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Identifying and Evaluating Geological Risks of Tunneling with TBMs (Case Study: Aras Water Tunnel)

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Abstract Due to their specialized characteristics, water tunneling is considered as a risky and or venturesome industry. Therefore risk evaluation is one of the most important project management phases in these cases. In addition, as a result of high complexity of researches in this context, it is crucially necessary to analyze and evaluate state of the art risks in all phases of project execution. Considering this content, the present thesis tries to identify risk factors and evaluate their occurrence probability as well as measuring the extent of impacts of each risk. This paper presents a risk evaluation procedure with the help of risk probability-impact matrix in order to analyze the identified risks regarding geological issues of Aras Water Transfer Project. In order to do so, interview sessions were held with domain experts in addition to reviewing project documents and distributing a specific inventory among project experts. Based on results of analyses, approximately 61% of potential risks of the project should be mitigated and reduced to acceptable levels despite the costs of doing so. On the other hand, 22% and 17% of identified risks were respectively medium and low and they need to be managed during the execution of project and do not require special considerations.

Keywords Risk evaluation, Risk probability-impact matrix, Occurrence probability, Impact severity.

Introduction

In general, tunnels and other undersurface structures are dramatically risk prone due to several factors including unpredictability and uncertainty of underground environments. These risks can threaten the safety and or economy of projects. Evaluating and ranking risks in venturesome projects such as meachanized tunneling projects are among the necessary actions that need to be taken by the management in order to react to related risks. This requires identification and determination of risk factors. Underground projects including tunnels are generally complex projects taking effects from several variables.

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Table 1. General risks of tunneling and excavation projects.

Operation	Technical and engineering	Equipment	Support	Human resource	Organizational and external
Unsuitability of reservoirs	Collapse of tunnel	Deterioration of equipment	Lack of proper transfer of equipment to project site	Injury of workers at work	Lack of financial support and lack budgets
Workers' strike or reluctance	Breakage of drill augers	Lack of in time repairs and lack of adequate spare parts	Lack of in time transfer of equipment to the inside of tunnel	Lack of familiarity with functions of equipment	Lack of adequate monitoring while extracting data
Loss of saved data	Collapse of tunnel	Technical flaws in equipment	Delay in transfer of equipment and workforce	Lack of monitoring of work of human forces	Lack of setting clear contract terms
Software and hardware issues	Lack of proper air fixing of reservoirs	Equipment breakdowns	Lack of existence of necessary parts in storage	Lack of expertise of human resources	International sanctions
Undesirable weather conditions		Technical flaws and defects in contractors' equipment			Delay in decision making

In this cases the yielded information are usually obtained indirectly. This situation imposes significant risks on almost every component of the project even those indirectly associated with the project. In addition these risks results in further expenses and time delays. In time and proper management of such risks mitigates the probability of occurrence of risks as well as their negative impacts of project goals. Lack of certainty regarding geological conditions associated with construction of such tunnels, creates obligations in terms of evaluation of risks during design, boring and sustaining phases [1].

Risk

Risk is defined as a function of occurrence of a specific event and consequences, and is always accompanying all affairs related to natural earth [2]. In general, geotechnical risks associated with tunnel drilling are signs of geotechnical conditions of risks that are affected by undesirable impacts of tunneling project. Geotechnical risks have always been a challenge in tunneling projects and need to be measured during the construction phase in order to mitigate the associated risks. According to the categorization of the International Tunnel Association (ITA), the process of risk identification and ranking should be initiated from the very initial design phase. In this phase, risk size can result in changes in practical solutions and may also impose a change in work perquisites.

The process of risk identification includes determination of risks effective on the project in addition to documentation of their characteristics. In general, participants of the risk identification process include project team, risk management team, experts from other sections of executing organization, costumers, find consumers, other project managers, stakeholders and finally, outside experts [3].

