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A Study on Risk Assessment in Tunnelling Construction for Klang Valley Mass Rapid Transit (KVMRT) Putrajaya Line

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Abstract: Effective management of risk factors is crucial for the successful implementation of such complex projects. The underground projects in Kuala Lumpur will encounter a range of constraints and challenges in terms of design and construction, which are specific to the city's geology. This study focuses on the specific risks and challenges associated with tunnelling construction in the KVMRT project. Through a comprehensive literature review, risk factors related to tunnel construction were identified. The Analytic Hierarchy Process (AHP) was employed to analyze potential factors contributing to problems during tunnelling works. Industry experts from the KVMRT project were interviewed using a semi-structured approach to gather data, with a specific focus on the TU3 drive from Hospital Kuala Lumpur Crossover to Ampang Park Station of the MRT Putrajaya Line. The results revealed that ground conditions emerged as the primary factor causing problems in tunnelling construction. A risk register was utilized to identify potential mitigation plans. The study concludes with key findings, recommendations, and conclusions pertaining to the project. The ground condition poses risks such as tunnel collapses, ground subsidence, and water ingress. Thus, future studies should focus on this factor.

Keywords: Analytic Hierarchy Process (AHP), KVMRT, Ground Condition

1. Introduction

Due to the restricted amount of land available for development, there has been an increase in underground space exploration and utilization [1]. With the growing and fast development of underground projects, tunnelling construction has remained active in Malaysia these recent years. The subterranean works will be subject to all the limitations and difficulties in both design and construction

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that are particular to Kuala Lumpur's geology, land use, and social-economic structure [2]. When a wide span tunnel or underground space is excavated, the in situ stress field is always disturbed, resulting in ground movements and surface settlement that could seriously harm nearby structures. For big span urban tunnel projects in soft ground, choosing an appropriate excavation technique is crucial to the project's success [1]. Therefore, tunnelling using tunnel boring machines (TBM) will be the main method of construction for the MRT underground alignment, whilst stations will be developed by excavating the station box from the surface.

There will be little disruption to the cityscape and current highways due to tunnelling. Also, it will reduce the impact of traffic and commercial activity while work is underway. To increase the constructability of tunnels and lessen the influence on neighboring structures, several tunnelling methods, including the slurry and variable density tunnel boring machines have been developed. Kuala Lumpur Limestone is known for its highly erratic karstic features. Exposures of Kuala Lumpur Limestone are mainly found in tin mining areas. If the underlying karstic limestone bedrock is overlooked or not dealt with appropriately, it will pose great uncertainties and difficulties in foundation construction. In less fortunate cases, adjacent properties suffer damages or failures after completion [3]. To solve this problem, meticulous soil investigation work must be performed to gather as much information as possible about the soil characteristics along the tunnel path. In addition, the right type of TBM must be deployed for the right type of geological formation.

The aim of this study is to propose a risk assessment approach in tunnelling construction. Therefore, to achieve the aim, the objectives of this study were; (1) to identify the risk and challenges in tunnelling construction by qualitative research, a semi – structured interview with expert, (2) to analyses the potential factor that cause problems during the tunnelling works via Analytic Hierarchy Process (AHP), and (3) to conduct a mitigation plan to reduce the risk in tunnelling works using risk register and validate with industry expert. The karstic limestone with its changing geological conditions and unpredictable subsurface cavities requires mechanical engineers and tunnel builders to perform at their very best. This research will benefit a lot of parties because the underground railway network becomes popular due to the scarcity of the land especially in an urban area. This study can provide insights into how to mitigate the risks and challenges effectively. This can lead to improved safety and efficiency in tunnelling construction, reducing the likelihood of accidents and delays, and ensuring that it is practical and feasible to implement.

1.1 Tunnelling construction

The adoption of appropriate technologies and techniques is necessary for the construction and design of a tunnel. Due to the varying ground conditions, choosing the best approach for tunnel excavation is primarily relied on field experience rather than calculations based on theoretical knowledge. Despite this, there is no other clear-cut or adequate rule for this. In metropolitan environments, the order of a tunnel's design and excavation method typically depends on the complex interactions between elements including timetable considerations, cost, and safety [4].

