Koc. J. Sci. Eng., 6(1): (2023) 13-25 https://doi.org/10.34088/kojose.1051138

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

The Benefits of Uncertainty and Risk Assessment Studies on the M5 Metro Line (Istanbul - Turkey)

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Article Info

Research paper

Received : *December 30, 2021*
Accepted : *August 16, 2022*

Keywords

Uncertainty
Underground Construction
Risk Assessment
Tunnel

Abstract

Uncertainty is often the most significant source of risk associated with a project in tunnel and underground construction. Unforeseen uncertainties can lead to significant construction problems leading to reduced tunnel advances and delays, cost increases, damage to existing infrastructure and/or damage to building equipment. The M5 metro line, which is the subject of the study, is located in Uskudar – Umraniye - Cekmekoy - Sancaktepe district on the Asian side of Istanbul. The line is approximately 17.5 km long and has 16 cut and cover stations. M5 metro line was used the four earth pressure balance (EPB) tunnel boring machines. The effect of uncertainty on risk assessment and decision-making is increasingly given priority, particularly for large infrastructure projects such as tunnels where uncertainty is often the primary source of risk. This article is intended to explain the tangible benefits of underground uncertainty and risk assessment of the M5 metro construction for underground project stakeholders, local authorities, designers, practitioners and researchers.

1. Introduction

Tunnels and underground construction are in high demand in many engineering projects around the world [1]. The construction of tunnels has provided a powerful boost to rapid economic growth over the last 10 years. However, due to a variety of risk factors related to complex project environments, breaches of safety law often occur in tunnel construction, leading to serious problems with related project activities [2-4]. Tunnels and underground construction are always present with uncertainties and risks [5-6]. Decisions will be affected at every step of the project, from design, planning to execution, uncertainties, particularly geotechnical ones. The effect of uncertainty is known as risk to the target. These risks may have an impact on the functioning, productivity of construction and the environment [7]. It is essential for successful risk management to have competence with a thorough understanding of the risk situation [8]. Reducing the risk will be at the center of the risk management process. Various approaches can be implemented depending on the problem. Significant problems emerge from complexities in tunnel engineering and the need to integrate them into research, design and practice. Different types of uncertainties can affect a specific site's engineering efficiency, geological analysis, site characterization, geotechnical data provision, safe and efficient construction. Fluctuations in construction time and cost estimates arise from natural variation in construction results, as well as the occurrence of special events such as tunnel collapse [9].

Numerous methods of risk analysis are available, such as fault tree analysis, event tree analysis, consequence or cause-consequence analysis, probabilistic risk analysis, decision analysis, multi-risk analysis, preliminary hazard analysis, Bayesian Networks, hazard and operability analysis, bow-tie analysis and fault mode analysis [10-15]. Sousa and Einstein [16] describe the Bayesian Network model, which estimates the expected utility as the sum of the expected costs and the risk of a tunnel collapse. Probabilistic risk analysis by Spackova et al. [17] of tunnel construction time and statistical data processing technique for determining inputs.

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The metro line M5, located on the Asian side of Istanbul, is a 17.5 km (double tube) with 26.985 km EPB-TBM tunnel, 18.666 km of the New Austrian Tunneling System (NATM) tunnel and 16 stations. It has several other features as well as being a fully tunneled station. The geological setting of the M5 metro line is highly complex, consisting of limestone, sandstone, siltstone, mudstone, claystone, andesite and quartzite. Geological units are often cut by dykes of the andesite, which have significantly fractured contact zones. These zones are potentially dangerous areas at more than 20 sites that are likely to face collapse. The project area is very densely populated and the overloading of tunnel lines between 10-80 m and historic buildings is one of the most significant risks to be faced during tunnel operations. It is expected that in some areas there are likely to be some ancient water wells, which may cause some serious settlement problems [16]. The complex geometry and geology of the station dictated the utmost care for the NATM sections' excavation and final liner design to ensure stability during excavation and adequate structural capacity in case of a seismic event [19]. M5 metro construction started in 2012 and was completed in 2017. This paper outlines the tangible benefits of the underground uncertainty and risk assessment of the M5 metro construction for key underground project stakeholders, local authorities, designers, practitioners, and researchers.