Risk identification is a repeatable process. The first phase of this process may be conducted by a portion of the project team and or the risk management team. The next phase is probably undertaken by the entire members of project team and major stakeholders. In order to obtain a fair analysis, the final phase of risk identification process may be conducted by people who are not directly engaged with the project. As soon as the risks are identified, it becomes feasible to discover effective and yet simple solutions. At certain occasions, only parts of these simple and effective solutions may be implemented.

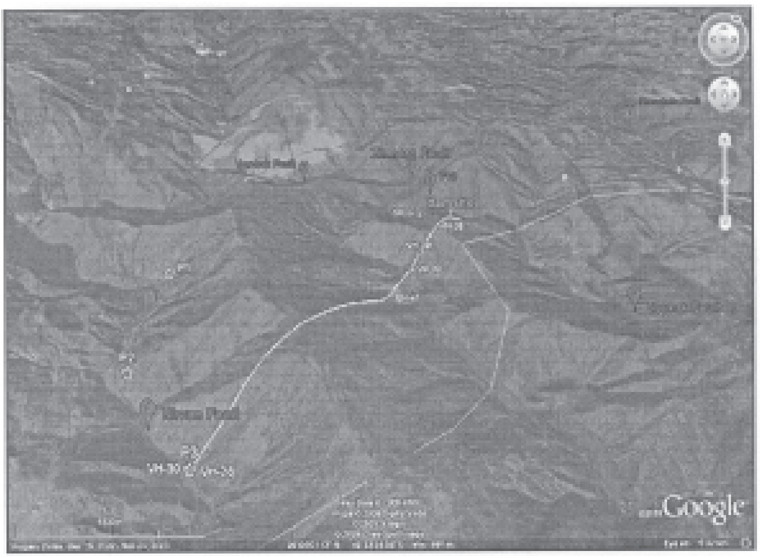

Fig. 1 Tunnel path map.

Risks of excavation and tunneling

Basically there are several problems and risks associated with traditional methods of tunneling including sustaining the earth, prevention of subsidence of ground in urban areas, prevention of flood of underground waters and most importantly, safety and health of working personel.Considering these factors, mechanized excavating has been the best substitute for traditional methods since it has provided the opportunity for drilling long tunnels under different geotechnical conditions while employing the minimum amount of human forces and time. In past, various methods were used for tunneling among which it can be referred to the Austrian method. Nowadays, tunnels are mostly drilled using TBMs (Tunnel Boring Machines).Occurrence of several common geotechnical incidents in long and deep tunnels have resulted in higher risks, higher costs and more delays. This issue is basically due to lack of suitable and proper interpretation of local observations on the one hand and, limited knowledge of stone masses in depth of tunnels on the other hand. Mechanical tunnel drilling has accelerated the trend of progression and deployment of tunneling industry. However, as a results of uncertainties these projects are consistently presented with a high level of risk. On this basis and with respect to high cost and time required for execution of mechanical tunnel drilling, it is highly crucial to identify and prioritize the risks associated with excavation machines used. Studying accidents and injuries related to underground structures is a useful tool for understanding transient phenomena and mechanisms we face while constructing our structures. Main causes of accidents breakdowns and failures include insufficient geotechnical studies, design errors, errors in numerical calculations, construction errors, and errors occurred during operation of structures and unpredictable ac cidents and events associated with underground projects. Design and implementation of mining projects require significant investments and are included among most venturesome projects. Therefore risk management is of crucial importance in these projects. Identification of risk factors and awareness about severity and type of impacts in addition to proper ranking are considered as effective steps towards proper evaluation of associated risks and subsequently, reacting to them and may reduce the extent of damages in case of occur-

Table 2. Phenomena of risk from the perspective of geotechnical and geo-mechanical issues.