Numerous elements, including tunnel depth, tunnel shape, tunnel length, tunnel diameter, circumstances of ground water present, usage of tunnel, tunnel excavation supporting logistics, and proper risk management, influence the method used for tunnel construction [5] [6]. In tunnelling projects, it is essential to control and predict the ground surface settlements observed during and after the excavation process that may cause damage to the structures present on the earth’s surface. Otherwise, project time and tunnelling cost significantly increase due to damage to structures caused by the surface settlement that occurs above the bearable limits. Therefore, the tunnel construction methods need to be chosen and used very carefully. Also, a deep understanding regarding the various aspects and issues related to these tunnelling methods is very necessary. There are various methods of tunnel construction, each with their own advantages and disadvantages that have been grouped as shown in figure 1 below.

Tunnel construction method		
Drill and blast method	Cut and cover method	Tunnel boring machine method
- New austrian tunnelling method	- Bottom – up method - Top – down method	- Slurry TBM - Earth pressure balance TBM - Variable density TBM

Figure 1: Types of tunnel construction method

For the KVMRT project, the tunnel was excavated using two different types of TBMs. Earth Pressure Balance (EPB) TBMs were used for the alignment that went through the Kenny Hill Formation, and Variable Density (VD) TBMs were utilized for the alignment that went through the Kuala Lumpur Limestone Formation. Tunnel boring machines limit the surrounding ground disturbance and provide a smooth tunnel wall throughout the tunnel excavation operation [5]

1.2 Risk/challenges in tunnel construction

Tunnel failure refers to an unexpected and catastrophic outcome that poses a significant risk to the safety of underground structures. Common instances of tunnel construction failures include cave-in collapses, tunnel flooding, portal instability, excessive deformation of the tunnel tube, and overburden-related incidents [7]. The potential factors contributing to the failure were attributed to the selection of the construction method, inadequate monitoring, the presence of weak geological formations, increased stress from additional excavation, drainage issues, and delays in the installation of tunnel support [8].

During TU3 tunnelling operation, 2 sinkhole incidents were recorded. These were due to Shallow Kuala Lumpur Limestone extends from KBNS to ESC2 and is overlain by Alluvium. HKL Crossover discovered a sinkhole at the slip road near the demolished Satay KL Shoplots along the northbound alignment. From the analysis of the mining conditions/ parameters, it can be deduced that the sinkhole occurred largely due to unstable ground conditions, where operation team saw a sudden transition from harder to softer ground. The groundwater movement seen during the intervention would have also cause voids within the ground profile itself, making it unstable.

Water ponding found in the KBNS station shaft at a level 0.2m below the floodwall which is after the exit of KBNS station. No overflow observed beyond the floodwall. The presumption is that the water accumulated due to the ground water ingress and KBNS excavation works at the station shaft. TU3 informed KBNS to dewater immediately and provided KBNS with a more substantial capacity pump to help manage the water accumulation at the tunnel floodwall. Flowmeter installed to monitor the water discharge. It is suspected that the water ingress into the tunnel from station excavation work. The possible water ingress is from KBNS station shaft since there has been no sign water leaks observed from inside the tunnel after dewatering completed.

During construction at Education Institute Quarters, various mitigation measures were implemented including the ground treatment works such as Jet grouting and Wet Soil Mixing to be done ahead of the trenching of transfer beam wall. However, due to risk associated from original hand dug cassion, therefore inclined coring method from ground surface has been introduces and implemented in this works to reduce the impact and the risk. Pile removal is required for existing structures where their foundation pile obstruct tunnel construction. Underpinning is required for Education Quarters due to encroachment of existing pile to KVMRT SSP line tunnel. Close instrumentation monitoring will be carried out during underpinning works and tunnelling works. Ground improvement using Wet Soil Mixing method are proposed to facilitate transfer beam construction and soil stabilization during coring of existing RC pile.

2. Methodology

Basically, the methodology of this research can be divided into three main components; (1) Semi – Structured Interviews for the information and data collection, (2) Analytic Hierarchy Process (AHP) for the root cause analysis, and (3) Risk Register to analyze and conduct the mitigation plans.

2.1 Methods

The strategy employed to achieve the project's objectives is presented. Figure 2 provides an outline of the methods for this research.