1. Material and Methods

Due to the complexity and variability of the surrounding medium in tunnel and underground construction, it is difficult to predict some underground responses to excavation processes. Uncertainty refers to a scenario in which there is insufficient and/or unknown knowledge to accurately depict the current state, future consequences, or multiple possible outcomes [18]. Uncertainty and risk analysis are becoming more and more common in the fields of science and engineering, including design, project management, and finance and insurance [21-22]. In order to determine the geological and geotechnical uncertainties in the M5 metro line, which is the subject of the study, drilling studies and field tests were carried out at suitable locations along the route. Then, laboratory experiments were carried out on the samples obtained from the drillings. The tunneling activity was started and completed with the evaluation of route research together with field and laboratory experiments. M5 metro transports 1.5 million people in a day and travels in 27 minutes between Uskudar and Sancaktepe (Figure 1). It has significantly reduced traffic on the Asian side, and passengers save 33 minutes per journey. The reduction in traffic has resulted in a reduction in CO_2 emissions to the atmosphere about 77 thousand 246 metric tons per year [23].

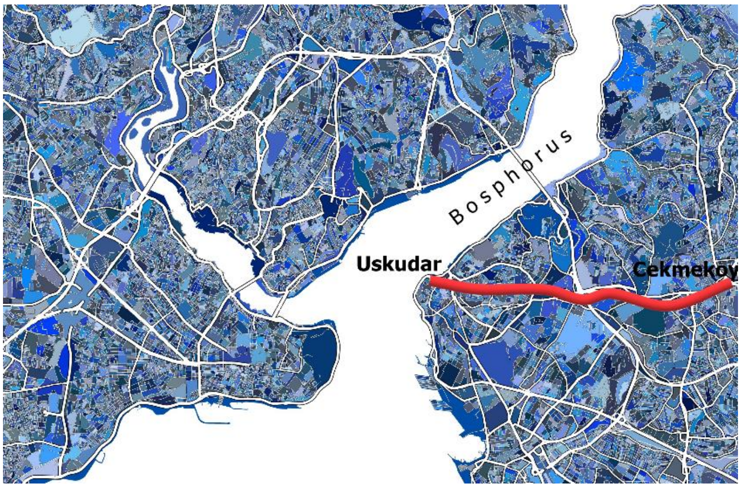

Figure 1. M5 tunnel route map [24]

2. Uncertainty Assessment

Uncertainty is an inevitable part of rock engineering. Natural variation in rock mass properties, inadequate data, measurement errors, sampling bias, load uncertainty, model simplifications and assumptions are the sources of uncertainty [15; 25-27]. Management of uncertainty is a critical problem for any underground project, and a certain degree of flexibility and responsiveness must be included in the design process to avoid the expensive effects of unexpected circumstances [28].

2.1. Uncertainties and Risks Related to Tunnel Engineering

Tunnel design and construction in dense urban environments present unique risks and challenges. The parameters that make up the risks are still unknown, some are intrinsic, and some emerge from the lack of knowledge of certain parameters.

