	11 – 15	11	30 – 40	0.1145
9	Blasting Expert	Associate Degree	16 – 20	9	30 – 40	0.0937
10	Head of Executive Office (Supervision)	MSc	6 – 10	10	30 – 40	0.1042

x-axis. This method achieves a balance between optimism and conservatism.

The equation for converting a trapezoidal fuzzy number to definite numbers is as follows:

$$\frac{1}{3} \frac{(a_4 + a_3)^2 - a_4 * a_3 - (a_1 + a_2)^2 - a_1 * a_2}{(a_4 + a_3 - a_2 - a_1)} \quad (1)$$

The resulting non-fuzzy number is still a representation of possibility rather than probability, given the probabilistic nature of the fault tree. To convert this possibility number into a probability, the following equation can be employed (Lavastre et al., 2016):

$$FFP = \begin{cases} \frac{1}{10^k} & FPS \neq 0 \\ 0 & FPS = 0 \end{cases} \quad (2)$$

$$k = \left[ \frac{1 - FPS}{FPS} \right]^{\frac{1}{3}} * 2.301 \quad (3)$$

FFP: Probability of failure of any terminal event

FPS: Possible number from the non-fuzzy step

Subsequently, the determination of high probability rates, importance, and classification of minimum cut sets is carried out. By utilizing the formulas for logical AND (formula (4)) and logical OR (formula (5)), the probability rates of intermediate and top events can be calculated.

$$P(E0) = \prod_{i=1}^m P(E1) \quad (4)$$

$$P(E0) = 1 - \prod_{i=1}^m (1 - P(E1)) \quad (5)$$

### 5. Assessing the risk of flyrock in blasting operations of road construction projects in hard rock by fuzzy fault tree analysis method

#### Case study:

##### 5.1 Determine the probability of occurrence

Risk assessment can be approached through two main categories: quantitative and qualitative methods. Quantitative risk assessment involves the use of numerical data

**Table 5.** Experts' answers to the questions of the basic events regarding the probability rate in the form of linguistic variables.

Top event		Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6	Expert 7	Expert 8	Expert 9	Expert 10
	Intermediate event										
Fly rock	Improper delay time	H	H	H	VH	VH	VH	VH	VH	H	M
	Improper arrangement of blasting	VH	H	H	VH	VH	VH	H	H	H	M
	Low Amount of spacing	H	VH	M	VH	VH	VH	H	VH	M	H
	Low Amount of burden	H	VH	H	H	H	H	VH	VH	L	L
	sub drilling	M	VH	M	VH	VH	VH	M	VL	L	L
	Large diameter of the hole	M	VH	M	VH	VH	VH	H	H	M	M
	Low Stemming length	H	H	L	H	H	H	VH	VH	L	L
	Low Hole length	H	M	M	H	H	H	H	M	L	H
	Improper selection of explosives	H	H	M	VH	H	VH	VH	H	M	H
	Improper slope of the hole	H	H	M	H	VH	H	M	H	H	H
	Incorrect estimation of natural effects	M	H	M	H	VH	H	L	M	H	H
	Spending quality	VH	VH	H	VH	VH	VH	M	H	VH	H
	Type of drilling machine	L	M	L	H	H	H	VL	VL	VH	M
	Failure to hold retraining courses	H	M	M	H	VH	H	L	M	H	H
	Lack of effective accountability and monitoring	M	M	M	VH	H	VH	L	H	L	H
	Inexperience	L	H	H	H	VH	H	M	H	H	M
	Unmotivated	M	M	VH	VH	VH	VH	L	H	M	M
	Long working hours (fatigue)	M	H	VH	VH	VH	VH	M	H	VH	M
	Lack of work conscience	M	H	H	VH	VH	VH	M	H	VH	M
	Mental preoccupation	L	M	H	VH	VH	VH	M	H	VH	M
Unpredictable	L	M	M	H	VH	VH	M	VH	H	L	
time limit	M	H	H	VH	VH	H	M	VL	H	M	
Lack of access to facilities and equipment	H	H	H	H	VH	H	M	L	H	L	