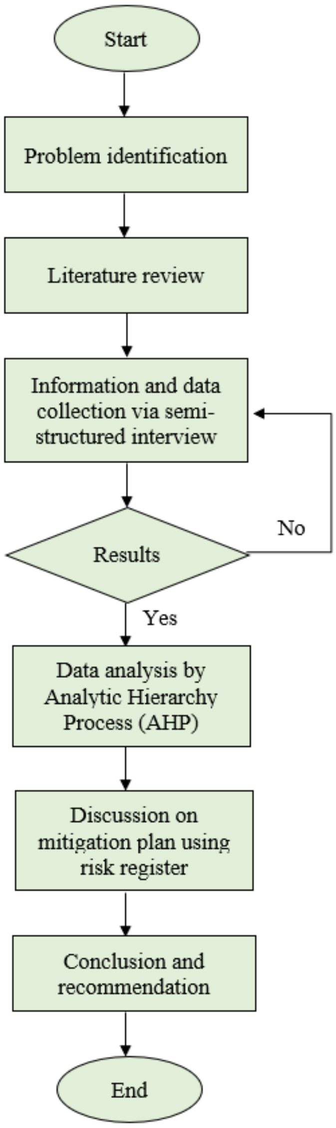

Figure 2: Methodology flowchart

2.2 Semi – structured interviews

A comprehensive examination of the risk and challenges involved in tunnelling construction was conducted. Data was gathered through semi-structured interviews with 3 industry experts from KVMRT project. Additionally, a survey was developed to assess potential factors that could contribute to issues during the construction process. Informal discussions were also held with professionals in the railway industry to gather valuable insights. The semi-structured interviews involved discussing a predefined list of risks and sub-risks associated with tunnelling construction projects in the KVMRT. The survey was designed in a semi-structured format to provide respondents with some flexibility to identify additional risks that may have arisen based on their own project experiences.

Many risk factors can affect tunnel construction safety. A total of 15 variables from 5 categories; human factor, materials factor, geological exploration, technical management, and safety management are measured in the survey. The questions allowed the respondents to assess the extent to which each factor influenced the safety of the tunnel construction project.

2.3 Analytic Hierarchy Process (AHP)

The data obtained from the survey of experts was analyzed using the Analytic Hierarchy Process (AHP). By integrating qualitative judgments and quantitative measures into a unified analysis, AHP serves as an appropriate approach to convert the qualitative judgments provided by the key personnel involved in the survey interviews into a quantitative risk ranking. Analytic Hierarchy Process (AHP) is a decision-making process that enables the establishment of priorities among various attributes. AHP has gained extensive usage in reflecting the importance and relative weights of factors associated with priorities. Numerous notable studies have explored the application of AHP in diverse areas such as alternative selection, resource allocation, conflict resolution, process optimization, and more [9] [10].

There are three fundamental steps involved in the Analytic Hierarchy Process (AHP) method. Initially, the problem is divided and organized into a hierarchy of sub – problems. Next, data is gathered and assessed by means of pairwise comparisons between attributes. Lastly, the priority weights of factors or items at each level are computed. A judgment or comparison involves assigning a numerical value to represent the relationship between two elements that share a common parent. The complete set of relative comparisons is then presented in a square matrix, where the elements are compared to one another.

In order to examine the risk factors impacting tunnel construction, the research began with a literature review, followed by interviews with three tunnel construction experts from MRT to assess their risk ratings. Five primary categories were established, namely human factors, materials factors, geological exploration, technical management, and safety management. Subsequently, the sub-factors within these five categories were identified. To determine the degree of importance associated with each risk factor, a hierarchical structure was utilized to decompose them into sub – problems. The topmost level in the hierarchy represents the goal to be achieved, while the elements in the lowest level correspond to the specific factors. The intermediate levels consist of criteria or categories used to evaluate these factors. In this study, the hierarchy of all categories and factors was categorized into three levels, as depicted in figure 3.