No.	Risks	Factors and marginal conditions
Z1	Contacting shattered zones and faults	Lack of possibility of progression of TBM, flood of water through zones of fault
Z2	Fall of stone blocks	Work cessation, reduction of progression rate, damaging the disks
Z3	Flood of water to the inside of tunnel	Resulting in delays and increased costs
Z4	Combined working conditions	Reduced machinery efficiency, impacting the cutters
Z5	Karst potential	As a result of lack of soluble rocks there is no possibility for formation
Z6	Gas leak	Exit of water from opening is accompanied by a huge amount of gases, results in increased work difficulty reduced the personnel's efficiency and may cause fire
Z7	Squeezing phenomenon	Breakages along the tunnel path due to high load, deformation of sections of the tunnel
Z8	Contacting falling dust	Existence of sand layers within fully-saturated anaphylactic compounds
Z9	Existence of expanding soil	Areas of northern and southern parts that contain clay fines

rence of such events. It is worth mentioning that as a result of high uncertainty of their immediate environment, underground spaces are accompanied by high risks. Among the causes of these risks it can be referred to the following: Unpredicted high volume of water, a determining factor of all time, Transportation activities impose a great deal of weight and are highly energetic, The work is done in environments less lit compared to surface structures' environment, High humidity and temperature in work environment of underground/undersurface structures, Having to use high-voltage explosives [4].

Considering the above content, it is clear that every underground activity requires massive investment and proper high precising schedules. In this case ignoring the risks associated with the project in hand results in increased costs and time as well as troubling the progression of project. At every stage of design, construction and implementation, every project is faced with a wide variety of risks that need to be identified and controlled in time.

Reily and Brown have counted the following as various risks associated with tunneling projects:

1) Risk of Damage with potential of killing or injuring the personnel or impacting the economy or equipment of the project; and or discrediting the involved parties.

2) Risk of deviation from standards and criteria determined during design, operation, support and quality assurance.

3) Risks of crucial delays at the end of project and initiation of income generation.

4) Risks associated with dramatic increases in project costs and supporting them.

Yauger has introduced a general risk categorization for risk management of tunneling projects. He has divided risks into four types including natural

Table 3. The phenomenon of risk from the perspective of design and TBM obligations.

No.	Risks	Factors and marginal conditions
Z10	Insufficient water sealing system	TBM maker and designer
Z11	Lack of adequate machinery robustness	TBM maker and designer
Z12	Lack of quickness of shields	TBM maker and designer
Z13	Inadequate draining syatems	TBM maker and designer
Z14	Lack of proper work pressure design	TBM maker and designer
Z15	Insufficient electro-mechanical equipment	TBM maker and designer
Z16	Insufficient and defective repairing and maintenance processes	TBM maker and designer

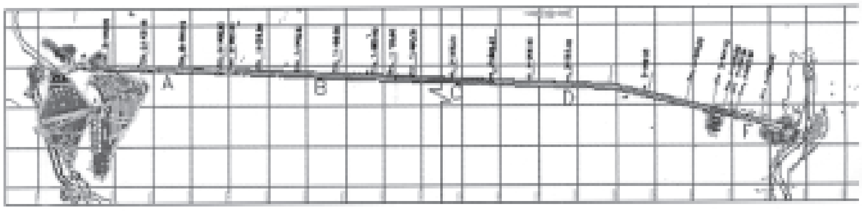

Fig.2. Divisions of working orientations in excavation of tunnel.

(flood, earthquake); external (Economic, political); internal (strategies, weak design) and, human resources (accidents resulting in injuries). In addition, Dudek has presented the following categorization for risks associated with underground projects. Categories of this categorization include structural, contractual and operational.

This categorization is to a high extent related to time and life-cycle of an underground structure. Therefore operational risks are related to the length of exploitation of an underground structure and include failures related to the goals of construction of the structure [5]. Among these types of risk, with respect to having its own time period, structural risks are mainly concerned with engineering issues. These failures may happen either during excavation of an underground structure or afterwards. Contractors are responsible for failures that occur after the period of construction. Among these risks it can be pointed to risks associated with swollen stones or fracturing of water reservoir walls. Contractors are responsible for these risks.