**Table 6.** Probability rate of major flyrock events in firefighting operations.

Row	Basic event	Event probability rate
1	Improper delay time	0.0392
2	Improper arrangement of blasting	0.0318
3	Low Amount of spacing	0.0328
4	Low Amount of burden	0.0199
5	sub drilling	0.0075
6	Large diameter of the hole	0.0212
7	Low Stemming length	0.0136
8	Low Hole length	0.0117
9	Improper selection of explosives	0.0271
10	Improper slope of the hole	0.0194
11	Incorrect estimation of natural effects	0.0113
12	Spending quality	0.0374
13	Type of drilling machine	0.0036
14	Failure to hold retraining courses	0.0109
15	Lack of effective accountability and monitoring	0.0093
16	Inexperience	0.0144
17	Unmotivated	0.0126
18	Long working hours (fatigue)	0.0242
19	Lack of work conscience	0.0220
20	Mental preoccupation	0.0163
21	Unpredictable	0.0114
22	time limit	0.0111
23	Lack of access to facilities and equipment	0.0111

and precise calculations to evaluate risks, while qualitative risk assessment relies more on subjective judgments and descriptions of risk factors. Both approaches have their own advantages and can be useful depending on the context and available information.

Fault tree analysis is a widely used technique for quantitative risk assessment. It provides a systematic and structured approach to analyze and evaluate the probabilities and effects of various events leading to a specific undesired or hazardous outcome. By graphically representing the logical relationships between events and their causes, fault tree analysis allows for a thorough examination of the risk factors involved.

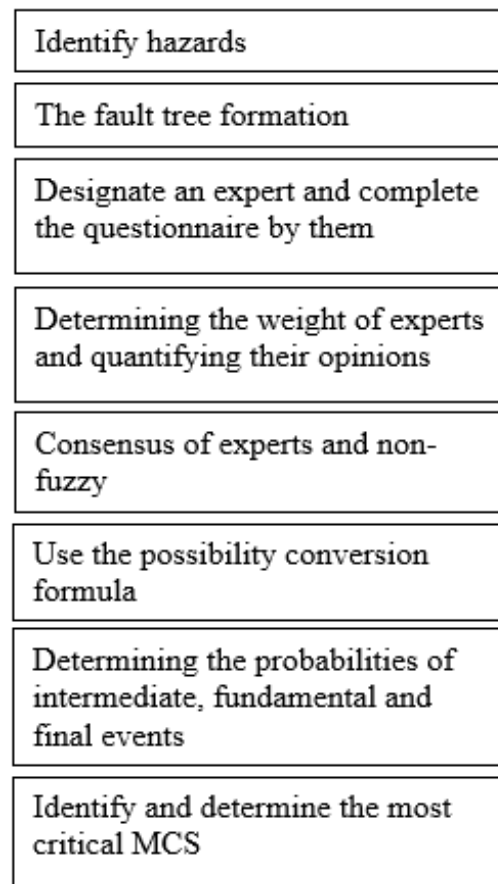
However, it is important to note that fault tree analysis requires sufficient information regarding the probabilities of equipment failure rates. Accurate and reliable data on failure rates are essential inputs for the analysis to generate meaningful results. Without this information, the effectiveness and accuracy of the assessment may be compromised. In the context of the specific study mentioned, the fuzzy fault tree analysis method is employed to assess the risks associated with blasting and explosions in road construction projects involving hard rock. Fuzzy

fault tree analysis combines the principles of fault tree analysis with the concept of fuzzy logic, allowing for the consideration of uncertainties and imprecise data in the analysis process.

Figure 6 outlines the specific steps undertaken in this research, providing a visual representation of the methodology employed. These steps likely include defining the top event (blasting or explosion), identifying the basic events and their logical relationships, assigning probabilities or fuzzy numbers to the basic events, and conducting the analysis to determine the overall risk of the identified events occurring.

By utilizing the fuzzy fault tree analysis method, this study aims to provide a comprehensive assessment of the risks associated with blasting and explosions in road construction projects involving hard rock. This approach allows for the consideration of uncertainties and imprecise data, enabling a more robust and realistic evaluation of the potential risks and their impacts. The findings of this research can inform decision-making processes, risk mitigation strategies, and the implementation of appropriate safety measures in such projects.