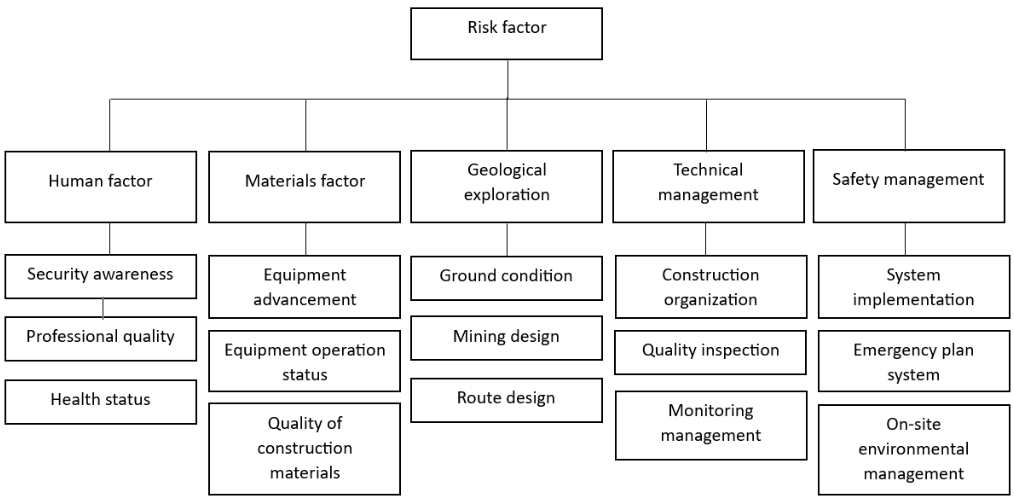

Figure 3: Hierarchy model of risk factor

Three MRT employees were interviewed to gather their perceptions regarding the prioritization of factors and categories, as depicted in figure 3. To determine the importance of factors influencing tunnel construction, participants were asked to assess the significance of each factor in comparison to others within the same category, utilizing a pairwise comparison scale outlined in table 1. The data were extracted from the surveys and entered pairwise comparison matrices as scores on the pairwise comparison scale. Table 1 displays the comparisons on a scale ranging from 1 to 9, representing the level of dominance or contribution to the project.

Table 1: Pairwise comparison scale

Rating	Description
1 – Equal	Both alternatives have equal importance.
3 – Moderate	One of the alternatives is slightly more important than the other one.
5 – Strong	One of the alternatives is strongly more important than the other one.
7 – Very Strong	One of the alternatives is very strongly important compared to the other one.
9 – Extreme Importance	One of the alternatives is strictly superior to the other one.

Table 2 displays a sample pairwise comparison matrix for the five categories. The values within each cell of the matrix indicate the weighting results, highlighting the relationship between the alternative in the row and the alternative in the column. For example, the element in row 3 and column 4 is 7, which means the respondent answered that geological exploration is very strongly more important than technical management. Comparing human factor and technical management, the respondent strongly favored technical management thus, the value in row 1 and column 4 is 1/7. The values in the diagonal of the matrix are always 1, representing equal importance when an alternative is compared to itself. Additionally, the lower triangular values in the matrix are reciprocal to the corresponding upper triangular values. Consequently, pairwise comparisons are only necessary for half of the matrix, excluding the diagonal. The construction of pairwise comparison matrices for factors follows a similar approach.

Table 2: Sample pairwise comparison scale matrix

Categories	Human factor	Materials factor	Geological exploration	Technical management	Safety management
Human factor	1	1/5	1/9	1/7	1/3
Materials factor		1	1/7	1/5	3
Geological exploration			1	7	9
Technical management				1	7
Safety management					1

The importance of factors is represented by their priority weights, which can be classified into two types: local priority weights and global priority weights. Local priority weights indicate the relative importance of nodes within a group of factors in relation to their respective categories. These local weights are derived from the pairwise comparisons conducted at each level. Global priority weights, on the other hand, are obtained by multiplying the local priorities of factors with the global priority of their corresponding categories. This process ensures that the importance of each local factor is balanced by the significance of its category. To calculate the weights in the AHP model based on the pairwise comparison matrices, an AHP web-based calculation and Excel software were utilized.

2.4 Risk register

A risk register is a crucial document that identifies and assesses potential risks to a project, process, or organization. To effectively analyze and evaluate these identified risk events, several tools are utilized, including risk parameters, likelihood ratings, and a risk matrix. These tools aid in estimating the probability of occurrence and the severity of impacts associated with each risk event. Figures 4 shows the risk matrix.

