# Analysis and management of risks experienced in tunnel construction

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*In this study, first of all, the definitions of "risk", "risk analysis", "risk assessment" and "risk management" were made to avoid any confusions about these terms, and significance of risk analysis and management in engineering projects was emphasized. Then, both qualitative and quantitative risk analysis techniques were mentioned and within the scope of the study, Event Tree Analysis method was selected in order to analyze the risks regarding TBM (Tunnel Boring Machine) operations in tunnel construction. After all hazards that would be encountered during tunnel construction by TBM method had been investigated, those hazards were undergoing a Preliminary Hazard Analysis to sort out and prioritize the risks with high scores. When the risk scores were taken into consideration, it was seen that the hazards with high-risk scores could be classified into four groups that are excavation + support induced accidents, accidents stemming from geologic conditions, auxiliary works, and project contract. According to these four classified groups of initiating events, Event Tree Analysis was conducted by taking into care four countermeasures apart from each other. Finally, the quantitative and qualitative consequences of Event Tree Analyses, which were undertaken for all initiating events, were investigated and interpreted together by making comparisons and referring to previous studies.*

***Key words:*** *Tunneling, hazard, risk analysis, event tree analysis, occupational accident*

## 1. Introduction

The risk is a basic and natural element of life and defined as "the chance of something happening that will have an impact on objectives" meaning risk can be either positive or negative [1]. In some literature, risk can also be defined as an expression of the impact and the possibility of a mishap in terms of potential mishap severity and probability of occurrence [2]. However, in adverse chance, it is defined as "the possibility of loss, injury, disadvantage, or destruction". The risk is short exposure to the consequences of uncertainty that will have an impact on project objectives. It is present in all aspects of engineering projects, whatever their type is, and understanding and controlling risk are an essential component of project management. The key to controlling the risk lies in having a clear comprehension of what is a risk, risks relevant to the project underway and risk acceptance thresholds determined by the owners and stakeholders of the project. As these three requirements are easy to demand, they are more difficult to implement in real life.

The risk is inherent all engineering applications. The common practice area of mining and civil engineers, tunnel construction, is also prone to several hazards originating from different sources. The risk in tunneling has always been the object of attention because of time and cost overruns associated with tunnel construction projects. Although Porter [3], Healey [4] and Perry & Hayes [5] have expressed risk as exposure to economic loss or gain arising from involvement in an engineering process; Mason [6] and Moavenzadeh [7] have regarded this as an exposure to loss only. Bufaied [8] describes risk in relation to tunnel construction as a variable in the process of an engineering project whose variation results in uncertainty as to the final cost, duration and quality of the project.

Mining projects, as well as tunnel construction projects, tend to be large, complex, and expensive infrastructure undertakings that encompass various types of risks throughout the project lifecycle that arise from the uncertain nature of the underground. Uncertainty is the source of risk that dominates almost all engineering enterprises, and it refers to the event with an unknown parameter: occurrence, impact, possible outcomes and etc. [9]. For this reason, a careful risk analysis is of high importance in mining and tunneling projects in order to prevent potential occupational accidents.

## 2. Risk analysis, assessment and management

The terms "risk analysis" and "risk assessment" are often confused or used in place of each other. In fact, risk analysis could be described as a structured process that identifies both the likelihood and consequences of hazards arising from any given facility or activity [10]. The main steps of a risk analysis process are outlined in Figure 1, encompassing planning, risk assessment and risk treatment stages. On the other hand, risk assessment is the comparison of the consequences of a risk analysis process with acceptable criteria and other decision parameters [10]. Besides, the term known as "risk management" refers to the overall process by which decisions

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are made to accept known risks or the implementation of actions that are supposed to be taken to reduce unacceptable risks down to acceptable levels. Figure 2 shows the diagram of a risk management process developed after ISO 31000 together with its components. Risk management is an important tool to cope with substantial risks in the tunnel construction industry by: (a) assessing and ascertaining project viability; (b) analysing and controlling the risks in order to minimize loss; (c) alleviating risks by proper planning; and (d) avoiding dissatisfactory projects and thus enhancing profit margins. A risk management process typically comprises the establishment of context, risk identification, risk analysis, risk evaluation and risk response [11]. The primary component of risk management is risk-response, which involves choosing appropriate measures in advance to eliminate the likelihood of occurrence or mitigate the consequence of each risk. The risk management life cycle consists of four major steps: risk-identification, risk-analysis, risk-response, and risk monitoring and evaluation (Fig. 2). Risk-identification entails defining four risk components, namely, risk-sources, risk-factors, risk-events, and risk-impact. The risk - impact can be analyzed in a qualitative or quantitative manner to assess the degree (criticality) of each risk.