2.1.1. Geological Uncertainties

Tunneling and underground construction are associated with inherent dangers due to a lack of awareness of the site's geological features and other unknowns [29]. Geological uncertainties not only affect the design of underground structures, but also have an impact on the construction process. Due to a lack of awareness of the site's geological features and other unknowns, tunneling and underground construction are connected with inherent dangers. It is unavoidable that the geological conditions will not be fully understood before the tunnel is excavated, and even then, errors in estimating geological behavior can occur [30]. Tunnel and underground excavations can be complicated by poor geological conditions. Some possible ambiguities exist in the geological features of Istanbul's Asian side. The Paleozoic continuous sedimentary succession in the Istanbul area is well-developed, unmetamorphosed, and poorly deformed. During the excavation, the Trakya, Tuzla, Kurtköy, Gözdağ, Dalayoba, and Sultanbeyli Formations were identified. The Gözdağ Formation, which is found at the top of the Kurtköy Formation, is made up primarily of high-strength claystone-shale layers and quartzite rocks that are rich in feldspar and abrasive. Trakya Formation consists of claystone, sandstone and limestone. Thin laminated mudstones found at Tuzla Formation. The geological structure of the Kurtköy Formation is important for tunnel excavation. Quartzite is the main unit of the Kurtköy Formation and generally consists of sandstone and mudstone (Figure 2).

Figure 2. Tunnel face in Kurtköy Formation in M5 metro line Umraniye station

2.1.2. Geotechnical Uncertainties

Geology is the primary source of uncertainty in geotechnical engineering. Unidentified ground features can cause unexpected behavior, whereas identified ground variables may not be quantifiable or have unknown behavior [28]. The more geotechnical data is collected and examined, the more likely profile correlation and modification will occur, resulting in cost savings. It is necessary to install a support system in tunnels to ensure geotechnical stability in top and bench excavation (Figure 3 a, b). Planning decisions may be incorrect if reliable geological information is not available [31]. Disruptions, weathering, and tectonic contacts in geological formation transition zones are examples of geotechnical uncertainties.

Figure 3. Top and bench excavation (a) and installation of the support system (b)

Furthermore, unexpected uncertain conditions can be used to illustrate the location of dykes, fault zones, local weathering zones, and groundwater levels. The details of the above conditions, and their position projections, are often very difficult. Despite potential uncertainties, both geological and geotechnical scenarios are potentially assessed along the tunnel route. Underground structures are generally man-made objects built within a complex and heterogeneous natural environment. Therefore, it is important to define the actions of the geological environment according to the criteria that can be used in the structural analysis and in the planning and monitoring of the construction process for the planning and design of the structures. The geotechnical parameters along the tunnel line are given in Table 1. The uncertainty analysis performed includes rock mass quality assessment based on the Q-system (Q), Rock Mass Rating (RMR) and Geological Strength Index (GSI) of rock mass classification for the M5 metro line (Table 2).

Table 1. Summary results of the geotechnical parameters [32-38]

Formation characteristics		Geotechnical Properties					
				Strength parameters		Deformation parameters	
Formation	Unit	Unit weight (kN/m^3)	Cohesion c (kPa)	Uniaxial Compressive Strength (MPa)	Internal friction angle Ø (○)	Young modulus E (GPa)	Poisson ratio υ
Trakya Formation	Claystone	28.6-28.9		67-185	30-34		0.16-0.22
	Sandstone	27.2-27.4		16.7	20-26		0.23-0.30
	Limestone	26.0-28.0	18-20	15-105	55-58		0.14-0.40
Tuzla Formation	Limestone	26.3-28.4		40-165	40-56	4.9-5.40	0.23-0.39
	Claystone-Shale	25.5-27.0		15-65	30-35		0.28-0.26
	Claystone	23.4-27.6		12-17	20-55	1.90-4.58	0.20-0.24
Kurtköy Formation	Quartzite	26.5-26.9		48.2-49.3	45-50		0.37
Gözdağ Formation	Claystone	22.0-27.0		9-21	41-48		
	Claystone-Mudstone	25.7-26.0		7-8			
	Sandstone	26.8-27.2		26-28			0.23-0.47
	Andesite	26.2-26.8	7.5	7-38.3	53-54		0.27-0.40
Dalayoba Formation	Limestone	26.4-27.5		18.1-52.5	56-57		0.43
Sultanbeyli Formation	Claystone-Shale	22-24		20-60	15-20		
	Claystone	26.0-27.7		18-28			0.12-0.28

