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RISK ASSESSMENT FOR TUNNEL CONSTRUCTION USING AHP BY EVALUATION OF RISK FACTORS

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ABSTRACT

Tunnel construction is a high-risk engineering process influenced by various uncertainties, including geological conditions, environmental factors, structural integrity, and human error. Effective risk assessment is essential for ensuring safety and project success. This study employs the Analytic Hierarchy Process (AHP) to systematically analyse and prioritize risks associated with tunnel construction. To achieve this, a 54-question questionnaire is developed and circulated among professionals in the tunnel industry. The responses are evaluated using the Saaty's scale, allowing for a structured assessment of risk factors. The identified risks were categorized into four main clusters, viz; Geotechnical Condition Risk – including ground instability, seismic activity, rock mass behaviour, and water ingress. External Condition Risk – covering environmental hazards, extreme weather conditions, and third-party influences such as regulatory changes and social impact. Management Condition Risk – encompassing insufficient planning, workforce safety, lack of proper risk control measures, and time constraints due to over-demand and project rush. Risk Management Condition – involving inefficiencies in systematic risk assessment, inadequate maintenance strategies, and failure in learning from past near-miss incidents. Through expert judgment and mathematical consistency checks, this study identifies the most critical risk factors and proposes mitigation strategies to enhance safety and efficiency in tunnel construction. The results obtained through this study will emphasize the importance of structured risk assessment models for informed decision-making, improved project execution, and sustainable infrastructure development. By integrating quantitative methods like AHP, this research provides valuable insights for project managers, engineers, and policy makers, promoting safer and more efficient tunnelling practices while ensuring resilience against potential risks.

Keywords: Adolescents, Risk Analysis, AHP, Saaty Scale, Expert Judgment

Introduction

The construction of tunnels is one of the most complicated and dangerous operations in civil engineering considering the uncertainty of ground conditions and the complications associated with the works [1]. The success of these works rely on a risk assessment methodology that anticipates and ranks all risk and risk mitigation from the beginning of the construction/ownership life cycle to the completion. The major risk factors include: unpredictable geology and hydrology, environmental factors such as the force of nature, equipment failures and human factors which collectively lead to a potentially more complex risk situation that requires awareness of the risk to life, accident costs and project delays and disruption all of which may occur, if they go unmanaged [2]. Risk assessment goes beyond technical assessment here; it is also an essential aspect of planning and delivery. Tunnel construction includes uncertainties that are site specific and thus an instance in which a new path failures of more traditional assessments of risk that encapsulate the dynamism and interdependence of risk [3]. The Analytic Hierarchy Process (AHP) provides a systematic and structured approach to solving complex decision-making processes containing both qualitative and quantitative considerations [4]. AHP is useful because it breaks down the overall goal—safe and efficient tunnel construction—into hierarchical levels of risk categories and sub-factors, allowing project stakeholders to make pairwise comparisons and determine priority weights for each risk based on expert opinions.

This study implements the AHP methodology to analyze and rank the uncertainties related to tunnel construction by distributing a structured, 54-question questionnaire to experienced practitioners working in the field of tunneling. The responses will be analyzed using Saaty's 9-point scale and the responses will need to logically check out and create an objective hierarchy of risks [5]. The risks are categorized into four major groupings: Geotechnical, External Conditions, Management, and Risk Management Conditions—each grouping has key sub-factors, such as, ground instability, seismic activity, environmental risks, health and safety of personnel, and improper maintenance planning. The risk model architectural framework developed through this study assists better decision making by providing a clear picture with the relative importance of different risk factors [6] . It emphasizes early identification of key risks, improvement of mitigation efforts, and cultivation of resilience in tunnel work. By combining AHP with expert knowledge from the real-world, it advances risk-informed project management, ultimately facilitating safer, more predictable, and less costly tunneling projects.

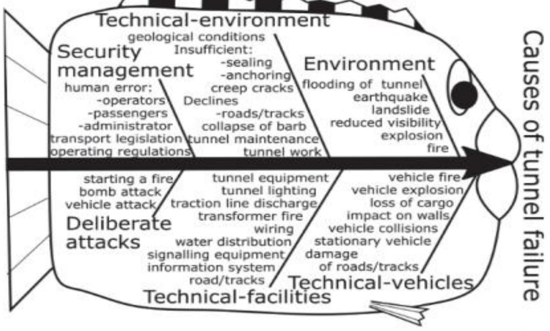

Fig. 1. Sources of risk of tunnel failure on the routes [7].

Tunnel construction involves high levels of uncertainty due to complex geological, environmental, and technical factors [8]. If not handled properly risks become overruns, delays and safety issues. Traditional risk assessing typically are unstructured, and difficult to rank as to importance. Analytic Hierarchy Process (AHP) offers a structured way to examine numerous risk factors through pairwise comparison and expert evaluation. AHP identifies risks and also increases the ability to challenge, define, evaluate and rank criteria. In this project AHP was use to organize risk into primary, sub-factors as credential (AS / BS, and additional sub factors) giving the initial opportunity to prioritize systematically based on information and data. Overall I expect this new model of AHP provided a more rational systematic assessment of risk and a more rational order of decision making and risk management for tunnelling project [9].