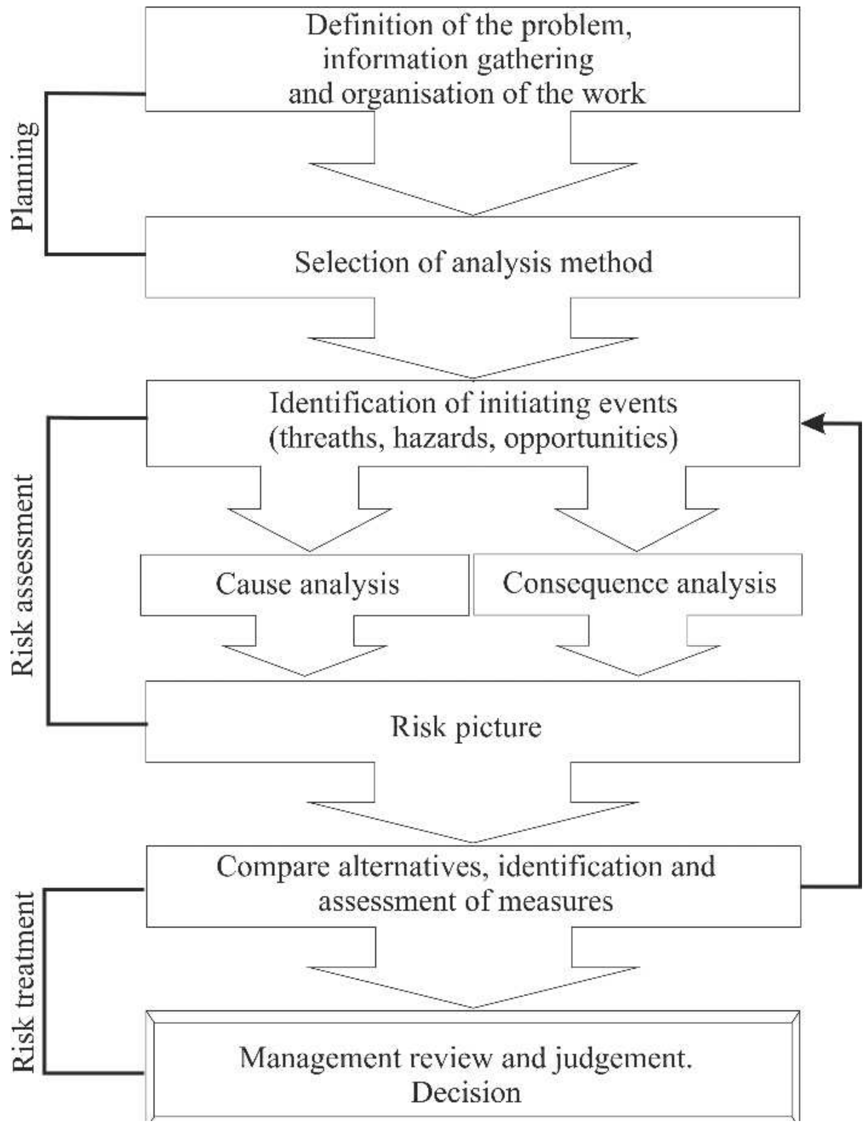


*Fig. 1 Main steps of risk analysis process [12].*

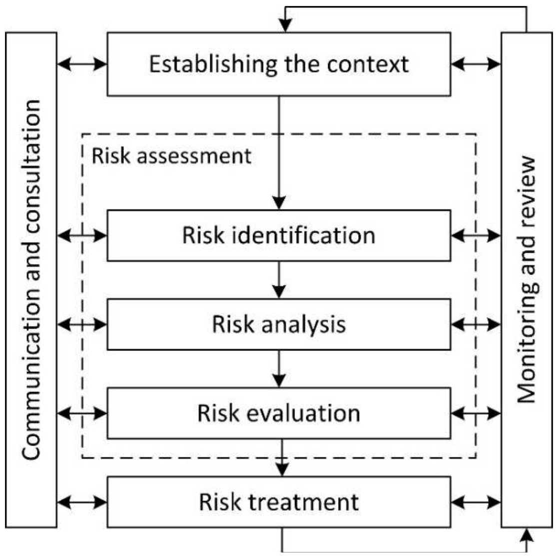


*Fig. 2 Risk Management Process [12].*

## 3. Risk analysis techniques

Risk analysis is the systematic use of available tools to identify hazards and to estimate the risk to individuals, property and the environment. Risk analysis is always a proactive approach in the way that it deals with potential accidents [13]. A risk analysis is carried out in 3 main steps as given below:

1. Hazard identification: In this step, hazards and threats related to the system are identified together with potential hazardous events. As part of this process, assets that may be harmed are also identified.
2. Frequency analysis: This step is usually a deductive analysis to identify the causes of each hazardous event and to estimate the frequency of the mentioned event based on experienced data and/or expert judgments.
3. Consequence Analysis: In this step, an inductive analysis is carried out to identify all potential sequences of events that emerge from the hazardous event. The objective of the inductive analysis is usually to identify all potential end consequence and also their probability of occurrence.

Risk analyses may be either qualitative or quantitative. A qualitative risk analysis prioritizes the identified project risks using a pre-defined rating scale. Risks will be scored based on their probability or likelihood of occurring and the impact on project objectives should they occur. Probability/likelihood is commonly ranked on a zero to one scale (for example, 0.3 equating to a 30 % probability of the risk event occurring). The impact scale is organizationally defined (for example, a one to five scale, with five being the highest impact on project objectives - such as budget, schedule, or quality). A qualitative risk analysis will also include the appropriate categorization of the risks, either source-based or effect-based [11]. The qualitative risk analysis techniques are Checklist, Preliminary Hazard Analysis (PHA), Safety Flowchart, What If Analysis (WIA), Bow-Tie Analysis, HAZOP, Layers of Protection Analysis (LOPA) and Security Vulnerability Analysis (SVA).

On the contrary, a quantitative risk analysis is a further analysis of the highest priority risks during which a numerical or quantitative rating is assigned in order to develop a probabilistic analysis of the project. A quantitative analysis:

- Quantifies the possible outcomes for the project and assesses the probability of achieving specific project objectives.
- Provides a quantitative approach to making decisions when there is uncertainty.
- Creates realistic and achievable cost, schedule or scope targets.

The best known quantitative risk analysis techniques are Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA). Among these quantitative methods, ETA was employed in the study because it is a logic model that mathematically and graphically portrays the combination of failures of events and circumstances in an incident sequence [13].

## 4. Model study of tunnel construction

### 4.1 Tunneling Methods

Tunneling costs, soil profile, safety requirements, and construction time are the main factors that determine the type of construction method to be employed. The common methods of soft ground tunneling are listed below:

- NATM – for excavation in cohesive or stabilized ground.
- TBM – for uniform ground with no serious obstacles. The TBM method with the shield is used for tunnels in the previous ground below water level.
- Cut-and-cover is a simple method of construction of shallow tunnels where the tunnel way is excavated manually or by using mechanical equipment; later, the roof is covered or left open, depending on the requirement. This method is most commonly used while the ramp is being constructed that leads to the underground or water at the starting point and ending point of the tunnel. The portions of tunnel excavation is done underground or below water are then constructed by using various other methods like NATM, the TBM method, and the Immersed method, etc.