Table 2. Summary results of the rock mass classification in the study area

Lithology	Q- system (Q)	Rock Mass Rating (RMR)	Geological Strength Index (GSI)
Limestone	0.08-0.09	24-30	28-39
Claystone-Sandstone	0.06-0.08	26-31	30-35
Claystone-Shale	1.20-1.65	45-58	35-45
Quartzite	2.20-3.50	60-62	40-60
Andesite	10.5-11.5	65-69	50-65

2.1.3. Hydrogeological uncertainties

In terms of M5 subway tunnel excavation works, basic hydrogeological issues that should be considered as potential sources of uncertainty or risk are important. In EPB-TBM and NATM methods, attention was paid to the hydrogeological properties of rock units, in particular their permeability. During the excavation, the characteristics of the groundwater (chemical composition, temperature, etc.) were checked and their impact on the quality of the concrete was investigated. Consideration was provided to the hydraulic load at the construction depth because the station at Umraniye, where the excavation had started, was below sea level. The pace at which the water inlet was entering the excavation works was always under control (Figure 4).

Figure 4. Water in tunnel

2.1.4.Uncertainties Surrounding Fundamental Structures

Rock masses are often and rarely cut by andesite and diabase dykes. M5 metro tunnels have often recorded collapses during construction and low progression rates in complex geological conditions characterized by faults, dykes connected to dissolved and fractured zones [39]. Furthermore, a dense cataclysm zone in contact with the main rock was found locally. Magmatic intrusions take place every 50-70 meters during tunnel construction. İBB [39] mapped a total of 39 dykes in the Istanbul settlement area. The thickness of these dykes ranges from a few decimeters to a few meters.

Weathering and fracturing effects: The fractured rock mass is weathered by active tectonic movements. Because they are formed from the fractured rock mass process, the weak zones and the fault zones provide an intensifying weathering environment. As a result, the weathering effect may be below the surface more than a hundred meters. Tunneling in such a setting must be dealt with carefully in the preparation and implementation phases in relation to the evaluation of rock mass consistency. At some underground depths, the formation of weathered rock is undisclosed and irregular. In transition zones, the weathered rock can pass from a rock zone to a good rock mass, then return to a weathered rock mass. Nevertheless, due to changes in continental mineralogy or weathering, in weathered or calcified rock, "undifferentiated blocks" of varying sizes can be used as "floating blocks." It should be noted that karstic cavities may exist in the limestone zones. The (dissociated or undifferentiated) ground cover, as well as the calcareous rock masses, may provide essential conditions for these morphologies.

High abrasive rock effect: The presence of abrasive rock environments at the M5 metro was reported based on field and laboratory test results. Those are the quartzite, andesite, and diabase dyke lithology.

Squeezing of the soil and its effects: Due to the formation of Sultanbeyli clay there was no evidence of severe swelling problems. Nevertheless, it is critical that the risk of local swelling in the Sultanbeyli Formation is not ignored.

Adhesion: The formation of clay lithology of the Sultanbeyli Formation has such a potential according to laboratory test results.

Karst structures: This is particularly important for the Trakya Formation limestone lithology in the project region. Water may fill the voids, even without water. Important conditions can occur in both calcareous rock masses and in their interactions with weathered or unweathered rock masses for these morphologies.

Collapse risk: Collapses in tunnel linings may occur because of lateral pressure in areas where low-strength rocks are present. It is accompanied by the presence of dykes in the project's most vulnerable locations, as well as the threat of huge fragmented rock in small areas. As a percentage of the size of the shattered rocks created, such scenarios can also cause the crushed rock to reach the surface of near-surface tunnels, posing a threat to tunnel excavators and personnel.

Block stability: The rock conditions encountered during the excavation are properties that may block instability depending on the degree of discontinuity and tunnel geometry. Discontinuity and geometry of the intersection may cause such instability to occur as a slip or fall.