1.1 Problem Statement

Tunnel construction is inherently complex and fraught with numerous uncertainties due to variable geological conditions, environmental factors, technical challenges, and management inefficiencies [10]. These risks may result in delays to the delivery of the project, budget overruns, structural failures/damage, and safety concerns. Most risk assessment approaches currently utilized provide little to no systematic assessment of risk factors and are not sufficiently proactive, resulting in reactive rather than pro-active decision-making. Most people do not have a structured approach for identification and quantification of major risks therefore the effectiveness of the risk management plans is negatively influenced in relation to their risk mitigation strategies. The use of expert judgements are frequently cited however with no formalizing of some approach to ensure there is consistency on the ultimate risk prioritization. As a result, critical risks may be omitted and lesser issues have resources assigned to them.The Analytic Hierarchy Process (AHP) is a powerful and systematic multi-criteria decision-making method that addresses these challenges by enabling experts to systematically perform pairwise comparisons and to weight risk factors based on their relative importance [11]. However, the application of AHP in relation to risk management as it relates to tunnel construction, remains limited in applicability and application. Understanding this research contributes to the development of a clear AHP-based framework to identify and assess tunnelling construction risks that may be helpful for project teams making more informed, consistent and effective risk management choices across the project life cycle.

1.2 Objectives

1. To identify and categorize the key risk factors associated with tunnel construction.
2. To develop a structured risk assessment framework using the Analytic Hierarchy Process (AHP).
3. To evaluate the relative importance of each risk factor through expert judgment and pairwise comparisons.
4. To determine the most critical risk factors affecting tunnel construction and propose targeted mitigation strategies.
5. To enhance decision-making capabilities for project managers and stakeholders in tunnel construction projects.

II. LITERATURE REVIEW

This study is strongly supported by the research of Garsole et.al (2023) who used the Analytic Hierarchy Process (AHP) as a structured risk assessment in their risk management works of tunnel constructions project [12]. Using their methodology, expert surveys and Saaty's Scale, they built a hierarchy on risk factors as well. In addition, Sanchia Maria Morris and Dr. B.V. Gopala Krishna were able to enrich that structure by utilizing Importance Index methodologies and case studies from large scale tunneling projects in India [13].

The research paper titled 'Development of a Risk Management Framework for Tunnel Construction in India' by Sanchia Maria Morris and Dr. B.V. Gopala Krishna (2020) also included approaches for the identification, assessment and management of risk on tunneling projects. The methodology used in the paper included a review of the literature, interviews with industry practitioners, and case studies. There was a detailed list of internal and external risks that affect the completion of tunneling jobs. The importance Index (IMP.I) technique was used to quantify risk. The study provided a risk assessment of the frequency and severity of occurrence for each risk, and developed a probability-impact matrix of risk assessment along with a priority ranking of the high risk exposures [14]. The main findings showed that government policies, labour issues, other site condition issues, and land disputes - external risks - were the most severe risks and usually resulted in cost and time overruns. The findings showed that risk planning at the outset was necessary, good mitigation plans and processes as well as checking at all points in the risk management process promoted the likelihood of success in project outcomes. Examples from large projects supported the framework; BMRCL Tunnel Phase I, Atal Tunnel and Kuthiran Tunnel.

The first study on AHP based risk assessment of tunnel construction was presented by A. Syed and Dr S.A. Bokil who provided a framework of a hierarchy of risks for tunnel projects [15]. Other contributions include Sanchia Maria Morris and Dr. B. V. Gopala Krishna, who used Importance Index and field surveys to develop a risk management model, as well as Konstantinos Kazaras, Konstantinos Kirytopoulos, and Athanasios Rentizelas, providing two studies concerning the STAMP method and substantiate the premise that a road tunnel might be assessed at both the "organizational" and "technical" levels using the structured analysis of the system safety to assess risk. These authors generally represent a multi-faceted rationale for the assessment and risk mitigation in tunnels [16].

This research draws upon the foundational work of A. Syed and Dr. S. A. Bokil, who utilized AHP to prioritize risks in tunnel construction [17]. Sanchia Maria Morris and Dr. B. V. Gopala Krishna brought forth real-life advice with importance index analysis in tunneling conditions. Marcel Suchomel and Jiri Martinek presented a plethora of safety indices in tunnel infrastructure assessments. Finally, Matteo Buzzi and Sandro Martinoia from the recent linked publication described the safety programs in Europe to change the behaviours of nations, control systems, and users. All of this to say that both the theoretical aspects and real-life contributions have provided a wealth of knowledge about risk assessment in tunnels [18].

This research has its foundation mainly on the work of A. Syed and Dr. S. A. Bokil, who applied Analytic Hierarchy Process (AHP) for systematically assessing the construction tunnel risks [19]. The referenced literature shows similar work by Sanchia Maria Morris and Dr. B. V. Gopala Krishna who used the Importance Index to assess priority hazards from tunneling. Konstantinos Kazaras, Athanasios Rentizelas and their colleagues articulated the STAMP model for assessing systemic safety. Their works referenced Petr Pospisil, Marcel Suchomel, and Jiri Martinek's assessment of multiple indices that could be applied for tunnel risk assessment which included economic gains. The multi-dimensional pathway for assessing risks for tunnels and the performance monitoring relying on European, and Czech tunnel safety frameworks correspondingly reinforced contribution practice based activities as reported upon by Matteo Buzzi, Sandro Martinoia and J. Sýkora,[20].