In brief, New Austrian Tunneling Method (NATM) and the Tunnel Boring Machine (TBM) method is utilized in soft ground medium, whereas drilling-blasting method is employed in rocky mountain tunnels together with TBMs to a less extent. When the medium is water, then shielded construction and immersed technologies are consulted [14].

Rapid urban expansion caused by social and economic development has led to an enormous increase in traffic density and, as a result, to increase transit time for commuters. The non-availability of surface space for expanding the existing road network and the presence of other obstacles necessitate the development of other options available for better transportation. Tunnels have been a viable solution to the problem of managing the ever increasing traffic with minimal surface land utilization. Tunnels are underground passages that provide a safe transit for the travelling population. Since underground openings are a viable way of transportation in modern life and urban metro tunnels, where more problems are likely to occur, they are widely driven by using this main method. In this study, the tunneling method by TBM at shallow depths beneath civil settlements was adopted as the study topic on which risk analysis was carried out.

### 4.2 Preliminary Hazard Analysis

Within the scope of the study, initially, a thorough preliminary risk analysis, which is a typical qualitative risk analysis method, was conducted, and the outstanding hazards were prioritized. Regarding TBM operations in tunnel construction, a sum of 35 different hazards, which would lead to occupational accidents during and in the aftermath of tunnel construction, were analyzed. As the first step, the severity of the hazards was classified conforming to the written literature as in Table 1.

*Tab. 1 Hazard Severity Categories [15].*

| Description | Rating | Definition |
|---|---|---|
| Catastrophic | 5 | Death, system loss or severe environmental damage |
| Critical | 4 | Severe injury, severe occupational illness, major system or environmental damage |
| Serious (Major) | 3 | Moderately graded injury, moderate occupational illness, moderate system or environmental damage |
| Marginal (Minor) | 2 | Minor injury, minor occupational illness, minor system or environmental damage |
| Negligible | 1 | Less than minor injury, slight occupational illness, less than minor system or environmental damage |

Then, the likelihood of occupational accidents that are anticipated to occur was taken into care as in Table 2, and a quantitative risk assessment matrix was formed similarly to the one depicted in Table 3.

*Tab. 2 Quantification of Frequency Levels [15].*

| | | |
|---|---|---|
| **1** | Very unlikely | Once per 1000 years or more seldom |
| **2** | Remote | Once per 100 years |
| **3** | Occasional | Once per 10 years |
| **4** | Probable | Once per year |
| **5** | Frequent | Once per month or more often |

*Tab. 3 Quantitative hazard risk assessment matrix [16].*

| Likelihood / Severity | Negligible (1) | Marginal (2) | Serious (3) | Critical (4) | Catastrophic (5) |
|---|---|---|---|---|---|
| Very Unlikely (1) | 1 | 2 | 3 | 4 | 5 |
| Remote (2) | 2 | 4 | 6 | 8 | 10 |
| Occasional (3) | 3 | 6 | 9 | 12 | 15 |
| Probable (4) | 4 | 8 | 12 | 16 | 20 |
| Frequent (5) | 5 | 10 | 15 | 20 | 25 |

In Table 3, risk scores were found for all 35 events, by multiplying the severity of the event with the frequency level.

Risk Score = Severity x Probability

The regions marked with "yellow" colour in Table 3 emphasizes risk scores at "negligible" (1) and "acceptable" levels (2-6). In the same table, the regions marked with "blue" colour display risk score levels described as "moderate" (8, 9, 10, 12). In Table 3, the regions marked with "pink" colour illustrate risk scores at "unacceptable" levels (15, 16, 20) and at intolerable (25) levels. In addition, the reciprocal of the likelihood of occurrence of events are given in Table 4 and explicitly illustrated in Figure 3 terms of numerical values versus decision criteria.

*Tab. 4 Risk Score vs Decision Criteria [16].*

| Risk Score | Decision Criteria |
|---|---|
| Intolerable (25) | Stop operations immediately and rectify until the risk is reduced to an acceptable level. In case the risk is not reduced despite rectifications, then the operation should be precluded. |
| Unacceptable (15, 16, 20) | The operation should be stopped and risk should be reduced to an acceptable level. If the risk relates to the continuation of the work, the activity should no longer be achieved. |
| Moderate (8, 9, 10, 12) | Acceptable only with upper management review. Necessary activities should be started to decrease the determined risks. However, a risk reduction measure may take some time. |
| Acceptable (2, 3, 4, 5, 6) | Acceptable without review. Additional control processes may not be required to discard the existing risks. |
| Negligible (1) | Almost no or insignificant damage. It is not necessary to plan control processes or save the records of activities. |