2.1.5. Risk of Earthquake Events

The world's most earthquake-prone countries include China, Indonesia, Iran, and Turkey. There is a high chance that a tunnel will be damaged if it undergoes intense shaking, is located near an earthquake fault, or has problematic geological or building conditions. M5 metro tunnel line is located approximately 20 km from the North Anatolian Fault Zone, in a seismically active area (Figure 5). Two flexible seismic joints / segments for extraction / reduction with a shear displacement limit of 50 mm and a shear limit of 75 mm have been invented, specially designed, and installed in marine sediments near both ends of the section to reduce the seismic stress / stress below the permissible level. The tunnel's behavior during an earthquake was built for Mw = 7.25, and it was tested for operation and safety using earthquakes with return periods of 500 and 2500 years [40].

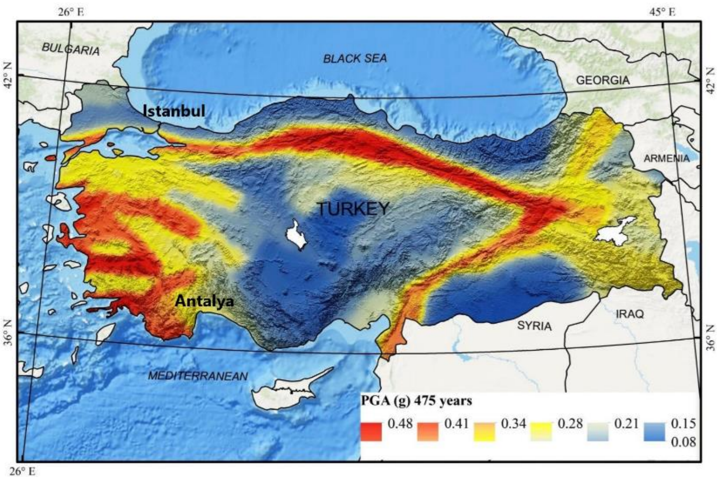

Figure 5. Probabilistic seismic hazard map from the National Seismic Hazard Model [41]

3. Evaluation of Risk Factors (RF)

A risk factor is defined as the effects on the outcomes or project objectives, as well as the likelihood of these outcomes occurring [42]. British Standards Institute provided a Risk Management process. According to BSI-6079-3 [43], there are two broad phases within the risk management process. The first phase concentrates on defining the scope of risks to be managed. This situation can be looked at as a problem-framing activity. The second deals with assessing and managing risk. The flowchart below depicts the step-by-step procedure for evaluating the risk factor (Figure 6).

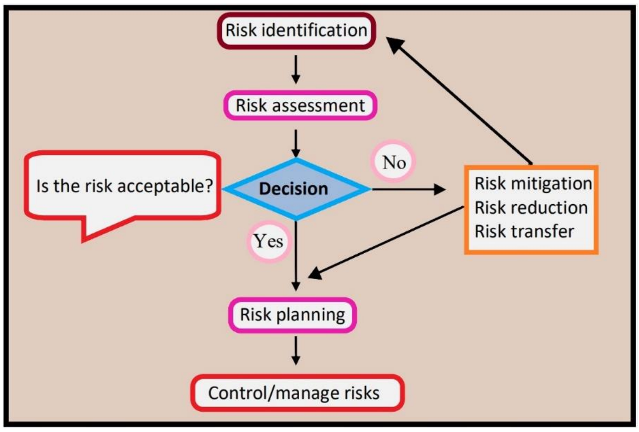

Figure 6. Risk factor evaluation methodology

The risk factor can be calculated by using the following formula [44]:

$$RF = P + C - (P * C) \quad (1)$$

Where; RF = Risk factor.