Likelihood	Magnitude of impact				
	1 Minimal	2 Minor	3 Moderate	4 Major	5 Severe
Almost certain	Medium (5)	High (10)	High (15)	Extreme (20)	Extreme (25)
Very likely	Low (4)	Medium (8)	High (12)	High (16)	Extreme (20)
Likely	Low (3)	Medium (6)	Medium (9)	High (12)	High (15)
Unlikely	Low (2)	Low (4)	Medium (6)	Medium (8)	High (10)
Very unlikely	Low (1)	Low (2)	Low (3)	Low (4)	Medium (5)

Figure 4: Risk matrix

The use of risk matrix as per table 3.7 is to estimate the level of risk rating based on likelihood of occurrence and the impacts of each risk event. For risk level "Extreme" with risk score ≥ 20, the risk has now become imminent, therefore urgent mitigation actions required to reduce its exposure. Next, the "High" risk level with score ≥ 10 until 16, urgent action to review and put in place further actions to reduce risk. The "Medium" risk level with score ≥ 5 until 9, action of monitor, review and put in place further action if cost effective to do so. For risk score with ≤ 4 which is "Low" risk level, the risk is tolerable. Risk score 4-5 is to monitor and no action required for risk score 1-3.

3. Results and Discussion

The proposed application of the Analytic Hierarchy Process (AHP) for ranking various factors related to tunnelling construction is motivated by its superior performance compared to relying solely on experts' subjective assignment of absolute priorities or relying solely on qualitative analysis. By utilizing this technique, the relative importance of each attribute can be compared to others, enabling a more effective calibration of their significance. Experts have expressed that comparing attributes provides a more straightforward approach to assessing their importance. The barriers to successful implementation of factors impacting tunnelling construction were categorized into two levels: categories and their corresponding factors.

Table 3: Pairwise comparison matrix for geological exploration factors

Geological exploration factors	Ground condition	Mining design	Route design
Ground condition	1	6	7
Mining design		1	5
Route design			1

According to table 3, the scores rating for sub-risk in geological exploration factors is presented. In row 1 and column 2, the score is 6, indicating that the ground condition is very strongly more important than drilling design. Similarly in row 1 and column 3, the score is 7, highlighting that ground condition is also very strongly more important compared to route design. On the other hand, for the element in row 2 and column 3, the rating from experts is 5, implying that drilling design is strongly more important than route design.

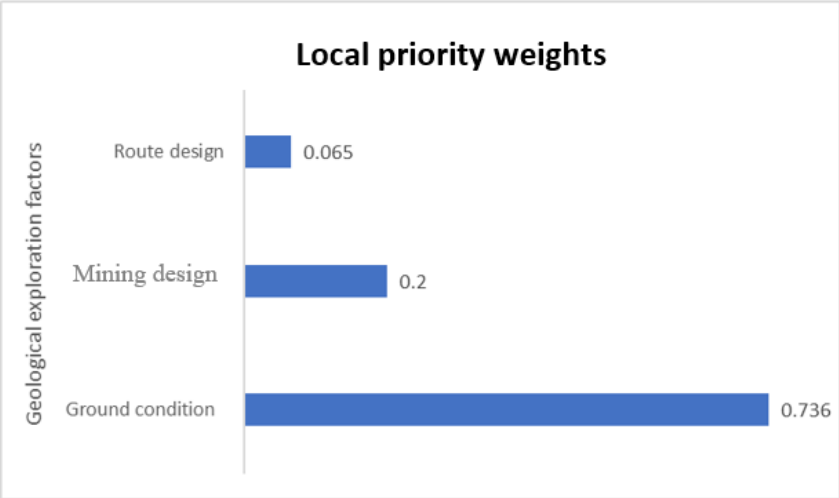

Figure 5: Ranking for geological exploration factors

Figure 5 shows the results of risk ranking for geological exploration factors. Ground condition has been ranked as the most prioritized risk compared to drilling design and route design. The ranking of ground condition as the highest-priority risk can be attributed to its critical role in influencing the success and safety of tunnel construction projects. Insufficient understanding of ground conditions may result in unexpected ground collapses, rockfalls, or the need for extensive ground reinforcement, all of which can have significant cost implications and pose serious safety threats to construction workers and infrastructure.