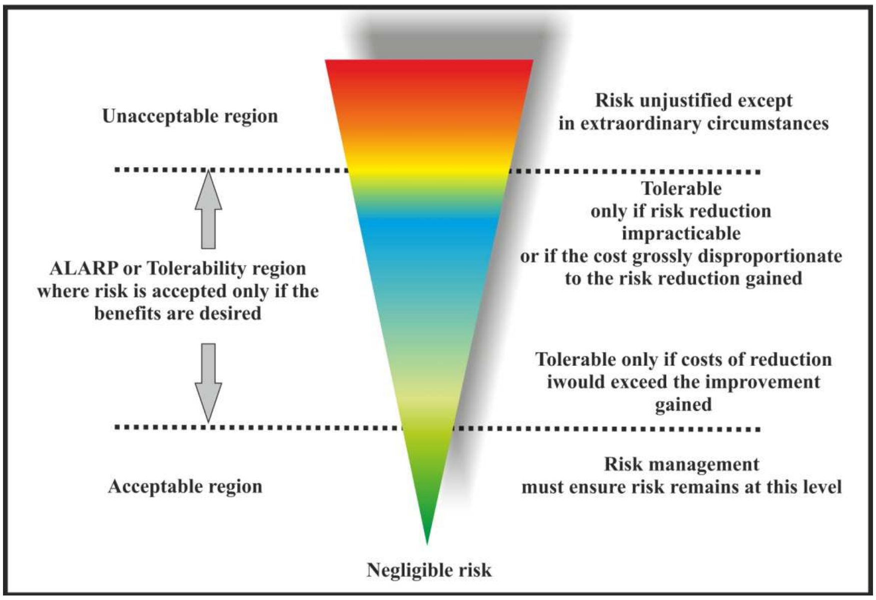


*Fig. 3 The ALARP Principle in Risk Analysis.*

When the risk scores obtained for potential 35 hazards are evaluated subject to Table 4 and Figure 3, risk scores having a value greater than 12 were sorted out because as depicted in Table 4, risk scores up to 12 are called "moderate" risk scores and acceptable with upper management review and also necessary activities should be started to decrease the determined risks, thus requiring no urgency. There is a transition zone between the values 12 and 16 as shown in Table 4 and Figure 3. Therefore, among all 35 hazards investigated, the events having a risk score greater than 12 formed the baseline of the study. When the hazards greater than 12 were sorted out, it was seen that the initiating events that would trigger occupational accidents in tunnel construction could be divided into 4 main headlines.

Depending upon the performed preliminary hazard analysis; occupational accidents in a tunnel construction seem to arise from basically 4 events, which are namely excavation + support induced accidents, accidents stemming from geologic conditions, auxiliary works, and finally, project contract. For this reason, those 4 events were selected as initiating events for the event tree analysis. After this determination; 4 countermeasures (also called pivotal events) were considered for each initiating event to prevent it from leading to an accident. These considered countermeasures were constrained with their weights in terms of percentage. While determining the percentage values, a diligent literature survey was made, and in addition, expert opinions and accident database of some construction companies operating in Turkey were also consulted. The countermeasures considered for each initiating event are given as follows:

A) Excavation + Support Induced Accidents in TBMs:
- Keeping the cutterhead under control 87 %
- Sustaining the stability of the face and proper support applications in front and behind the tunnel face 92 %
- Immobility of the operator within the TBM machine 73 %
- Periodical health safety and technical education programs for the machine operator 60 %

B) Geologic Conditions:
- Determination of soil and rock masses encountered underground and their geotechnical features 90 %
- Recognition of frequency of discontinuities like faults and joint sets 83 %
- Taking precautions in case of ground water and correct determination of water table 80 %
- Planning against any possible seismic activity, especially for the places that are located within major earthquake zones 65 %

C) Auxiliary Works (Ventilation, transport, dewatering, lighting and etc.):
- Planning an appropriate ventilation network for the underground opening and providing sufficient air for the workers underground 88 %
- Periodical measurement of combustible and toxic gases and dust that may be released underground 85 %
- Periodical maintenance of the machinery-equipment related to transport of material and dewatering operation 56 %
- Providing adequate lighting for underground works and proper insulation of electrical tools 64 %

D) Project Contract-Induced Accidents:
- Adherence to the employer and the project group to the signed contract 75 %
- Review and approval of the project contract by impartial third parties like universities and research institutes 70 %
- Duration of the contract and fixing an approximate deadline for any possible delays 55 %
- Financial and ethical reliability of the contractor company 68 %

## 5. Risk analysis in tunnel construction based on ETA and discussions

Event tree analysis (ETA) is a forward, bottom up, logical modelling technique for both success and failure that explores responses through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis. This analysis technique is used to analyse the effects of functioning or failed systems, given that an event has occurred [17]. ETA is a powerful tool that will identify all consequences of a system that have a probability of occurring after an initiating event that can be applied to a wide range of systems including: nuclear power plants, spacecraft, and chemical plants as well as tunnel construction. This technique may be applied to a system early in the design process to identify potential issues that may arise rather than correcting the issues after they occur. With this forward logic process, use of ETA as a tool in risk assessment can help to prevent negative outcomes from occurring by providing a risk assessor with the probability of occurrence. ETA uses a type of modelling technique called an event tree, which branches the events from one single event using Boolean logic [17].

There are a number of ways to construct an event tree. They typically use Boolean (or binary) logic gates, i.e. a gate that has only two options such as success/failure, yes/no, on/off. They tend to start on the left with the initiating event and progress to the right, branching progressively. Each branching point is called a node. Simple event trees tend to be presented at a system level, glossing over the detail [18].

Building the event tree starts from an initiating event. In the case of events characterized by two states only, the event tree will be a binary tree. In this case, depending on whether the next event from the chain occurs or not, the main branch splits into two branches. Each of these splits into two new branches depending on whether the third event occurs or not. This process continues until all events from the chain have been considered. For a chain of *n* events, there will be $2^n$ possible final states. A unique path will correspond to each final state. Paths that obviously do not lead to the undesirable event may not be developed. The probability of a particular state is equal to the probability of the path leading to this state. This probability is determined as a product of the probabilities of the branches composing the path. The probability of the undesirable event is the sum of the probabilities of all paths (outcomes) which lead to this event.

According to the details of initiating events and their countermeasures, even tree analysis method was employed yielding both quantitative, and qualitative risk analysis results from the study. In all those event tree analyses; the anticipated frequency of occupational accident was taken as "probable" corresponding to "once per year" as shown in Table 2 in order to be able to make an easier comparison. It is also noted that, subject to the general probability rule of statistics, $P_{SUCCESS} + P_{FAILURE} = 1$ for all four event tree analyses which means $P_{YES} + P_{NO} = 1$ in the relevant Figure 4 through 7.