In this particular study, an investigation was carried out



**Figure 6.** Steps of conducting research.

to assess the occurrence of flyrock on mountain roads located in the southeastern regions of Iran. Flyrock refers to the phenomenon where rocks are propelled into the air during blasting operations, posing a significant safety risk to nearby personnel and infrastructure.

To determine the factors influencing the occurrence of flyrock, a comprehensive approach was adopted. Firstly, the insights and expertise of industry experts were sought to gather valuable knowledge and practical experiences related to flyrock incidents. Additionally, a thorough examination of scientific literature was conducted to explore existing research and studies on flyrock mitigation strategies and risk factors.

Furthermore, on-site observations were made to directly observe and analyze the behavior of rock fragmentation and the potential causes of flyrock. This hands-on approach provided practical insights into the specific conditions and challenges faced in the studied mountain road locations.

Using the information obtained from experts, literature review, and on-site observations, an analysis of intermediate and basic events related to flyrock was performed. Intermediate events refer to the events or conditions that contribute to the occurrence of flyrock, while basic events represent the individual factors or parameters that influence flyrock risks.

Based on the identified intermediate and basic events, a fault tree specific to the top event of flyrock was constructed. The fault tree, depicted in Figs. 7-10, visually represents the

logical relationships between events and factors that lead to the occurrence of flyrock. This graphical representation aids in the understanding of the complex interactions and dependencies between various parameters.

The study findings indicate that certain parameters have an inverse relationship with flyrock occurrence. These include spacing (the distance between blastholes), burden (the vertical distance between the lowest point of the blasthole and the ground), delay time (the time delay between the initiation of individual blastholes), stemming (material placed in the blasthole above the explosive charge), and sub-drilling (the depth of the drill hole below the rock surface). As these parameters increase, the likelihood of flyrock decreases.

Conversely, other parameters were found to have a direct relationship with flyrock occurrence. These parameters include explosive power (the energy released by the explosive charge), hole diameter (the width of the drill hole), and hole length (the depth of the drill hole). A higher level of these parameters increases the potential for flyrock incidents.

Understandably, these findings can serve as valuable insights for road construction projects in mountainous regions to mitigate the risk of flyrock. By considering and optimizing the parameters identified in the study, engineers and blasting professionals can enhance safety measures, minimize flyrock-related hazards, and ensure the smooth execution of blasting operations in such challenging

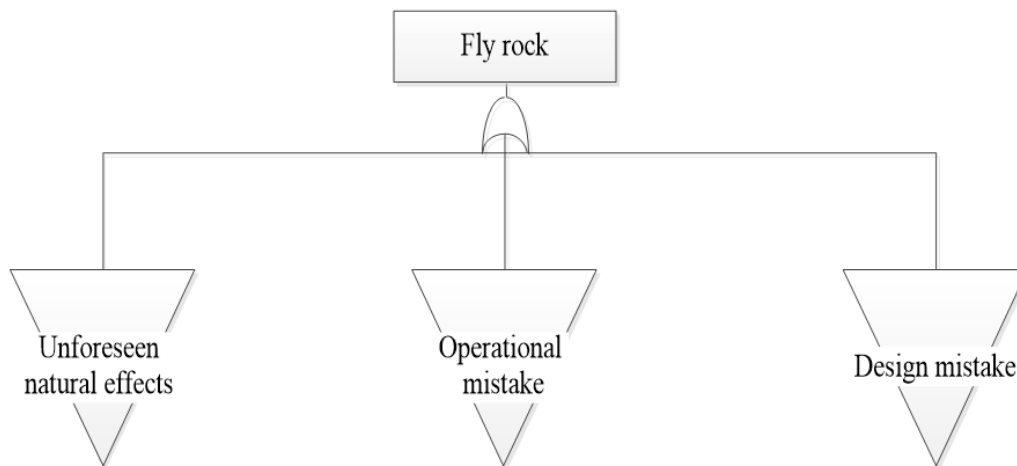


Figure 7. Tree chart of the flyrock top event.

terrains.