Guo et al. (2025) proposed a new risk assessment model for shield tunnel construction, adjacent to existing tunnels, consisted of an enhanced fuzzy Analytic Hierarchy Process (FAHP) combined with game theory and cloud models [21]. The model is designed to accommodate nonlinear risk factors, leading to a more thorough and reliable risk assessment. The study developed index system and applied the model to the risk assessment of shield construction projects of Changsha Metro, demonstrating the operational feasibility of the model [22].

The research by Pyakurel and Adhikari (2023) focuses on risk assessment in tunnel construction using the Analytic Hierarchy Process (AHP)[23] . Their study, which was a case study of 2 tunnels in Nepal, acknowledged a broad range of risks to tunnel projects and how geotechnical risks were the most significant. By using the AHP method, they ranked all these risk factors, allowing the project manager to see which risk factors were more significant (for example, geological conditions, safety, natural hazards, etc.) and can delay projects and increase costs in tunnels.

Aagat Pyakurel and Basanta Raj Adhikari (2025) conducted a study on the evaluation of tunnel safety in the Nepal Himalaya by performing a comprehensive risk assessment using the Analytic Hierarchy Process (AHP) [24]. The paper highlights the most significant risk factors in tunnel construction, including geo-technical risks, natural hazards, and construction safety risks, particularly in hilly contexts like Nepal. The study will provide guidance to future tunneling in Nepal by demonstrating how risk can be systematically analyzed and mitigated [25].

III. METHODOLOGY

This project applies the Analytic Hierarchy Process (AHP) as a structured multi-criteria decision-making (MCDM) technique that will serve to help facilitate evaluating and ranking the risks associated with tunnel construction projects. AHP is a mathematical process that assists in establishing a valid risk hierarchy using expert opinion. Using expert opinion from industry experts and an exhaustive literature review in the preliminary stages, a minimum of 4 levels of risk domains were derived for the tunnel construction project area of study. The experts, based on their professional and practical experiences were able to rank the levels of risk domains which are: Geotechnical conditions; External environment; Management conditions; and Risk management practices. Each risk domain contains additional sub risk factors; such as but not limited to ground instability, seismic activity, adverse weather conditions, unsafe conditions, and inadequate maintenance; that factor into the integrated risk domains. A consistent, structured survey originally containing 54 pairwise comparisons, was developed in accordance with Saaty's 9 point scale, and allowed raters to compare and rank the aspects of relative importance of one risk factor against another. The survey was administered to professional civil engineers, project managers, and tunneling professionals; while the supply chain of participants was limited, it allowed for participants to make a weighting decision on the aforementioned risk factors.

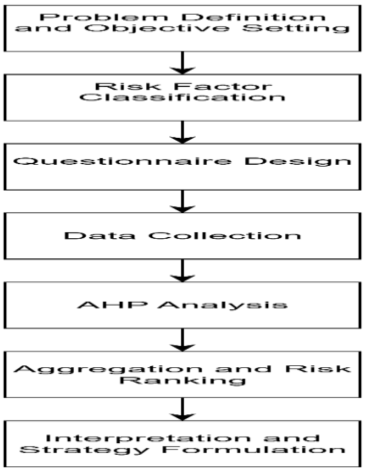

Fig 2. Methodology Flow for Risk Assessment in Tunnel Construction Using AHP

The responses were used to create pairwise comparison matrices for each category of risk. Priority weights were established using the eigenvalue method influenced by the responses, in essence, indicating how relatively important each of the factors assessed were. The Consistency Ratio (CR) was then calculated to verify those judgements. A CR value of less than 0.1 was accepted and demonstrated the experts were consistent in their response. After determining the priority weighting of sub-factors, the normalization of these values into values, their respective clusters summed to obtain an overall risk rank. The output of the AHP model then permits determination of those high priority risks which would inform the project mitigation plan. The structured process not only provides transparency and consistency, but also rationalizes decisions, while enabling a user to account for the complexities involved in tunnel construction.

IV. RISK ANALYSIS

The risk assessment process for tunnel construction was conducted through the Analytic Hierarchy Process, which enabled Importance Index (II) analysis for assessing relative importance for each of the risks that were identified. The application of AHP-IIs in this study utilized relevant quantitative frequency and severity ratings and qualitative statement of expert judgement in order to balance theoretical defensibility and practical validity.

A. Questionnaire Survey

A structured questionnaire was sent to professional tunnel construction practitioners to rate the frequency and level of severity of risk factors identified in the literature. Responses were from engineers, contractors, and safety practitioners, using a 5-point scale for frequency and severity, and expert ratings were used for AHP using pairwise comparisons. AHP responses for analysis were organized with a Consistency Ratio ≤ 0.1.

Table 1. Summary of Questionnaire Survey Design and Parameters

Section	Description
Respondents	Engineers, contractors, safety officers
Sample Size	[55]
Rating Scale	0 (Very Low) – 9 (Very High)
Risk Factors	[54]
Method	Frequency, Severity scoring + AHP pairwise comparisons
Data Validity	Consistency Ratio ≤ 0.1

A. Importance Index (IMP.I) Technique

The Importance Index (IMP.I) is a combined score that ranks risks in terms of the chance of occurrence and the severity of consequences. It is obtained by combining two factors: the Frequency Index (FI) and its Severity Index (SI) into a single percentage score.