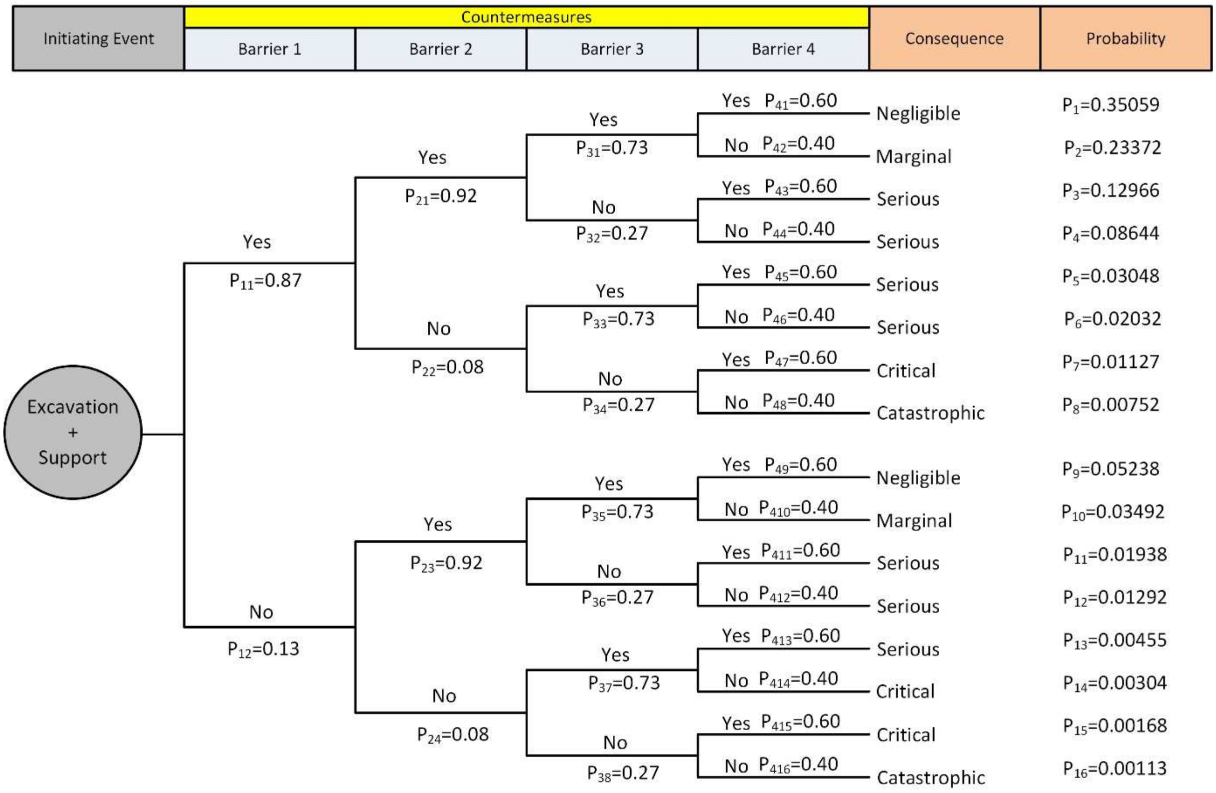


*Fig. 4 Results of ETA for Initiating Event-A.*

In the case of Initiating Event-A (excavation + support induced accidents); it is assumed that keeping the cutterhead under control and sustaining the stability of the face and proper support applications in front and behind the tunnel face have very significant effects on the outcomes with percentages of 87 % and 92 %, respectively. The third countermeasure, which is sustaining the immobility of the operator within the TBM machine, also has a significant role with a percentage of 73 %, whereas periodical health safety and technical education programs for the machine operator have relatively less effect with a percentage of 60 % when compared to other three barriers. According to Figure 4; the resultant probability of each path is computed by multiplying the probability values of the branches that form the path to each other (for example, $P_1 = P_{11} \times P_{21} \times P_{31} \times P_{41}$ and $P_{16} = P_{12} \times P_{24} \times P_{38} \times P_{416}$). In Figure 4, it is clearly seen that $P_1$ path has the highest probability to occur with a value of 0.35059 whereas $P_{16}$ path has the lowest probability to occur with a value of 0.00113. In Figure 4, the sum of paths ending with "negligible" consequence is 0.40297 ($P_1$+$P_9$), and the sum of paths ending with "marginal" consequence is 0.26864 ($P_2$+$P_{10}$). The sum of paths ending with "serious" consequence is 0.30375 ($P_3+P_4+P_5+P_6+P_{11}+P_{12}+P_{13}$) while the sum of paths ending with "critical" consequence 0.01599 ($P_7+P_{14}+P_{15}$). Eventually, the sum of paths ending with "catastrophic" consequence is 0.00865 ($P_8+P_{16}$).