Following the formation of the fault tree and considering the basic events, it was observed that sufficient information regarding the determination of the probability failure rate for the basic events was not available. To address this challenge, fuzzy logic was employed to estimate the probability rates. The process commenced by assembling a team comprising specialists and experts with relevant knowledge. Expert opinions were then gathered through questionnaires utilizing linguistic variables. The questionnaire templates are provided in Table 3.

Once the questionnaire was prepared, it was distributed to 10 experts in blasting operations for their completion. The completed questionnaires were then collected for analysis. To assess the expertise of the participating experts, the expert feature score table was calculated based on the opinion of Renjith (Renjith et al., 2010). The corresponding

scores can be found in Table 4. Subsequently, the answers provided by the experts were compiled and organized in Table 5.

By referring to Fig. 5. And Table 2. The experts' opinions regarding each event were inputted into an Excel sheet, allowing for the formulation of the probability rates for each event. The calculated probability rates for the basic events are presented in Table 6.

Upon the completion of probability rate calculations for each basic event using the logical and logical or formulas implemented in Excel software, the intermediate events were computed, leading to the evaluation of the top event, flyrock. The resulting probability rate for the flyrock event was determined to be 0.4907, indicating a high likelihood of occurrence within the context of blasting operation events.

Fig. 11. Showcases the probability rates of the intermediate

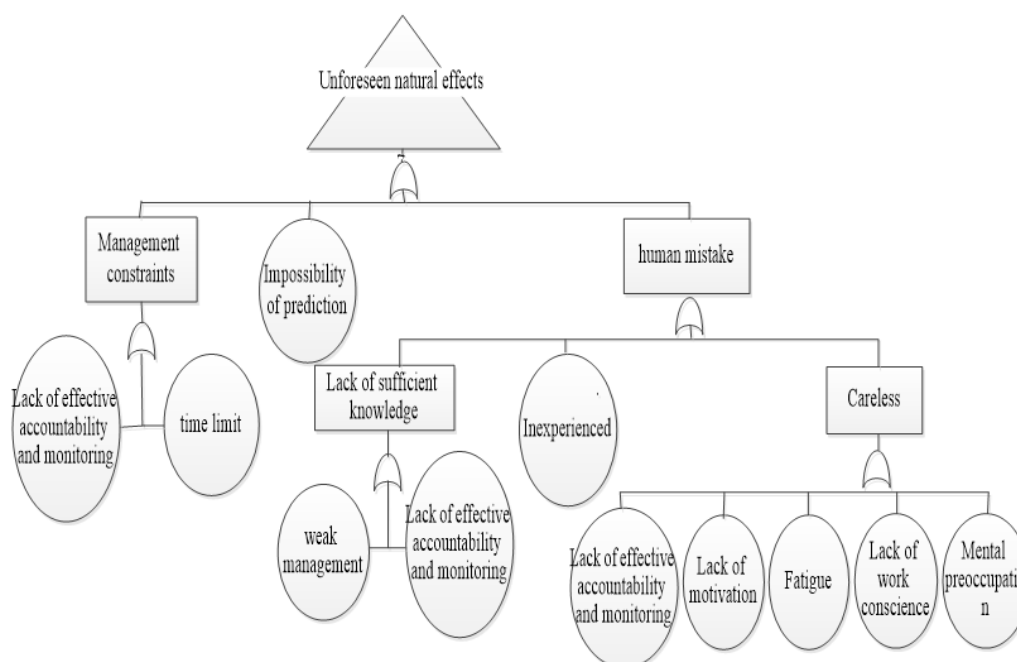


Figure 8. Continue the tree diagram of the flyrock intermediate event.