With respect to this content it con be stated that risk analysis includes the processes of identification and measurement and mitigation of risks associated with specific hazards. Investigation of geological and geotechnical hazards, and risks associated with these hazards in issues related to design and implementation of stone structures such as tunnels are among the most important factors that need proper attention. In this regard and with respect to previously mentioned content, the present research tries to identify and evaluate the geological risks associated with tunneling with tunnel boring machines (TBMs) in case of Aras water transfer project.

Reviewing of literature

Duzgun and Einstein [6] conducted a study and investigated the risks of collapse of ceiling of underground coal mines in Turkey according to frequency of occurrence of ceiling collapses throughout a year.Two main components used in these analyses included occurrence and consequence of occurrence. In most of their research studies, in addition to in vestigating the precess of risk management in tunneling and undersurface projects, Rely et al. [7] have expressed the cost and time of design and construction phases while considering for risk as a probability function. They have investigated correlation and independence coefficients of various risks by only making use of two common indices of probability and risk impact for evaluation of risks. Evans et al. [8] pointed out that one of the main limitations of the common methods of risk evaluation is that they are mostly focused on avoidance of negative events. They emphasized that while applying the sustainable development point of view, it is also crucial to account for positive events as well. They have tried to develop a novice method to be implemented for three Australian coal mines while also paying attention to necessities of sustainable development.

Arshadi et al. [9] tried to analyzed the risks of collapse of buildings in tunneling with TBMs. Their case study was the lane 2 project of Mashhad urban train system. This paper introduces a new combined

Table 4. Phenomenon of risk from the perspective of construction period (mechanized excavation, TBM driving and installation of concerte covers).

No.	Risks	Factors and marginal conditions
Z17	Insufficient pressure in work front	Improper operation by contractors during constrution
Z18	Improper injection	Improper operation by contractors during constrution
Z19	Improper machine guidance	Improper operation by contractors during constrution
Z20	Insufficient safety measures	Improper operation by contractors during constrution
Z21	Breakdown of machinery	Improper operation by contractors during constrution
Z22	Over trafficking of machinery	Improper operation by contractors during construction
Z23	Loss of pollutants	Improper operation by contractors during constrution

Table 5. Phenomenon of risk from the perspective of humane factors.

No.	Risks	Factors and marginal conditions
Z24	Sanctions	International sanctions troubles the allocation of machinery and foreign personnel
Z25	Lack of experience	The contractor is not employing expert personel
Z26	Lack of experience of contractor	The contractor lacks adequate experience
Z27	Improper organizing by the contractor	The contractor lacks adequate experience
Z28	Contractual issues	The contract between the employer and contractor is defective and includes uncertainties that may result in suspension of work

method for evaluation of risks of collapse of various structure along the direction of tunneling. In addition collapses of a major building were analyzed and calculated. Results have shown that the presented method is robust in determining the risk level imposed on buildings. Ultimately by taking into account these determined risk values certain decisions could be made regarding specific buildings.

Malakooti and Gharibi [10] conducted a study and tried to analyze the risks of mechanized tunneling operations through energy tracking and obstacle analysis methods. This research tries to evaluate the risks of tunneling using a TBM in a certain domestic tunneling project. This descriptive case study uses the energy tracking and obstacle analysis techniques for analysis of risks. Energy sources, goals and consequences of hazards have been identified by several working groups and experienced experts. Ultimately the identified risks were prioritized and subsequently, adequate control measures were recommended for each case.

Tabatabaei and Farshadnia [11] analyzed the risks of excavation and its impacts in under construction tunnel of Amirkabir based in FMEA methods. This descriptive study has divided the process of excavation into three operational phases. Authors of this paper calculated the cumulative abundance and cumulative abundance percentage of risk values and prioritized them using a Pareto chart.The highest risk values were associated with 4 hazards including collision of excavation machines into personnel, collision of machines into other machines and or equipment, fall of equipment and fall of people from different parts of drilling platforms.

Materials and Methods

With respect to its nature and goal, the present study is an applied-descriptive study. In order To further explain it can be said that this research tries to investigate the hazards and evaluate geological risks of tunneling with TBMs in Aras water transfer project. After categorization and scoring the identified risks, the entire risks are represented in a risk probability-impact matrix. The entries of the aforemantioned matriex have been derived from multiplying the value of probability by risk severity.In addition it should be mentioned that the software of SPSS has been used for analysis of data.