Table 4: Pairwise comparison matrix for risk categories

Categories	Human factor	Materials factor	Geological exploration	Technical management	Safety management
Human factor	1	1/5	1/9	1/7	1/3
Materials factor		1	1/7	1/5	3
Geological exploration			1	7	9
Technical management				1	7
Safety management					1

Table 4 depicts in detail the scores rating for the overall five risk category. The element in row 1 column 2, and element in row 2 column 4, the score is 1/5. It means that the materials factor is strongly more important than human factor while technical management is also strongly more important than materials factor. For element in row 1 column 3, and element in row 3 column 5, which is in rating 9, the geological exploration is strictly superior to human factor and safety management. Move to element in row 1 column 4, element in row 2 column 3, element in row 3 column 4 and element in row 4 column 5, the rating from expert is 7, means that technical management is very strongly important compared to human factor while the geological exploration is very strongly important compared to materials factor and technical management. Technical management is also very strongly important compared to safety management. Last, for element in row 1 column 5 and element in row 2 column 5, the safety management is slightly more important than human factor and the materials factor is slightly more important than safety management.

Figure 6: Ranking for five categories of risk factors

Figure 6 presents the results of risk ranking for the five categories of risk factors that have the potential to impact tunnelling construction. Among these categories, geological exploration has been identified as the most prioritized factor, carrying a weight of 0.612. This implies that geological exploration plays a crucial role in determining the success and effectiveness of tunnel construction projects. By thoroughly understanding and evaluating the physical properties and characteristics of the soil, rock, and geological formations, project teams can anticipate and address potential challenges and risks associated with ground conditions.

Following geological exploration, the next significant factor is technical management, with a weight of 0.225. This highlights the importance of effective management and coordination of technical aspects such as construction processes, resource allocation, and adherence to project specifications. Robust technical management practices contribute to streamlined operations, optimized resource utilization, and improved project outcomes. The materials factor, with a weight of 0.088, comes next in the risk ranking. This factor emphasizes the significance of utilizing high-quality construction materials that meet the required standards and specifications. By ensuring the use of reliable and durable materials, the risk of structural issues, material failures, and potential safety hazards can be mitigated.

Safety management is another critical factor, carrying a weight of 0.046. This underscores the importance of implementing comprehensive safety protocols and measures throughout the construction process. A strong safety management approach promotes a safe working environment, reduces the occurrence of accidents and injuries, and safeguards the well-being of workers and stakeholders. Lastly, the human factor, with a weight of 0.028, is identified as a significant consideration. This factor acknowledges the influence of human-related aspects such as skills, experience, and behavior on the success of tunnelling construction projects. By ensuring proper training, effective communication, and adherence to safety protocols, potential risks associated with human factors can be minimized.

To ensure equal significance was given to all participants' opinions, the geometric mean was employed as the aggregation method for calculating both the average local and global weights. This methodology helped maintain a balanced and fair assessment of the barriers throughout the analysis.