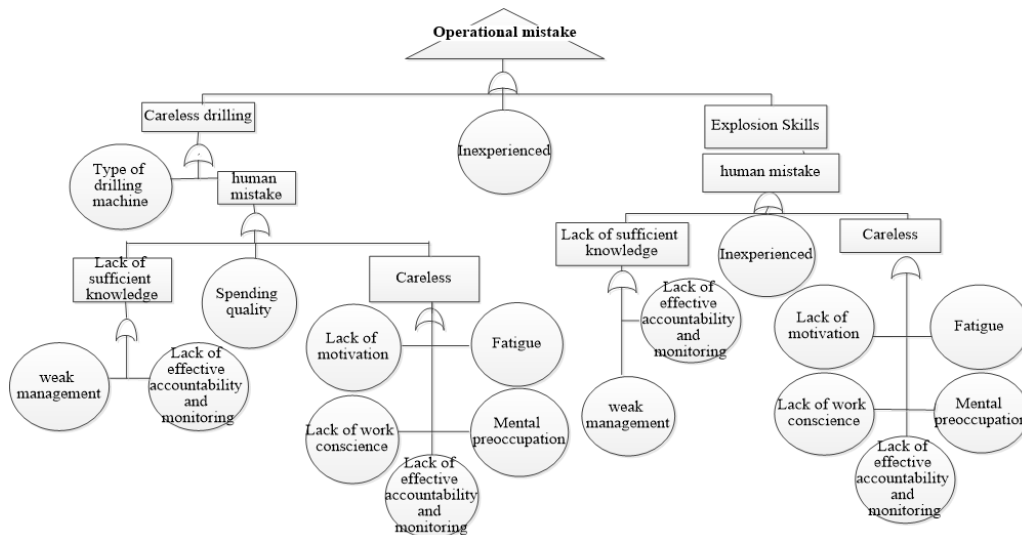


Figure 9. Continue the tree diagram of the flyrock intermediate even.

and top events, calculated using formulas (4) and (5). Moreover, the placement of flyrock basic events within the fault tree is illustrated.

**5.2 Determining the probability of the intensity of consequence with the fuzzy Delphi analysis hierarchical process (FDAHP)**

The fuzzy Delphi analysis hierarchical process provides a flexible framework that covers many obstacles related to imprecision, clarity, and uncertainty. Therefore, this method was used in the article. (Ataei, 2016):

The steps to implement this method are as follows: (Ataei, 2016):

- 1- Survey of experts
- 2- Fuzzy number calculation
- 3- Forming the fuzzy inverse matrix

4- Calculation of relative fuzzy weight of parameters

5- Un-fuzzy the weight of the parameters

By using the above steps, the probability of the intensity of the impact of the blasting events (flyrock) was calculated as follows:

In these tables, flyrock is marked with the C1, airblast and noise is marked with the C2, ground vibration is marked with the C2, abbreviation. A sample of experts' opinions regarding the severity of the consequences of explosive events is shown in Table 7.

The fuzzy numbers were calculated and then the fuzzy inverse matrix was prepared in the form of Table 8.

Calculations of the relative weight of the parameters and un-fuzzy of the weight of the parameters were done and the results were presented in Table 9.

The classification of the intensity of the consequence of events was done, which is shown in Tables 10-11.

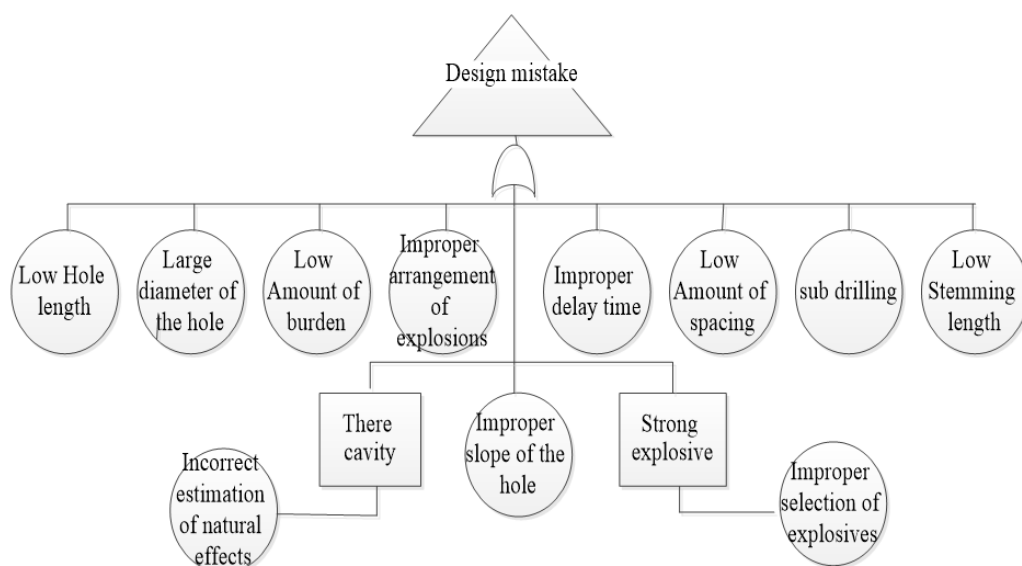


Figure 10. Continue the tree diagram of the top event of flyrock.