Step 1 – Frequency Index (FI)

The Frequency Index quantifies how often a particular risk is expected to occur, based on respondents' ratings.

$$FI(\%) = \frac{\sum_{i=1}^{n} f_i \times w_i}{A \times N} \times 100$$

Where:

- f_i = Frequency rating given by respondent i
- w_i = Weight assigned to each rating (0 = Very Low, …, 9 = Very High)
- A = Highest rating on the scale (9 in this study)
- N = Total number of respondents

Step 2 – Severity Index (SI)

The Severity Index measures the magnitude of the consequences if the risk occurs.

$$SI(\%) = \frac{\sum_{i=1}^{n} s_i \times w_i}{A \times N} \times 100$$

Where:

- s_i = Severity rating given by respondent i

Other terms are as defined above

Step 3 – Importance Index (IMP.I)

The Importance Index is the product of FI and SI, representing the overall significance of each risk factor.

$$IMP.I(\%) = \frac{FI(\%) \times SI(\%)}{100}$$

Interpretation:

- **High IMP.I%** → High-priority risk needing immediate attention
- **Low IMP.I%** → Lower priority in risk management plans

The results of the analysis suggest that, Unforeseen or Unexpected Ground Conditions (R2), Cover Span Ratio, Covering Depth and Tunnel Diameter (R15), and Soil Shear Strength (R7) are among the most significant risks since they exhibit Importance Index values greater than 36 %; and they are respectively critical to tunnel construction safety and performance. Several geotechnical and environmental factors, such as Hydrogeological Conditions (R21) and Societal Risk (R38), also rank high; thus suggesting that a site-specific investigations and stakeholder understanding and awareness are important. Similarly, risk items such as Structural Failures (R18) and lack of Scientific Methods for Perception (R39) should still be monitored as they would fall in the category of lesser severity or lower occurrence frequency. Overall, the outcomes indicate that most risks identified in the business case can be related to geotechnical uncertainties and design related parameters specify the risk profile and ultimately direct mitigation priority.

B. Risk Matrix:

The Risk Matrix is a quantitative tool that assesses risk by the probability of a risk occurring (Y-axis) and the impact to the project objectives (X-axis) related to cost or time. Each cell value in the risk matrix is the product of probability the risk occurs, and the impact it would cost in terms of severity. Risk scores are identified as 0.01 (Very Low), 0.81 (Critical). The Risk Matrix ranks risk from highest to lowest based on the risk scores—and a high-risk scored indicates a larger potential threats to managing risk, which would require immediate consideration of mitigation. The Risk Matrix provides a formal approach rational for permitting consideration of risk in the management of risk in tunnel construction.

Table 2. Risk Matrix Based on Probability and Impact on Project Objectives (Cost/Time)

	IMPACT ON PROJECT OBJECTIVE (cost/time)					
PROBABILITY	Y / X →	0.1	0.3	0.5	0.7	0.9
	0.1 (Very Low)	0.01	0.03	0.05	0.07	0.09
	0.3 (Low)	0.03	0.09	0.15	0.21	0.27
	0.5 (Medium)	0.05	0.15	0.25	0.35	0.45
	0.7 (High)	0.07	0.21	0.35	0.49	0.63
	0.9 (Very High)	0.09	0.27	0.45	0.63	0.81

Table 3. Risk Factors for Tunnel Construction with Frequency, Severity, and Importance Indices

RISK ID	Risk Factors	Frequency Index (F.I) (%)	Severity Index (F.I) (%)	Importance Index (%)	Ranking	AHP_Weight
R1	Risk	54.95	54.95	30.19	27	0.018423
R2	Unforeseen or Unexpected Ground Conditions	62.83	62.83	39.47	1	0.021065
R3	Variable and Mixed Face Conditions	60.00	60.00	36.00	8	0.020116
R4	Ground Loss or Collapse at the Tunnel Face	55.56	55.56	30.86	32	0.018626
R5	Man-Made Obstructions	55.96	55.96	31.31	25	0.018762
R6	Human Errors	53.13	53.13	28.23	39	0.017814
R7	Soil Shear Strength	60.81	60.81	36.98	3	0.020387
R8	Groundwater Table	54.55	54.55	29.75	35	0.018288
R9	Concrete Lining Segment Strength	51.11	51.11	26.12	44	0.017136
R10	Pile Bearing Capacity	48.69	48.69	23.70	50	0.016323
R11	Seismic Risk	58.18	58.18	33.85	11	0.019507
R12	Tunnel Deterioration	57.37	57.37	32.92	16	0.019236