P = Probability (occurrences) measure on a scale of 0 to 1.
C = Consequences (impact) measures on a scale of 0 to 1.
If either the probability P or the consequences C are high, or both, the risk factor will be high. This formula is only valid if P and C scale ranges from 0 to 1. The simple matrix shown in Figure 7 is used to combine the likelihood and consequences ratings in order to generate initial risk priorities. The risk matrix is plotted using two-dimensional scales of impact / consequences and occurrences/probabilities ranging from 0 to 1. A risk matrix provides information about the criticality of a risk. The risk matrix categorizes risks into four categories: low, medium, high, and critical. Group Low indicates that the risk is no longer important, and it may be ignored or dealt with as a last priority. Similarly, group critical means that all risks in this group require the project manager and team's undivided attention [45]. These risks must be addressed as soon as possible. A risk profile can be created by arranging calculated risk factors in descending order. Use an 'uncertainty and risk model' to assess the various risks identified in engineering projects and identify outcome and probability ratings, risk priorities, and inherent risk levels that will have an impact on project success if they occur [46]. Table 3 depicts the likelihood of the occurrence of various risks and their corresponding effects on the project. Table 4 displays the assessment scores, which range from 1 to 5. The numerical scores of events and impact for risk are converted from a 1 to 5 scale to a 0 to 1 scale using the formula below.

Required score = (responded score * 2) / 10 (2)

Risk factor (RF) or combined risk measure is then calculated for each risk by using Eq.1.

Table 5 shows the score and calculated risk factors for the study, and similar calculations are performed for the remaining case studies. In order to resolve it, risk matrices are plotted using two-dimensional scales 0 to 1 of Impact/Consequences and Occurrences/ Probability, which are also plotted with respect to the decreasing order of calculated risk (Table 6). A risk graph (Figure 8) and risk profile (Figure 9) are plotted for Metro Line, and similar risk matrices and risk profiles are computed for the remaining case studies. Risks profile where elements are arranged in descending order of RF as shown in Figure 10.

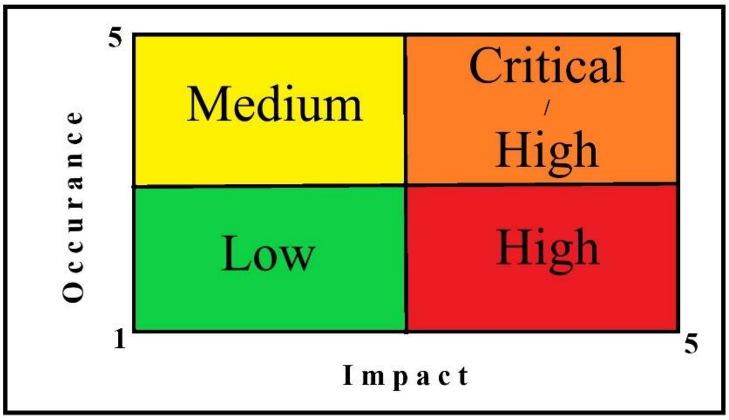

Figure 7. Risk occurrence versus impact matrix

Table 3. Probability and impact scales

Grade	Assessment of likelihood (P)	Assessment of impact
1	Rare	Minor effect
2	Considerable	Low effect
3	Medium	Medium effect
4	Frequent	High effect
5	Always	Extreme high effect

Table 4. Responses to questionnaires

Potential risk number	Risks shortlisted	Responses on scale 1 to 5	
		Occurrence	Impact
1	Geological risks	4	4
2	Geotechnical risks	3	3
3	Hydrogeological risks	3	3

Table 4. (Cont.) Responses to questionnaires

Potential risk number	Risks shortlisted	Responses on scale 1 to 5	
		Occurrence	Impact
4	Route selection risk	4	4
5	Excavation and design risks	1	1
6	Earthquake risk	2	2
7	Environmental related risks	1	2
8	Technology selection risks	2	2
9	Risks due to delay in approval of	1	2
10	detailed project report	1	3
11	Joint venture risks	1	2
12	Political and financial and risks	1	3

Table 5. Calculation of risk factors

Potential risk number	Occurrences		Impact		Risk factor
	Responded score	Scores (P)	Responded score	Scores (C)	
1	4	0.8	4	0.8	0.96
2	3	0.6	3	0.6	0.84
3	3	0.6	3	0.6	0.84
4	4	0.8	4	0.8	0.96
5	1	0.2	1	0.2	0.36
6	2	0.4	1	0.4	0.64
7	1	0.2	2	0.4	0.52
8	2	0.4	2	0.4	0.64
9	1	0.2	2	0.4	0.52
10	1	0.2	3	0.6	0.68
11	1	0.2	2	0.4	0.52
12	1	0.2	3	0.6	0.68