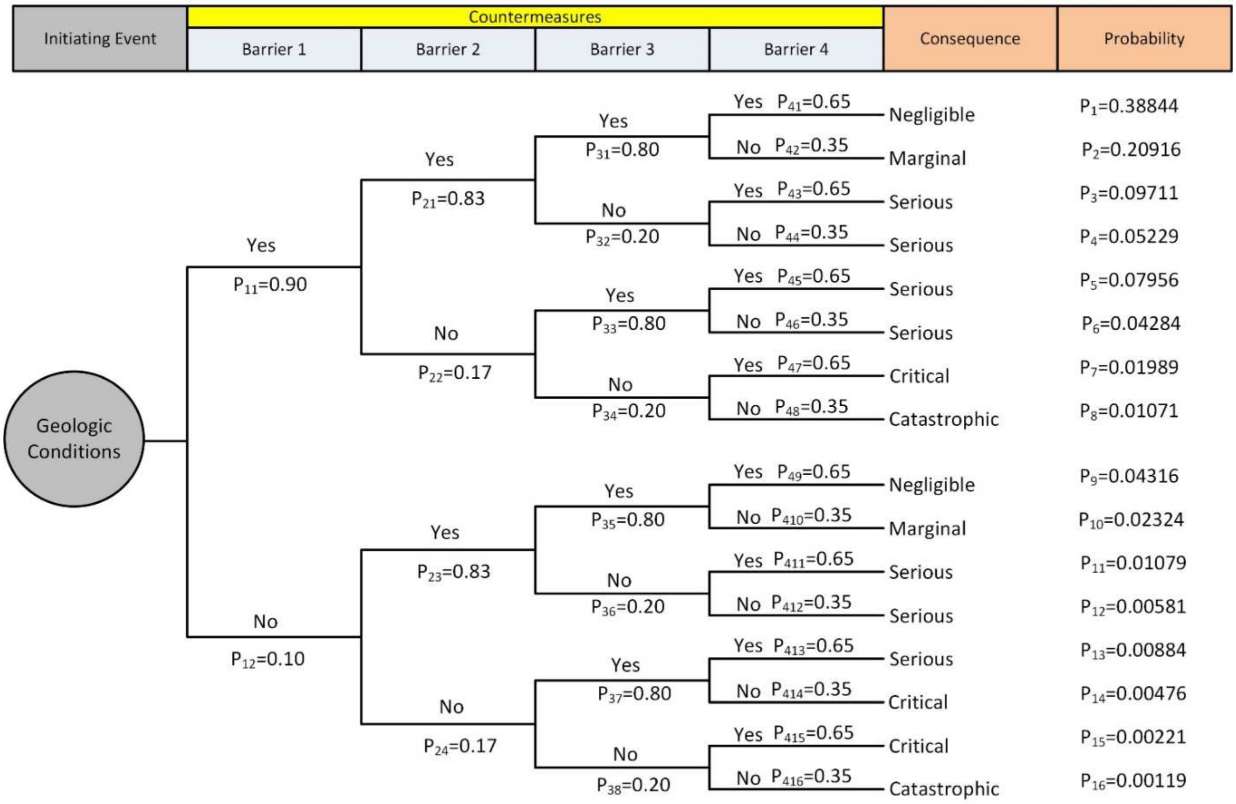


*Fig. 5 Results of ETA for Initiating Event-B.*

In the case of Initiating Event-B (accidents induced by geologic conditions); it is accepted that a proper determination of soil and rock masses encountered underground and their geotechnical features have a very significant effect on the outcomes with a percentage of 90 %. The second barrier, recognition of the frequency of discontinuities like faults and joint sets and the third barrier, taking precautions in case of ground water and correct determination of water table, also have important roles with percentages of 83 % and 80 %, respectively. The last barrier, which is planning against any possible seismic activity, especially in the places that are located within major earthquake zones have relatively less effect with a percentage of 65 % when compared to other three barriers. According to Figure 5; the resultant probability of each path is computed by multiplying the probability values of the branches that form the path to each other (for example, $P_1 = P_{11} \times P_{21} \times P_{31} \times P_{41}$ and $P_{16} = P_{12} \times P_{24} \times P_{38} \times P_{416}$). In Figure 5, it is clearly seen that $P_1$ path has the highest probability to occur with a value of 0.38844 whereas $P_{16}$ path has the lowest probability to occur with a value of 0.00119. In Figure 5, the sum of paths ending with “negligible” consequence is 0.43160 ($P_1$+$P_9$), and the sum of paths ending with “marginal” consequence is 0.23240 ($P_2$+$P_{10}$). The sum of paths ending with “serious” consequence is 0.29724 ($P_3$+$P_4$+$P_5$+$P_6$+$P_{11}$+$P_{12}$+$P_{13}$) while the sum of paths ending with “critical” consequence 0.02686 ($P_7$+$P_{14}$+$P_{15}$). Eventually, the sum of paths ending with “catastrophic” consequence is 0.01190 ($P_8$+$P_{16}$).

In the case of Initiating Event-C (accidents induced by auxiliary works such as ventilation, transport, dewatering, lighting systems); it is apprehended that planning an appropriate ventilation network for the underground opening and providing sufficient air for the workers underground, and secondly, periodical measurement of combustible and toxic gases and dust that may be released underground have both very significant effects on the outcomes with percentages of 88 % and 85 %, respectively. The third countermeasure, which is periodical maintenance of the machinery-equipment related to transport of material and dewatering operation, have a minor effect when compared to the former ones with a percentage of 56 % and the last countermeasure, providing adequate lighting for underground works and proper insulation of electric tools has quite an important influence with a weight of 64 % for the prevention of accidents. According to Figure 6; the resultant probability of each path is computed by multiplying the probability values of the branches that form the path to each other (i.e., P1 = P11 x P21 x P31 x P41 and P16 = P12 x P24 x P38 x P416). In Figure 6, it is clearly seen that P1 path has the highest probability to occur with a value of 0.26808 whereas P16 path has the lowest probability to occur with a value of 0.00285. In Figure 6, the sum of paths ending with “negligible” consequence is 0.30464 (P1+P9), and the sum of paths ending with “marginal” consequence is 0.17135 (P2+P10). The sum of paths ending with “serious” consequence is 0.45438 (P3+P4+P5+P6+P11+P12+P13) while the sum of paths ending with "critical" consequence 0.04587 (P7+P14+P15). Eventually, the sum of paths ending with "catastrophic" consequence is 0.02376 (P8+P16).