Aras water tunnel

Aras water tunnel has a length of more than 17 kilometers and is located in North-west of Iran and is aimed at transfer of water from the constructed site.

Table 6. Recording the geotechnical risks of Aras water tunnel project.

No.	Risk factors	Risk events resulting in damages	Risk evaluation Probability	Severity	Rank
1	Lack of recognition of constructors	Z10, Z13	5	8	40
2	Lack of in time installation of tools	Z15, Z19, Z21	5	17	85
3	Lack of identification of risk prone areas	Z1, Z3, Z8	5	18	90
4	Using low quality tools	Z20, Z21, Z24	3	17	51
5	Lack of ability in entering data	Z25, Z26	5	16	80
6	Lack of in time supplication of tools	Z26, Z27, Z28	4	12	48
7	Suspension of machinery due to transience of work environment	Z1, Z8, Z17, Z24	4	20	80
8	Machinery jamming	Z8, Z9, Z11, Z12, Z13, Z23	4	16	64
9	Leakage of poisonous and dangerous gases	Z6	3	15	45
10	Jamming of machine's shield	Z8, Z9, Z10, Z11, Z12, Z14, Z16, Z17, Z19, Z27, Z28	4	16	48
11	Occurrence of mechanical issues in machines	Z15, Z16, Z25, Z26, Z27	3	6	18
12	Lack of sustainability of tunnel walls	Z16, Z12	4	16	64
13	Chemical corrosion	Z18	5	10	50
14	Ring segments	Z18, Z25	4	12	48
15	Improper orientation	Z19, Z19, Z25, Z26, Z27	2	8	16
16	Lack of experience of personnel	Z25, Z26	3	20	60
17	Lack of equipment	Z24	4	4	16
18	Human forces risk	Z20, Z21, Z25, 27	4	20	80
19	Expiosion and fire	Z20, Z21	3	15	45
20	Water contamination	Z18, Z23, Z25	3	15	45
21	Water flood	Z10, Z13, Z14, Z18	4	12	48
22	Improper sealing	Z18, Z25	4	8	32
23	Low machinery progression rate	Z4, Z9, Z10, Z11, Z12, Z13, Z14, Z15, Z17, Z24, Z25, Z26	4	12	48

With respect to long length of this tunnel, it has been decided to use a TBM for drilling the tunnel since this method is highly safe and rapid. So as it has already been mentioned, the site under study is in far North-east of Iran and between the borders of Iran and Armenia. Since using TBMs is a new method and there are various ambiguities regarding these systems, risks associated with these methods is relatively high and therefore, the present paper tries to evaluate the existing risks and afterwards, tries to reduce the risks to an acceptable level.

General geology of project area

Considering the fact that several holes have been excavated along the length of this long water tunnel, evaluating the results obtained from these holes has made it clear that the rocks on the path of tunnel are mainly slate and metamorphosed sand stones with siliceous layers and ophiolite blends in some areas. The tunnel path goes entirely through a slate stone unit with a cleavage system with a general slope towards Eastern north. In other words, slate-sandstone layers' slope is towards the inlet opening and the most important structural hazard of tunnel path is faults. In terms of geology of site, this tunnel is located in a wide area of cretaceous sedimentary layers which has also passed a weak metamorphosis. In terms of lithology, the site is composed of shale and sandstone which have turned into slate and phillytes with discontinuous schistosity levels. Based on studies and investigations, it has been decided to use TBMs for excavation of the tunnel. Figure 1 shows the map of excavation path and structural consequences of turnel path.

In order to accelerate the speed of work in this

Table 7. Risk probability-impact matrix.