R13	Working Face Instability	56.36	56.36	31.77	19	0.018897
R14	Environmental Health Risks	60.61	60.61	36.73	8	0.02032
R15	Cover Span Ratio, Covering Depth, and Tunnel Diameter	62.42	62.42	38.97	2	0.020929
R16	Seepage and Drainage Issues	60.61	60.61	36.73	11	0.02032
R17	Tunnel Network Interdependence	54.55	54.55	29.75	32	0.018288
R18	Structural Failures	45.45	45.45	20.66	54	0.01524
R19	Excessive or Unexpected Groundwater Inflow	56.77	56.77	32.23	27	0.019033
R20	Unstable Ground or Unanticipated Ground Behavior	50.10	50.10	25.10	47	0.016798
R21	Hydrogeological Conditions	61.21	61.21	37.47	5	0.020523
R22	Soft Soil Layers	54.34	54.34	29.53	30	0.01822
R23	Poor Judgment or Error in Design Incompatible Selection of Means and Methods	48.08	48.08	23.12	52	0.01612
R24	Poor On-Site Management and Communication	52.12	52.12	27.17	39	0.017475
R25	Limited Response Capability in Confined Working Environments	59.80	59.80	35.76	11	0.020049
R26	Ground Movement Mechanism and Land Settlement	58.79	58.79	34.56	10	0.01971
R27	Geotechnical Uncertainties (e.g., Complex Geological Environments)	53.13	53.13	28.23	39	0.017814
R28	Geotechnical Conditions (Soil and Rock Composition)	57.98	57.98	33.62	11	0.019439
R29	Seismic Risks (for Tunnels in Seismic Zones)	54.55	54.55	29.75	10	0.018288
R30	Dynamic Process of Risk Identification	54.75	54.75	29.97	39	0.018355
R31	Defects from Tunnel Structures	48.08	48.08	23.12	19	0.01612
R32	Environmental Factors	48.48	48.48	23.51	34	0.016256
R33	Management and Operational Factors	53.13	53.13	28.23	30	0.017814
R34	Disaster-related Factors	53.74	53.74	28.88	52	0.018017
R35	Seismic Risk	60.40	60.40	36.49	49	0.020252
R36	Uncertainties in Risk Assessment	54.75	54.75	29.97	37	0.018355
R37	Risk-Perception Factors	51.92	51.92	26.96	35	0.017407
R38	Societal Risk	60.00	60.00	36.00	3	0.020116
R39	Lack of Scientific Methods for Perception	47.88	47.88	22.92	23	0.016053
R40	Lack of Decision-Making Mechanisms	56.16	56.16	31.54	45	0.01883
R41	Lack of Information Exchange Platform	50.30	50.30	25.30	6	0.016865
R42	Need for Technological Advancements	58.99	58.99	34.80	51	0.019778
R43	Learning from Near-Miss Incidents	50.10	50.10	25.10	27	0.016798
R44	Risk Management in Construction Industry	53.33	53.33	28.44	46	0.017881
R45	Risk Control Focus	55.56	55.56	30.86	11	0.018626
R46	Traditional Risk Management Methods	56.36	56.36	31.77	48	0.018897
R47	Systematic Risk Assessment	52.53	52.53	27.59	27	0.01761
R48	Timely Maintenance to Prevent Structural Failures	57.37	57.37	32.92	25	0.019236
R49	Risk Cost Optimized Maintenance Strategy	58.79	58.79	34.56	19	0.01971
R50	Infrastructure, Equipment, and Management Procedures	56.77	56.77	32.23	39	0.019033
R51	Societal Risk in Tunnel Systems	56.97	56.97	32.46	23	0.019101
R52	Technical Personnel Safety Management	55.56	55.56	30.86	6	0.018626
R53	Insufficient Time for Design and Review	53.33	53.33	28.44	17	0.017881
R54	Over-Demand and Pressure to Rush Projects	57.37	57.37	32.92	18	0.019236

V. RESULTS AND DISCUSSION

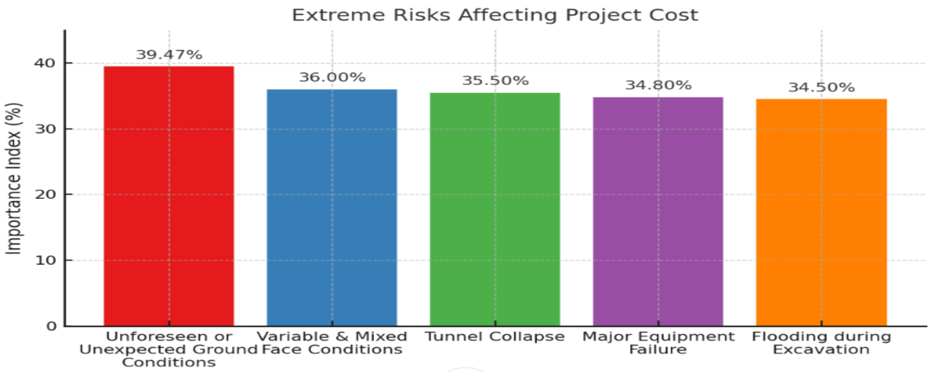

Fig 3. Extreme Risks Affecting Project Cost

The bar chart shows the most extreme risks created on project cost in tunneling or underground project. The extreme risks listed include "Unforeseen or Unexpected Ground Conditions" with a ranking of 39.47% in importance. Following that are "Variable and Mixed Face Conditions" (36.0%) and "Tunnel Collapse" (35.5%). Other major risks include, "Major Equipment Failure" (34.8%), and "Flooding during Excavation" (34.5%). Each of these risks has the potential to significantly increase the costs for the project and having a proactive strategy to mitigate is imperative.