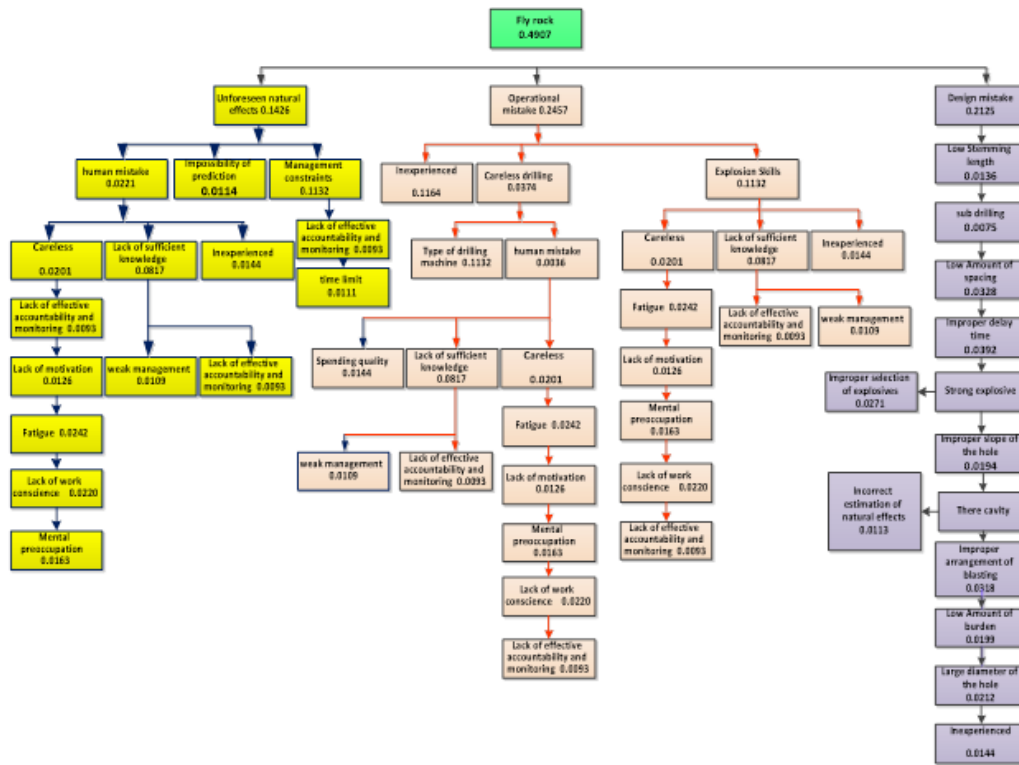


Figure 11. Intermediate and top events of fly rock probability.

5.3 Determine the risk number

In the final stage of risk assessment, it is essential to assign a risk number to each event by considering both the probability rank and the severity of consequences. This risk number is then used to place the events in the risk matrix. The risk matrix represents the intersection of the probability (Y-axis) and consequence intensity (X-axis), with the risk number being determined by multiplying these two factors. Regarding flyrock, the calculated risk number is as follows: (insert specific value). This value will be used to position the flyrock event within the risk matrix, based on the predefined probability and consequence intensity scales specified in the contract. The risk number is calculated by multiply the probability of occurrence with the intensity of consequence. The risk number for flyrock is follows: (Probability of occurrence (4)) \* (intensity of consequence (3)) = (Risk number (12))

6. Discussion and conclusion

In this study, our primary focus was on investigating flyrock, which is an important event that occurs during

blasting operations. To assess the probability and severity of this event, we employed two analytical methods: fuzzy error tree analysis for estimating the probability and fuzzy hierarchical analysis for evaluating the consequence severity.