Risk effect probability	4–8	9–12	13–16	17–20
5	1	13	5	2.3
4	17.12	6.7.21.23	8.10.12.14	4.18
3			9.11.19.20	16
2	15			
1				

project, the mentioned water tunnel has been divided into several smaller parts and in each part, operations are carried out independently. According to Figure 2, the tunnel excavation proceeds from the inlet towards depth of tunnel.

According to investigations, it was turned out that the existing aquifers were mostly of free and pressured types. The pressured types of aquifers have been transferred as a result of secondary elements such as excavation. Measurements performed in excavated holes shows that a major portion of the tunnel is located under the level of undersurface waters. With respect to existence of important faults including the Under-Death fault with a shattered zone and considering that the stones on tunnel path are made of slate and phyllite and are extremely weak and will even weaken further in case of having contact with water, rate of progression of excavation will certainly and significantly reduce in case of encountering undersurface water reservoirs. Results of experiments have shown that except for fault areas, a highly compressibly but of low permeability stone mass surrounds the tunnel. In addition stones forming the tunnel site are of high special weight and low porosity. It is also worth mentioning that the Under-Death fault has a length of 5 kilometers and based on field and experimental observations, this fault has a high slope towards north.

Risk evaluation process

Identification of potential hazards; defining a scenario; determining the probability of event; determining the severity and consequences, Evaluation of risk level using the matrix model, Determination of preventive measures and reassessment of risks.

Results and Discussion

Identifying and ranking project risks

By incorporating the ideas and opinions of experts and managers of Aras water tunnel project, we have identified the potential risks that could risk throughout the projects. The list of identified risks was further exposed to managers and experts and they were asked to determine the probability, cost impact and time impact of each risk. After collection of data and calculation of value of probability-impact for each risk; the most critical risks were determined. In addition with respect to risks of tunnel boring, a risk importance table has been developed. In second phase, a list of general risks associated with tunneling projects was extracted and afterwards, a specific cost has been assigned to each risk according to history of risk management for these risks in all operational phases (Table 1).

Afterwards we have elaborated on risk management based on risks specific to the project under study. We have tried to prioritize these risks according to the following:

Reviewing the project documents, Making use of experiences of previous projects, Employing inner-organizational and outer-organizational experts, Making use of survey forms and project identification checklists, Confirmation of prioritized risks in meetings.

Hazardous phenomena in Aras tunnel project

The following table presents a list of potentially hazardous phenomena (Tables 2–5).

Recording and evaluating risks

The following table provides a detailed explanation of entire evaluation phases of probability of occurrence of hazards and their potentials. The identified risks have been ranked after determination of parameters of probability and risk severity (Table 6).

The following table shows the results of investigations and risk mitigation measures in Aras water tunnel project (Table 7).

Upper tables have shown that most of prevalent risks are due to geologica, geo-mechanical and geotechnical elements.

Conclusion

In general economic advances in developing countries such as Iran require certain infrastructural projects including tunneling. For this purpose, there are several projects that are currently under operation in diferent parts of Iran. Many of these projects are exposed to certain risks. The present research was aimed at realization of a suitable and efficient risk management for these projects and it can play a significant role in terms of realization of goals of aforementioned projects. On this basis, in addition to introducing various risk mansgement approaches, the present research also tries to determine executive solutions for the case study of Aras water tunnel project. Among the advantages of this research study it can be pointed to making use of collective wisdom in all phases of the project. This issue has yielded more precies and error-free data since the risk matrix method provides a logical framework for making sufficient decisions. Additionally, incorporating expert work forces and selecting experienced contractors can eb considered as suitable solutions for prevention of occurrence of many risks. In this research, a great deal of experts have collectively agreed upon the necessity of expertise of work forces for management and controlling of risks.

The following are among the findings of this research study: According to the results of analyses of factors related to geotechnical and geological conditions of tunnel path, almost and or approximately 61% of the identified risks are of high destruction and or injury potential and therefore need to be carefully mitigated to at least tolerable and or acceptable levels. In addition 22% of the cases had a medium risk and 17% had a low level of risk. These risks need to be managed throughout the project but do not require special considerations in order to be mitigated.

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