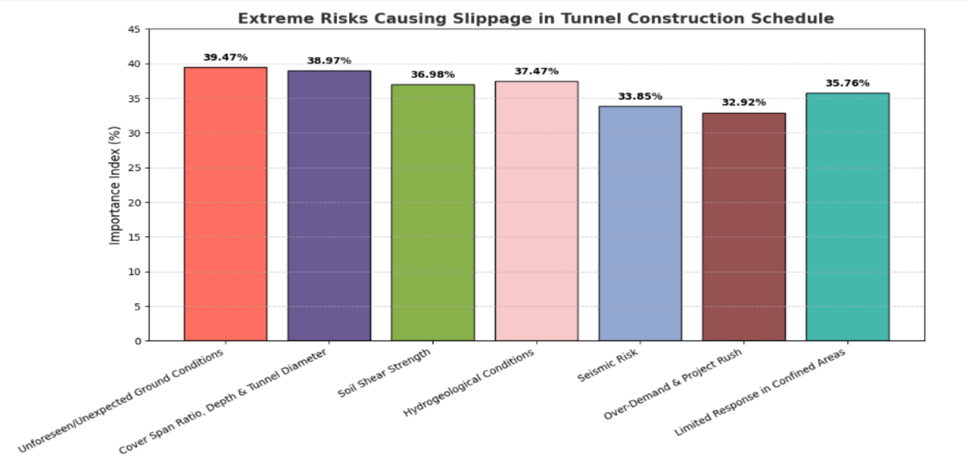

Fig 4. Extreme Risks Causing Slippage in Tunnel Construction Schedule

The graph depicts the most important risks to project delays in tunnelling construction, ranked according to Importance Index. Hidden or unexpected ground conditions are the highest (39.47%) followed by Design factors just as Cover Span Ratio, Depth & Tunnel Diameter (38.97%) and Soil Shear Strength (36.98%). Geotechnical and hydrogeological uncertainties, and restricted ability to respond in confined space are also important risks to project timelines. Overall, the results strongly emphasise the need for proactive geotechnical investigation, careful design management and responsive site management in order to efficiently manage schedule slippage.

In this study, AHP prioritization and Importance Index analysis identified Unforeseen Ground Conditions (39.47%), Cover Span Ratio & Tunnel Diameter (38.97%), and Soil Shear Strength (36.98%) as the most critical risks with influence on price and time. Geotechnical risks must be acknowledged and apply comprehensive site investigation and quality design.

Guo et al. (2025) developed a new nonlinear Fuzzy Analytic Hierarchy Process (FAHP) model which incorporated a combined weighting from game theory, with a cloud model, to evaluate the risk of shield construction adjacent to current shield tunnels. Application of the method for the Changsha Metro Line 4 project, situated next to Metro Line 2, highlighted three samples, with Sample 1 and Sample 3 classified as Level III (relative high risk), and Sample 2 classified as Level II (relative low risk). The results detailed how the model improved capture of the significance of critical risk factors, such as reinforcement effect, line geometry, and the relative distance, outperforming traditional FAHP evaluation methods in context with actual site conditions.

In the study by Sanchia and Dr.B.V. Gopala Krishna, the highest-rated risks by Importance Index were Site condition problematic- loose/hard soil (Cost: 0.57, Time: 0.55), Inflation/price escalation (Cost: 0.55, Time: 0.49), Land disputes (Cost: 0.47, Time: 0.50), Strikes & labour disputes (Cost: 0.46, Time: 0.50) and Change in government policies (Cost: 0.45, Time: 0.46). These factors, mainly external, were common in large tunnel projects, and the key drivers of cost overruns and schedule delays, which further confirmed the need to identify risks early, transfer risk where possible and to have an effective plan to mitigate.

VI. RISK RESPONSE, MONITORING, AND CONTROL

In tunnel construction projects, Risk Responsiveness, Risk Monitoring, and Risk Control are fundamental aspects of project management due to the significant high-impact risks identified by the AHP and Importance Index analysis that necessitate management action. Once the high impact identified risks have been prioritized (on the risk matrix) such as unknown ground conditions, soil shear strength issues or hydrogeological complications, it will be imperative to develop response strategies for the risks that will include avoidance, mitigation, transfer or acceptance based on the severity of the risk and the probability of its occurrence. Once responses and strategies have been decided upon, Risk Monitoring and Risk Control will ensure continued tracking of the identified risks, evaluation of new and emerging risks, and monitoring the effectiveness of response plans that must remain active for the length of the project. Tools such as risk registers, checklists, and real-time dashboards (or some overlap with BIM and IoT systems) can represent effective means of risk monitoring; however, performance indicators and thresholds must be established to prompt corrective action as required. Project site inspections, expert reviews, and communicating with project stakeholders, can all aid in the early recognition of deviations from the anticipated risk behaviour. The feedback loop of near-miss incidents and updated risk assessments provides a platform for managing adaptively which leads to a capacity to improve resilience and response to risk. In addition, it is required to carry out consistency checks (e.g., using Consistency Ratio in AHP) whenever new information is added. Ultimately, a responsive and integrated risk response and monitoring program is correlated with better safety, cost, and delivery for tunnel infrastructure projects.