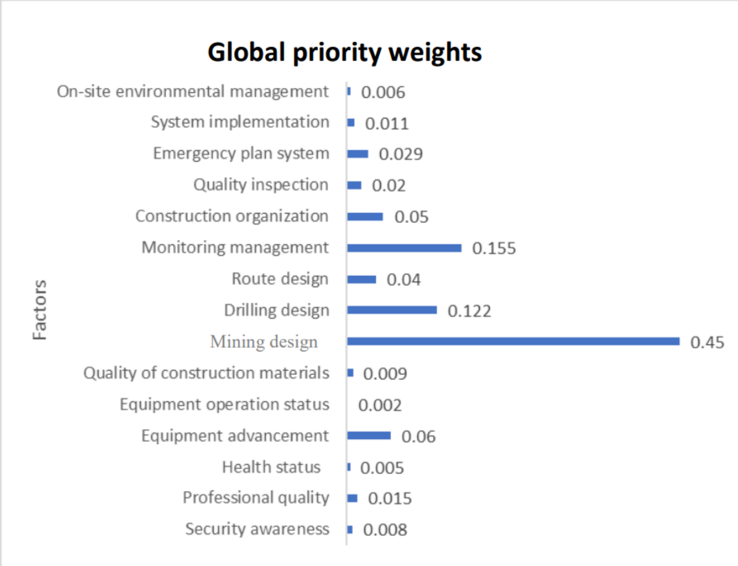

Figure 7: Ranking for five categories of risk factors

Figure 7 show the cases of outcome overall ranking of all 15 sub-risk within 5 risk categories. The highest risk ranking among the 15 sub-risk is ground condition. The study conducted on the KVMRT project of Putrajaya Line, specifically on the TU3 drive from Hospital Kuala Lumpur Crossover to Ampang Park Station, has concluded that the geological conditions pose the most critical challenges. The presence of karstic limestone with variable profiles has been identified as a significant factor contributing to the high risk ranking of ground conditions. Karstic limestone formations are known for their complex and unpredictable characteristics, presenting substantial challenges during tunnel construction. Understanding and addressing the challenges associated with ground conditions is crucial for successful tunnel construction projects. Thorough site investigations, geotechnical surveys, and geological assessments are essential in assessing the characteristics and behavior of the ground, allowing engineers and project teams to develop appropriate design solutions and support systems. These measures help mitigate risks such as ground instability, excessive settlements, and potential hazards arising from unfavorable ground conditions.

The risk register was utilized to propose a mitigation plan based on the analysis of three cases from the MRT Putrajaya Line TU3 drive. This plan aims to address and manage the identified risks associated with the construction project. Risk register for TU3 drive can facilitate all parties to take the necessary precautions during TBM passing through areas that has the high risk for the occurrence of any incident especially involving the public. Figure 8, 9 and 10 shows the risk mitigation for sinkhole near satay house and flooding inside the tunnel of MRT Putrajaya Line as well as the risk mitigation at education quarters respectively.

Risk: Sinkhole near satay house					
Likelihood		Impact		Risk score	
Very likely	4	Severe	5	Extreme	20
Mitigation: 1. Analysis the mining conditions and parameters 2. Close monitoring of the TBM operating parameters consistently 3. Communication with instrumentation and monitoring team for any instrument alert along the alignment					
Risk treatment: Accept			Control effectiveness: Satisfactory		

Figure 8: Risk mitigation for sinkhole near satay house

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Risk: Flooding of underground tunnel					
Likelihood		Impact		Risk score	
Very likely	4	Severe	5	Extreme	20
Mitigation: 1. Dewatering system – fully automated and available for 24 hours continuing pumping as required 2. Construct a flood wall to prevent water ingress into station box – designed according to each station flood level. 3. A well-prepared crisis management plan including own ERT team – standby 24 hours in case of emergency					
Risk treatment: Accept			Control effectiveness: Satisfactory		

Figure 9: Risk mitigation for flooding inside tunnel

Risk: Southbound TBM mining through 3 nos of piles in foundation					
Likelihood		Impact		Risk score	
Very likely	4	Permanent damage to structure	5	Extreme	20
Mitigation: 1. Prior TBM arrival – Underpinning and pile removal 2. During TBM arrival – Control TBM operations as to avoid over excavation. Bull gang to be on standby at surface subject to TBM mining through and monitor for any ground movement or blow out that may occur.					
Risk treatment: Accept			Control effectiveness: Satisfactory		

Figure 10: Risk mitigation at education quarters underpinning works

The sinkhole near satay house, underground tunnel flooding at KBNS to APPS and the risk at the education quarters have been assessed with a likelihood rating of 4 (very likely) and a risk parameter of 5 (severe). These evaluations result in a calculated risk level of 20, indicating an extreme level of risk for each situation. The proposed risk treatment measures have been accepted, and the control effectiveness is considered satisfactory based on the implemented mitigation actions.

4. Conclusion

To sum up, through the rigorous analysis of potential factors using the analytic hierarchy process (AHP) and conducting semi – structured interviews with industry experts intimately involved in the KVMRT project, a critical finding has emerged. It has been established that ground condition stands as a prominent and significant factor that contributes to various challenges in tunnelling construction. The ground condition encompasses a range of geological characteristics, including soil composition, rock strength, and geological formations present in the excavation area. This factor introduces several risks and complications, such as potential tunnel collapses, ground subsidence, and water ingress into the tunnelling works. To mitigate these challenges, a mitigation plan based on the risk register has been developed. The identified mitigation plan provides a framework for managing the risks and improving the overall effectiveness of the tunnelling construction process. It is recommended that the project stakeholders and decision-makers implement these measures to ensure the safe and efficient construction of tunnel.

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