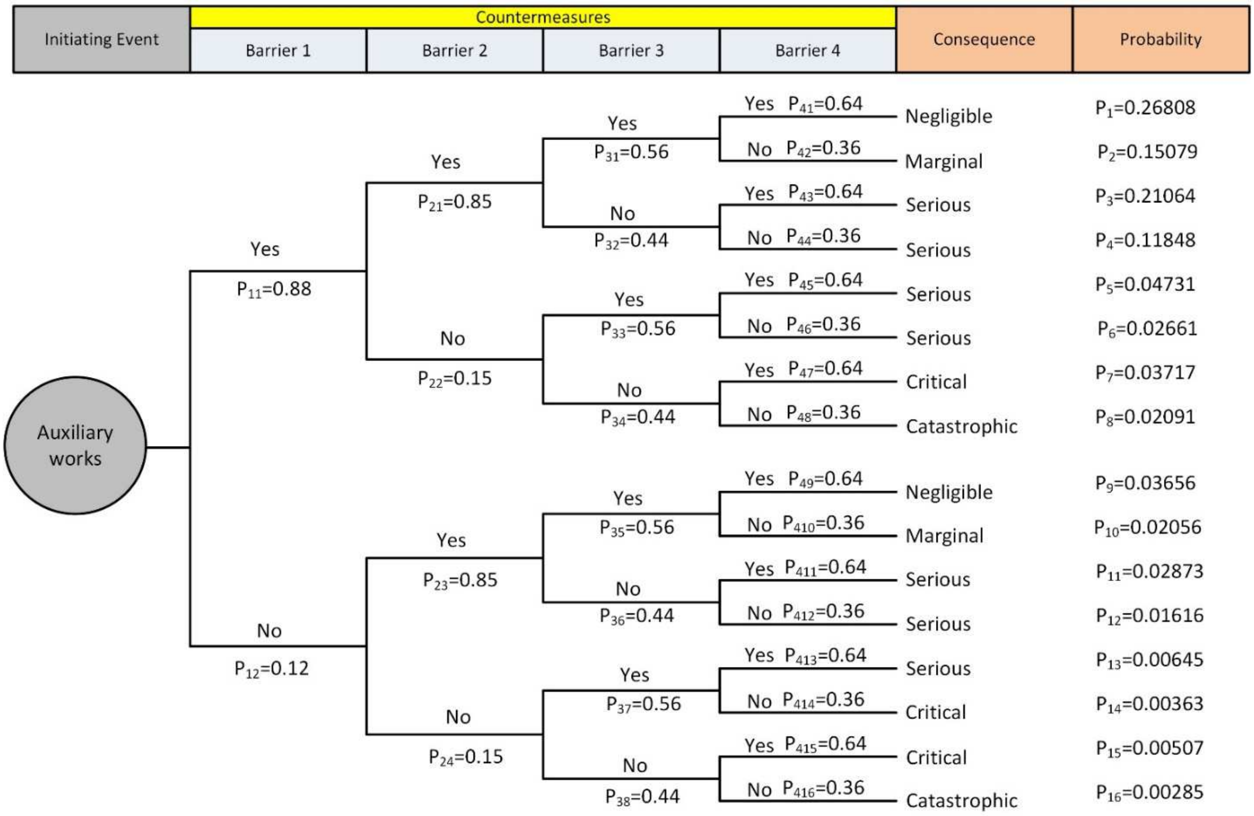


*Fig. 6 Results of ETA for Initiating Event-C.*

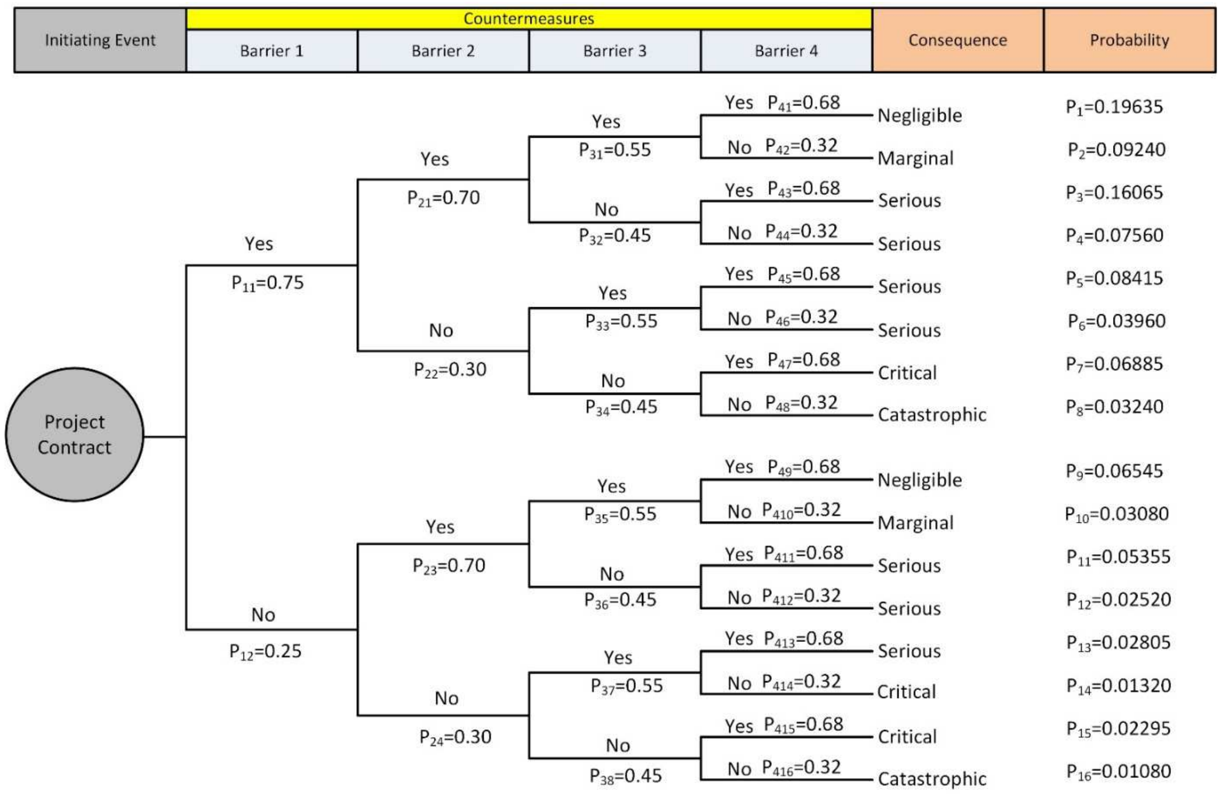


*Fig. 7 Results of ETA for Initiating Event-D.*

In the case of Initiating Event-D (accidents stemming from the loopholes in project contract); it is understood that both adherence of the employer and the project group to the signed contract and review and approval of the project contract by impartial third parties like universities and research institutes have important roles on the outcomes of the system on behalf of preventing accidents with percentages of 75 % and 70 %, respectively. The third barrier, duration of the contract and fixing an approximate deadline for any possible delays is slightly significant with a percentage value of 55 % while the last barrier that is the financial and ethical reliability of the contractor company have a relatively greater effect with a percentage value of 68 %. According to Figure 7; the resultant probability of each path is computed by multiplying the probability values of the branches that form the path to each other (i.e., $P_1 = P_{11} \times P_{21} \times P_{31} \times P_{41}$ and $P_{16} = P_{12} \times P_{24} \times P_{38} \times P_{416}$). In Figure 7, it is clearly seen that $P_1$ path has the highest probability to occur with a value of 0.19635 whereas $P_{16}$ path has the lowest probability to occur with a value of 0.01080. In Figure 7, the sum of paths ending with "negligible" consequence is 0.26180 ($P_1+P_9$), and the sum of paths ending with "marginal" consequence is 0.12320 ($P_2+P_{10}$). The sum of paths ending with "serious" consequence is 0.46680 ($P_3+P_4+P_5+P_6+P_{11}+P_{12}+P_{13}$) while the sum of paths ending with "critical" consequence 0.10500 ($P_7+P_{14}+P_{15}$). Eventually, the sum of paths ending with "catastrophic" consequence is 0.04320 ($P_8+P_{16}$).

When the quantitative consequences of the event tree analysis applied for 4 initiating events are rounded off in the form of 2-digit decimals, a summary of this qualitative and quantitative risk analysis can be obtained and summarized as in Table 5.

*Tab. 5 Summary of Quantitative and Qualitative Results of ETA.*

| Consequence | Excavation + Support | Geologic Conditions | Auxiliary Works | Project Contract |
|---|---|---|---|---|
| **Catastrophic** | **0.01** | **0.01** | **0.02** | **0.04** |
| **Critical** | **0.02** | **0.03** | **0.05** | **0.11** |
| **Serious** | 0.30 | 0.30 | 0.45 | 0.47 |
| **Marginal** | 0.27 | 0.23 | 0.17 | 0.12 |
| **Negligible** | 0.40 | 0.43 | 0.31 | 0.26 |

## 6. Conclusions

Risk analysis, being a proactive operation is very crucial for the preclusion of occupational accidents in engineering structures. Event tree analysis (ETA) was employed in the study because it is a logic model that mathematically and graphically portrays the combination of failures of events and circumstances in an incident sequence [19]. During the computations of the probabilities of all initiating events, no occupational accidents were assigned corresponding to "negligible" and "marginal" consequences, whereas accidents are expected to depend upon their degree of "serious", "critical" and "catastrophic". It is a known fact that there is a concept of "residual risk" in risk analysis. This is the reason, although all precautions are fulfilled indicated by the first path of ETA, why there is still a residual risk that may cause an occupational accident to happen. This is the reason why the very first paths of the trees are not assigned as "no damage" but "negligible damage" instead.