VII. CONCLUSION

The work presented in this paper has developed a complete, systematic risk assessment framework for tunnelling operations (using the Analytic Hierarchy Process (AHP)). The research has achieved this through expert opinion collated with quantitative methods and risk evaluation techniques, such as the Importance Index (IMP.I), while also identifying and classifying risk. The AHP methods were also able to rank risks and assess risk nature, which are the variances that rate risk levels (influences). Based on the research results, risk factors have been identified that were some of the largest contributors to time and cost delays and overruns to projects, which included Unforeseen or Unexpected Ground Conditions, Cover Span Ratio, Depth & Tunnel Diameter, and Soil Shear Strength (due to Construction Method). With inherent uncertainties, geotechnics can entail a heavier reliance on more elaborate site investigations (subsequent to whether previous investigations can be adduced) as well as more thorough design to ameliorate risk (associated costs). The way the study runs the risk assessment clearly delineates four categorically distinct clusters (Geotechnical, External Conditions, Management, Risk Management), which gives clarity on the associations and inter-relation of schema of technical risks and organisational risks. The Saaty scale and evaluating the consistency ratio also guarantees logical consistency amongst expert evaluations. The AHP-based model developed provides an applicable means of safeguarding informed decision making and prioritizing risk mitigation as well as allocation of resources for the cave construction stakeholders. It emphasizes the value of structured, data-informed approaches to navigate the complexities associated with underground construction. Ultimately, this research succeeds in contributing to safer, efficient, and resilient tunnel infrastructure construction, while also setting the stage for future collaboration with advanced technologies and methods, such as Bit Information Modelling (BIM), Internet of Things (IoT), and machine learning.

VIII. FUTURE SCOPE

The use of the Analytic Hierarchy Process (AHP) to assess and quantify risk factors for tunnel construction is a systematic and robust approach, although there is much room for improvement in the future. More developments can be carried out through further studying fused AHP or hybrid models as in, but not limited to, AHP-TOPSIS, or AHP-FMEA, to account for uncertainties and subjectivity in experts' judgments. Also, the use of project real-time data during a construction project—including but not limited to an ongoing tunneling project of geotechnical sensors, construction logs, other environmental data, etc.—to give better findings in risk modelling. Future research can also focus on dynamic risk, as the risk model could be updated as phases of the project progress. The same methodology can be applied to the different types of tunnels (urban metro, undersea, high-altitude tunnels, etc.) and regions of the world to generalize the hierarchy of risks. Coupling this process with Building Information Modeling (BIM) or Digital Twins could track risk propagation and mitigation decisions in a virtual space. The use of machine learning algorithms for predictive risk analytics could further serve to give project managers decision-making tools that relevantly evolve as data trends change. The current model can be progressed through some interdisciplinary techniques and technologies so that future research will assist in building safer, smarter, and less costly tunnel infrastructure worldwide

IX. REFERENCES

[1] T. Zvarivadza *et al.*, “On the impact of Industrial Internet of Things (IIoT) - mining sector perspectives,” *Int. J. Min. Reclam. Environ.*, vol. 38, no. 10, pp. 771–809, Nov. 2024, doi: 10.1080/17480930.2024.2347131.

[2] A. Shaktawat and S. Vadhera, “Risk management of hydropower projects for sustainable development: a review,” *Environ. Dev. Sustain.*, vol. 23, no. 1, pp. 45–76, Jan. 2021, doi: 10.1007/s10668-020-00607-2.

[3] R. Zhang, W. Wu, Q. Li, J. Liu, and A. Wang, “A dynamic calculation method for safety step distance in mechanized soft rock tunnel construction using multi-source data integration,” *Tunn. Undergr. Space Technol.*, vol. 165, p. 106867, Nov. 2025, doi: 10.1016/j.tust.2025.106867.

[4] M. J. Hill, R. Braaten, S. M. Veitch, B. G. Lees, and S. Sharma, “Multi-criteria decision analysis in spatial decision support: the ASSESS analytic hierarchy process and the role of quantitative methods and spatially explicit analysis,” *Environ. Model. Softw.*, vol. 20, no. 7, pp. 955–976, July 2005, doi: 10.1016/j.envsoft.2004.04.014.

[5] M. Danner, V. Vennedey, M. Hiligsmann, S. Fauser, C. Gross, and S. Stock, “How Well Can Analytic Hierarchy Process be Used to Elicit Individual Preferences? Insights from a Survey in Patients Suffering from Age-Related Macular Degeneration,” *Patient - Patient-Centered Outcomes Res.*, vol. 9, no. 5, pp. 481–492, Oct. 2016, doi: 10.1007/s40271-016-0179-7.

[6] Sanchia Maria Morris and National Institute of Technology, Surathkal, “Development of a Risk Management Framework for Tunnel Construction in India,” *Int. J. Eng. Res.*, vol. V9, no. 06, p. IJERTV9IS060958, July 2020, doi: 10.17577/IJERTV9IS060958.

[7] R. K. Haddad and Z. Harun, “Development of a Novel Quantitative Risk Assessment Tool for UK Road Tunnels,” *Fire*, vol. 6, no. 2, p. 65, Feb. 2023, doi: 10.3390/fire6020065.

[8] S. Li *et al.*, “Predicting geological hazards during tunnel construction,” *J. Rock Mech. Geotech. Eng.*, vol. 2, no. 3, pp. 232–242, Sept. 2010, doi: 10.3724/SP.J.1235.2010.00232.