Table 6. Risk prioritization

1st priority	1st and 4th risks
2nd priority	2nd and 3rd risks
3rd priority	10th and 12th risks
4th priority	6th and 8th risks
5th priority	7th , 9th and 11th risks
6th priority	5th risk

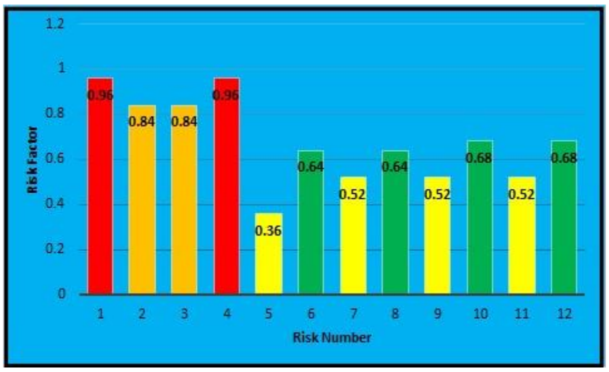

Figure 8. The risk graph for the Metro Line

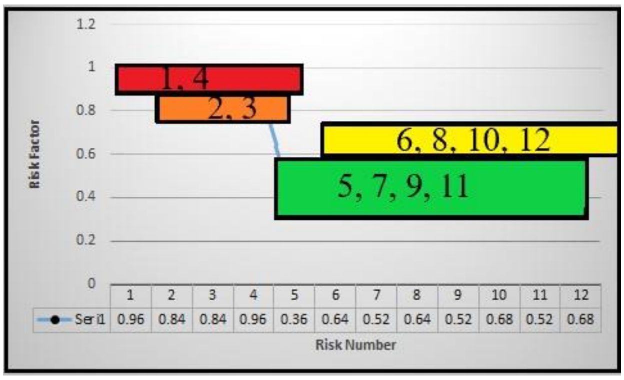

Figure 9. Profile of collective risk

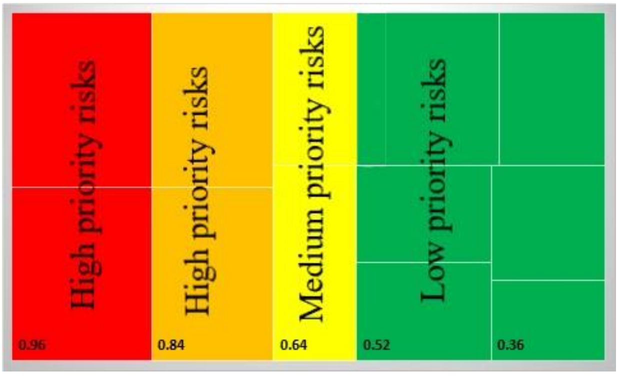

Figure 10. Risks profile with elements organized in descending order of Risk Factor

4. Results and Discussion

The quality of the rock mass through which the tunnel passes, as well as the rock support measures used during tunnel excavation, are critical to the success or failure of any tunneling operation [47]. Accurate assessment, analysis, and evaluation of rock mass quality are critical in this regard. The geological units are often cut with markedly fractured contact zones by andesite dykes. Contact zones are the possible vulnerable areas at more than 23 locations that are likely to face collapse. The most significant risks encountered during tunnel excavation include overburden changes of 10-80 m and old buildings located above tunnel lines. The NATM and EPB-TBMs are used to construct M5 Metro tunnels (Figure 11). EPB-TBMs designed the main metro line tunnels, each having a diameter of 6.57 meters, and the project's two lines. Due to the different cross-sections of these tunnels, the metro station platform tunnels, the switch tunnels and the depot area connection tunnel were constructed by NATM. At the beginning of the metro project, a depot connection tunnel with a cross-section of 74 m^2 was excavated with NATM. Nevertheless, additional soil boring has shown that soil conditions by the umbrella arch method require at least half the depot link tunnel section. As a result, this single tunnel was excavated with a cross-section of 2 x 34 m^2 as twin EPB-TBM tunnels. Constructing the EPB-TBM depot link tunnel as twin tunnels are estimated to be more cost-effective and quicker than constructing a single-wide tunnel. At the end of building the depot connection tunnels with the TBMs, it is found that the depot link tunnels were modified from NATM to EPB-TBM.