To identify the basic events associated with flyrock, we employed three distinct approaches. Firstly, we conducted a meticulous review of scientific and historical records related to flyrock incidents, studying documented cases and extracting valuable information. Secondly, we sought the expertise of professionals and specialists in the field of blasting operations, consulting with them to gain insights and knowledge based on their experience. Lastly, we conducted site visits and inspections to gather direct observations, examine the physical environment, and collect data and measurements specific to the blasting operations.

Using the information obtained through the aforementioned methods, we constructed a fault tree diagram that represented the event of flyrock occurrence. To gather expert opinions on these basic events, we designed questionnaires with linguistic variables and distributed them among selected experts in the field. These experts provided their insights and assessments of the basic events, which were

Table 7. Paired matrix of final events according to expert number 1.

	C1	C2	C3
C1	1	7	7
C2	0.14285	1	3
C3	0.14285	0.333	1

**Table 8.** Comprehensive pairwise comparison matrix of experts' opinions.

	C1			C2			C3		
	$\gamma_{ij}$	$\delta_{ij}$	$\alpha_{ij}$	$\gamma_{ij}$	$\delta_{ij}$	$\alpha_{ij}$	$\gamma_{ij}$	$\delta_{ij}$	$\alpha_{ij}$
C1	1	1	1	9	5.809061	3	9	8.24867	7
C2	0.3333	0.172136	0.1111	1	1	1	9	5.291879	3
C3	0.14285	0.121223	0.1111	0.3333	0.188956	0.1111	1	1	1

then recorded and collected.

To analyze the gathered expert opinions and convert fuzzy numbers into non-fuzzy values, we utilized formulas and calculations within Excel software. By converting these numbers into possibility numbers, we were able to calculate the probability rates of occurrence for the identified basic events. This calculation was based on logical AND and logical OR operations specified in the fault tree and relevant formulas.

Using Excel software, we also determined the probabilities of intermediate events and top events. Analyzing the collected data, we observed that the intermediate events with the highest probabilities of occurrence were operational errors, design errors, and unforeseen natural errors, respectively. Within the category of operational errors, the highest probability was attributed to drilling carelessness, with a value of 0.11641. This specific issue was found to be influenced by three basic events: long working hours (fatigue), lack of work conscience, and mental preoccupation of personnel. Among these influencing factors, long working hours had the maximum impact, while mental preoccupation had the least impact.

Regarding design hazards, we found that improper delay time, improper blasting sequence, and insufficient row spacing had the greatest impact on increasing the probability rate of occurrence. In the case of unforeseen natural disasters, human error was found to have the most significant influence on increasing the probability of occurrence.

Based on the research findings, we recommend employing adequate precision and conducting multiple calculations during the design phase, with the involvement of one or more consultants. Additionally, measures should be taken to address and mitigate human errors, especially by focusing on reducing working hours in challenging and hazardous work environments. If reducing working hours is not feasible within the project timeline, we suggest considering the employment of additional workforce to facilitate rotation among individuals, allowing for rest periods and mitigating the impact of fatigue. Furthermore,

training and guidance should be provided to enhance work conscience among workers, promoting a culture of attentiveness and responsibility.

Human errors in various work environments can be influenced by several factors, including long working hours, lack of work conscience, and mental preoccupation. Among these factors, long working hours have been found to have the highest probability of occurrence. It is crucial to address these human errors to ensure optimal performance and safety. To mitigate the impact of human errors, it is recommended to emphasize accuracy and employ multiple calculations during the design phase of projects. By involving one or more consultants, a diverse range of perspectives can be considered, reducing the likelihood of errors and improving the overall quality of the work.

Moreover, measures need to be taken to address the issue of long working hours, especially in challenging and hazardous work environments. If feasible within the project timeline, reducing working hours should be prioritized. This reduction allows workers to have adequate rest periods, decreasing fatigue and the likelihood of errors. However, if reducing working hours is not possible, alternative solutions should be considered.

One effective solution is the employment of an additional workforce. By having more workers available, individuals can work in rotation, ensuring that they receive sufficient rest. This approach helps to mitigate the impact of fatigue and reduces the chances of errors caused by tiredness or mental exhaustion.