Hence, for the case of Initiating Event-A (excavation + support induced accidents); the probability of no accidents is found 0.40+0.27 = 0.67. So, the probability of occurrence of an accident is found 1-0.67 = 0.33 which can also be verified by Table 5 (0.30+0.01+0.02).

In the case of Initiating Event-B (accidents induced by geologic conditions); the probability of no accidents is found 0.43+0.23 = 0.66. So, the probability of occurrence of an accident is found 1-0.66 = 0.34 which can also be verified by Table 5 (0.30+0.03+0.01).

In the case of Initiating Event-C (accidents induced by auxiliary works); the probability of no accidents is found 0.31+0.17 = 0.48. So, the probability of occurrence of an accident is found 1-0.48 = 0.52 which can also be verified by Table 5 (0.45+0.05+0.02).

In the case of Initiating Event-D (accidents stemming from the loopholes in project contract); the probability of no accidents is found 0.26+0.12 = 0.38. So, the probability of occurrence of an accident is found 1-0.38 = 0.62 which can also be verified by Table 5 (0.47+0.11+0.04).

When Table 5 is investigated in detail; any misconduct in auxiliary works and project contract may cause "serious" accidents at considerably high rates like 0.45 and 0.47, respectively. Meanwhile, "serious" accident rates for Initiating Event-A and Initiating Event-B were calculated equal to each other with a probability value of 0.30.

According to a categorization done by Brown [20], the sum of critical and catastrophic accidents lead to "disastrous" results such as loss of human life, total loss of tunnel and major damage to the environment and settlements above. So, catastrophic accidents may occur with a probability of 0.03 for initiating event-A, at a probability of 0.04 for initiating event-B, at a probability of 0.07 for initiating event-C and at a probability of 0.15 for initiating event-D. It can be concluded that when the particular and strict precautions are taken that are intended for the prevention of accidents in tunnel construction regarding technical operations like the first 3 initiating events, it is more likely to prevent accidents at a higher level. On the contrary, accidents that may be induced by the loopholes in the project contract seem to have the highest disastrous consequences should a strict and perfect project contract and agreement is not made and the project is not financed. Since the pivotal events that were investigated under the initiating event "project contract" have relatively lower influence on the prevention of accidents due to their low percentages, any missing or lacking part of the contract or in capital supporting the project would cause irreversible results in future. Therefore, all the scientific reviews plus necessary legislative, financial and reliability amendments should be achieved over the project contract before other technical attempts and operations.

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