[9] Y. Guo, J. Zheng, R. Zhang, and Y. Yang, “an evidence-based risk decision support approach for metro tunnel construction,” *J. Civ. Eng. Manag.*, vol. 28, no. 5, pp. 377–396, May 2022, doi: 10.3846/jcem.2022.16807.

[10] M. Deng, “Challenges and Thoughts on Risk Management and Control for the Group Construction of a Super-Long Tunnel by TBM,” *Engineering*, vol. 4, no. 1, pp. 112–122, Feb. 2018, doi: 10.1016/j.eng.2017.07.001.

[11] M. Tavana, M. Soltanifar, and F. J. Santos-Arteaga, “Analytical hierarchy process: revolution and evolution,” *Ann. Oper. Res.*, vol. 326, no. 2, pp. 879–907, July 2023, doi: 10.1007/s10479-021-04432-2.

[12] P. A. Garsole, S. Bokil, V. Kumar, A. Pandey, and N. S. Topare, “A review of artificial intelligence methods for predicting gravity dam seepage, challenges and way-out,” *AQUA — Water Infrastruct. Ecosyst. Soc.*, vol. 72, no. 7, pp. 1228–1248, July 2023, doi: 10.2166/aqua.2023.042.

[13] Sanchia Maria Morris and National Institute of Technology, Surathkal, “Development of a Risk Management Framework for Tunnel Construction in India,” *Int. J. Eng. Res.*, vol. V9, no. 06, p. IJERTV9IS060958, July 2020, doi: 10.17577/IJERTV9IS060958.

[14] J. B. H. Yap, I. N. Chow, and K. Shavarebi, “Criticality of Construction Industry Problems in Developing Countries: Analyzing Malaysian Projects,” *J. Manag. Eng.*, vol. 35, no. 5, p. 04019020, Sept. 2019, doi: 10.1061/(ASCE)ME.1943-5479.0000709.

[15] A. Pyakurel and B. R. Adhikari, “Tunnel safety evaluation in the Nepal Himalaya: a case study of utilising analytic hierarchy process (AHP) for comprehensive risk assessment,” *Discov. Civ. Eng.*, vol. 2, no. 1, p. 63, Mar. 2025, doi: 10.1007/s44290-025-00221-z.

[16] Y. Guo, J. Zheng, R. Zhang, and Y. Yang, “an evidence-based risk decision support approach for metro tunnel construction,” *J. Civ. Eng. Manag.*, vol. 28, no. 5, pp. 377–396, May 2022, doi: 10.3846/jcem.2022.16807.

[17] A. Pyakurel and B. R. Adhikari, “Tunnel safety evaluation in the Nepal Himalaya: a case study of utilising analytic hierarchy process (AHP) for comprehensive risk assessment,” *Discov. Civ. Eng.*, vol. 2, no. 1, p. 63, Mar. 2025, doi: 10.1007/s44290-025-00221-z.

[18] I. C. Cárdenas, S. S. H. Al-Jibouri, J. I. M. Halman, W. Van De Linde, and F. Kaalberg, “Using Prior Risk-Related Knowledge to Support Risk Management Decisions: Lessons Learnt from a Tunneling Project,” *Risk Anal.*, vol. 34, no. 10, pp. 1923–1943, Oct. 2014, doi: 10.1111/risa.12213.

[19] N. G. Gogate, Abhaysinha. G. Shelake, and P. Band, “Selection of most significant risk factors for Indian tunnel projects: an integrated fuzzy-based MCDM approach,” *Int. J. Constr. Manag.*, vol. 24, no. 2, pp. 161–176, Jan. 2024, doi: 10.1080/15623599.2023.2267852.

[20] D. Smažinka, Š. Kavan, and M. Hrinko, “Evaluation of the current technologies used for the physical security and safety of selected railway tunnel portals as a case study in the Czech Republic,” *J. Transp. Secur.*, vol. 17, no. 1, p. 6, Dec. 2024, doi: 10.1007/s12198-024-00275-7.

[21] T. Xu, Z. Song, S. Fan, and D. Guo, “Improved risk assessment model using the cloud theory of the existing tunnel in foundation pit construction environment,” *Eng. Constr. Archit. Manag.*, Feb. 2025, doi: 10.1108/ECAM-07-2023-0736.

[22] J. Tian *et al.*, “Urban Underground Space Geological Suitability—A Theoretical Framework, Index System, and Evaluation Method,” *Appl. Sci.*, vol. 15, no. 8, p. 4326, Apr. 2025, doi: 10.3390/app15084326.

[23] A. Pyakurel and B. R. Adhikari, “Tunnel Risk Assessment Using Analytic Hierarchy Process (AHP): Case Study of Two Tunnels of Nepal,” 2023.

[24] A. Pyakurel and B. R. Adhikari, “Tunnel safety evaluation in the Nepal Himalaya: a case study of utilising analytic hierarchy process (AHP) for comprehensive risk assessment,” *Discov. Civ. Eng.*, vol. 2, no. 1, p. 63, Mar. 2025, doi: 10.1007/s44290-025-00221-z.

[25] A. Pyakurel and B. R. Adhikari, “Tunnel safety evaluation in the Nepal Himalaya: a case study of utilising analytic hierarchy process (AHP) for comprehensive risk assessment,” *Discov. Civ. Eng.*, vol. 2, no. 1, p. 63, Mar. 2025, doi: 10.1007/s44290-025-00221-z.