In addition to addressing working hours, providing training and guidance to enhance work conscience among workers is essential. This includes educating employees on the importance of attention to detail, precision, and being mindful of their work. By instilling a strong work conscience, workers are more likely to approach their tasks with diligence and accuracy.

To summarize, to minimize human errors in various work environments, it is recommended to employ accuracy and multiple calculations during the design phase, involving consultants. Efforts should also be made to reduce working

**Table 9.** Determination of weight of final events.

	fuzzy number			Un - fuzzy number			Un - fuzzy weight
	$\gamma_{ij}$	$\delta_{ij}$	$\alpha_{ij}$	$\gamma_{ij}$	$\delta_{ij}$	$\alpha_{ij}$	
C1	5.17868	2.96091	1.629	0.1943	0.2209	0.2647	0.2248
C2	1.3627	0.73512	0.3659	0.05113	0.05484	0.05944	0.05503
C3	0.33588	0.22094	0.1458	0.0126	0.01648	0.02369	0.01701

**Table 10.** Ranking of the intensity of consequence.

Intensity of consequence %	Probability level	Rating
$\geq 24.068$	very probable	5
15.37 – 24.068	possible	4
6.68 – 15.37	might	3
0 – 6.68	improbable	2
0	very improbable	1

hours, either by adjusting schedules or employing an additional workforce for rotation. Training and guidance are crucial in enhancing work conscience among employees. By implementing these measures, the occurrence of human errors can be significantly reduced, leading to improved efficiency, productivity, and overall safety.

In addition to addressing factors such as long working hours and lack of work conscience, efforts should be made to cultivate enthusiasm and motivation among the workforce and effectively address any instances of intentional misconduct. Creating an environment that fosters positivity, teamwork, and job satisfaction is crucial for minimizing the occurrence of human errors and promoting a safe work culture.

Managers and officials who have direct contact with the workforce play a crucial role in addressing the issue of mental preoccupation. It is essential to establish a peaceful work environment where employees feel comfortable and supported. Building friendly relations and open lines of communication with the labor force allows for the identification of potential concerns and solvable problems. By actively listening to their concerns and taking appropriate actions to address them, managers can help alleviate mental preoccupation and improve overall well-being.

Support systems should be put in place to provide effective assistance and engagement for employees' mental well-being. This may include offering counseling services, stress management programs, and resources for work-life balance. Incorporating regular breaks, promoting recreational activities, and encouraging a healthy work-life balance can significantly contribute to reducing mental preoccupation and fatigue among workers.

Moreover, it is important to acknowledge that the recommendations outlined in this article are based on the experiences and expertise of a team of blasting experts from Iran. While the findings of this research may be generalized to some extent, further research and validation from a broader range of blasting experts and contexts are needed

to ensure comprehensive understanding and applicability.

The results of this research align with previous studies conducted by Norouzi Masir et al. (2021), Koohdarii et al. (2016), Al-Bakri and Sazid (2021), Hasanipناه and Bakhshandeh Amnieh (2020), Balakrishnan and Rai (2021), Blanchier (2013), and Ghasemi et al. (2012). These studies consistently demonstrate that flyrock poses a significant risk in blasting operations, both in terms of its occurrence and potential consequences. By implementing the recommendations outlined in this article, including addressing human errors and fostering a safe work environment, the occurrence of unfortunate events, damages, and work interruptions associated with flyrock incidents can be mitigated.

In conclusion, it is crucial to address the mental preoccupation and well-being of workers in addition to other factors contributing to human errors. By fostering a positive work environment, actively engaging with employees, and providing necessary support, companies can minimize the occurrence of flyrock incidents and promote a safe and productive working environment. However, further research and validation are necessary to ensure the generalized applicability of these recommendations across different blasting contexts and geographical locations.

#### Authors contributions

Authors have contributed equally in preparing and writing the manuscript.

#### Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

#### Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Table 11.** Ranking the intensity of the consequence of top events.

Event symbol	Intensity of consequence	Rating
C1	0.2248	3
C2	0.05503	2
C3	0.01701	2

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