A risk factor is defined as the effects on the outcomes or project objectives, as well as the likelihood of these outcomes occurring. Risks and uncertainties must be identified and evaluated in advance for engineering studies to be successful. More effort is required for risk assessment, particularly in metro projects. Tunnel designs are highly complex and are related to a variety of uncertainties owing to geological and geotechnical conditions, exterior loading and construction efficiency. During tunneling, these uncertainties can lead to future hazards for both the employees and the environment around them. In urban regions, surface settlements induced by tunnel excavation may be particularly important, with higher significance in blended soil circumstances.

Figure 11. EPB-TBMs in the M5 Metro Tunnel

5. Conclusions

Uncertainty is one of the most important aspects of tunnel design and underground construction. Professionals and academics are increasingly focused on how to deal with complexity in the risk management and risk control process. Uncertainty is one of the most important aspects of tunnel design and underground construction. Professionals and academics are increasingly focused on how to deal with complexity in the risk management and risk control process. This paper discussed how to cope with uncertainty and how to assess and make decisions under uncertainty. Risk and uncertainty analysis was carried out for the M5 metro project. According to geological studies, it was observed that there are different transition zones at 23 different points along the tunnel line. These are critical zones that can be collapsed in front of the tunnel face during the EPB-TBM excavation. In such cases, reducing the openings in front of the EPB-TBM cutter head can be a partial solution. EPB-TBM applications and reducing the openings prevent the reduction of the collapses in front of the tunnel face, especially when the contact zones are very fractured, especially when the RQD is low. Physical, mechanical tests and petrographic examinations were carried out on the drilling cores of critical zones. As a result of the uncertainty and risk assessment, EPB-TBMs are applied to the most appropriate procedures to be employed for opening the tunnel. The assessments carried out using the EPB-TBM system are the most relevant. The EPB-TBM can operate extremely smoothly and efficiently in these areas because the groundwater on the project route is collected as a lake in some places and the lithology of the path is composed of a wide range of rocks, ranging from relatively un-weathered to weathered rocks. Another important outcome of choosing this machine is that it has a ground pressure control mechanism to prevent collapses on the machine's flooring. Another reason to use EPB-TBM is that large constructions must be delayed during tunnel opening, as well as the possibility of faults. As a result, it was determined that the EPB-TBM excavation would be better suited for the M5 Metro line tunnel. For the project, four EPB-TBMs with a diameter of 6.57 meters per line and two sides are being hired. As a result, in order for the metro works to be successful, risks and uncertainties must be identified and evaluated in advance. In engineering projects, more work is required for risk assessment. The geological risks and the risk of route selection have been determined to have the highest value as a result of the risk assessments. It was calculated that it should be classified as high because it has a critical value in geotechnical and hydrogeological risks. The risk and uncertainty factors encountered along the M5 Metro line were evaluated in this study.

Acknowledgment

The author would like to thank the Editor and anonymous referees for their very helpful comments and suggestions, which allowed the article to be significantly improved, as well as the Doğuş Construction Group engineers and Istanbul Metropolitan Municipality managers for their assistance.

Conflict of Interests

No conflict of interest was stated by the author.

Declaration of Ethical Standards

The author of this article declares that the materials and methods used in this study do not require ethical committee permission and legal-special permission.

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