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# Using Energy Trace and Barrier Analysis Method for Risk Analysis of Automated Excavation Work: A Novel Approach to Huge Tunnels

Jafar Jafari*
Faculty of Industrial and Civil Engineering, Yerevan State University of Architecture, Yerevan, Armenia

**Abstract**— Today, Tunnel Boring Machine (TBM) is usually used for automated excavation, especially in huge tunnels with high operation rate. In recent years, numerous accidents have been occurred in tunneling projects, especially in excavation by TBM. Hazards should be controlled through risk management process. The current study is aimed to evaluate the risks involved in an automated excavation project using TBM. In the current descriptive case study, energy trace and barrier analysis were used for performing risk analysis. Observation, experience and judgment of personnel, checklist, related codes and standards as well as accidents and near misses recorded in safety office were used in data collecting process; identifying the resources of energy, goals, possibility and consequences of hazards were performed in numerous workgroups by experienced experts. The identified risks were prioritized and controlling measures were recommended. In the current study, 51 hazardous energy resources were identified in six energy groups. While 29.4% of the identified energy resources were related to the physical energies, 19.6%, 41% and 8% of the identified energy resources were related to chemical, mechanical, and electrical energies, respectively. However, only 2% of those resources were natural. The crane with 19.5% and the cutter-head and shield with 10% of total hazardous energy resources were the most and the least dangerous parts of tunneling process with TBM. According to the results of the current study, TBM operation involves various and numerous hazard resources. It can be possible to use energy trace and barrier analysis method ad an effective method for analyzing the risks involved in TBM operation.

**Index Terms**— Energy Trace, Barier Analysis, Risk Analysis, Excavation, Tunnel Boring Machine (TBM), ETBA Method, Huge Tunnels

## 1 INTRODUCTION

Tunneling is of increasing rate all around the world. In recent years, Tunnel Boring Machine (TBM) has been widely used in tunneling, especially in excavating huge tunnels with high operation rate [1-8]. Due to complexity of excavation process by TBM, there is a high risk of accident occurrence during TBM operation [9, 10]. Working in an environment with lack of natural light, possibility of failure of tunnel's walls, encountering with various types of air pollutants, hazards induced by explosion and fire are a number of factors leads to numerous risks that will be arisen in such environments [11]. If hazards of tunnels have not accurately identified and controlled, irreparable disasters will be occurred. In 2006, four people were died during excavation of a tunnel in west of Iran due to deficiency in ventilation system and emission of hydrogen sulfide in the tunnel [12, 13, 16, 17]. Occurrence of numerous accidents in recent years, leading to death in some cases, demonstrate that tunneling projects are hazardous in Iran [12-23]. In order to control these hazards, it is necessary to perform a systematic risk assessment for all activities in various stages of the project [24, 25]. Lack of comprehensive and compiled studies about analysis of occupational health and safety risks in automated excavation project and development of automated tunneling in projects such as metro, water conveying tunnels and road tunnels demonstrate the necessity of performing the current study to accurately identify and control occupational health and safety risks of the project.

The current investigation was carried out in one of the huge automated tunneling projects of Iran. Energy trace and barrier analysis (ETBA) technique, which has been previously used in numerous studies [26-42], was used in the current research. The successive structure of this technique causes to its more logical approach about identification of hazards and controls compared to many other analysis methods [43]. ETBA method is a process for identification of hazards induced by all hazardous energy resources. By evaluating controlling measurements, this technique provides a tool for assessing the unwelcome energy flows toward targets (persons, equipment and or environment). In fact, this technique, with the aim of identifying and assessing the hazards, evaluates all energy resources, which are potentially harmful [44-54].

TBM consists of two parts; main body and support mechanisms. The main body of TBM consists of various parts including cutter-head and disc cutters. Cutter-head consists of a series of disc cutters mounted on it. These discs consist of cutters which are designed and made as rotating in high pressure according to rock type and excavation capability. The excavated materials transported by conveyor belts to wagons and then exited from the tunnel.

Back up parts are responsible for supporting the activities of main body; removing and transporting the excavated materials and leaked water from the tunnel face, stabilizing tunnel walls using segment transporting equipment, pea-gravel injection and grouting are the activities of various parts of support mechanisms. These parts are mounted on successive wagons and trailed by TBM as excavation operation progresses.

- *Jafar Jafari, M.Sc., Corresponding Author, Master Degree of the Faculty of Industrial and Civil engineering of the Yerevan State University of Architecture and Construction in the Specialty of "Construction, Production of Building Items and Structures".*

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## 2 Investigating Method

The current investigation is a descriptive case study which has been carried out in 20 km length Karaj water conveyance tunneling project during 2010-2015. This tunnel was excavated using a Hard Rock double shield TBM with 4.66 m diameter. Since the most important and essential activity of automated excavation process is TBM operation, the hazards of this operation were investigated in the current study.

Energy Trace and Barrier Analysis method was used for hazard analysis. One of the characteristics of this method is that it can be used for hazard analysis of all types of energy systems [55-63].

For more accurate investigating the automated excavation process by TBM, the activities of 7 parts of the machine including cutter-head, shield, erector, crane, pea-gravel (tanks and injection), grouting and car mover were studied. Observation, interview and experience and judgment of personnel were used for data collecting. Personnel were asked for fulfilling a form named as "Personnel Experiences and Judgments Form" including the name, type of activity and career of them to document accidents and near misses experienced by every person and his co-workers. The form was included another part called "hazards identification and proposing controlling methods" in which worker noted hazardous experiences of his work and proposed his suggestions for controlling such hazards. Moreover, numerous observations and interviews in various shift works were performed during 6 months to ensure that all possible hazards are identified. Working codes and standards [64-69] were used to design checklists.

When identification of hazardous factors requires measuring data for comparing with occupational threshold limit values [70], the results obtained from studies in the under studied area, performed by academic centers, were used; some of the data was related to measurements of physical harmful factors such as noise, weather condition, electromagnetic fields and lighting and some of that was related to chemical harmful factors in tunnel.

The implemented steps followed in the current study and in using ETBA method are as following:

1- Identifying the energy resources; this step includes investigating the constituents of system and identifying all potentially hazardous energy resources. By completing checklists, reviewing accidents and near misses records in safety office and implementing technical meetings with field engineers, representative of workers and experts of safety office, energy resources were identified [71, 72].

2- Energy tracing; after identifying the energy resources, energy should be traced in the system from the start to the end. This step consists of identifying all targets which may be injured by hazardous energy resources. Energy flow graphs were used in which the variations of energy resource against energy target so that energy route and barriers (controls) were identified [73-75]. This step was performed by contributing TBM engineers.

3- Identifying the controlling measures and evaluating the system; by contributing experts, this step was performed by identifying all controls presented in the route of energy flow and determining the primary risk as well as recommending suggested controls to resist against energy flow and determining secondary risk induced by controlled energies [75-78].

The meetings were held with engineers, field authorities, representative of workers and technical experts of safety office and the intensity and probability of hazard were determined by considering the possible occurrence of hazards and records of accidents and near misses in the project and other similar ones. As the experience of technical team is of critical role in risk estimation, experts with more than five years experience were used in the current study. Seventeen meetings were held during all steps of the study [78-80].

By comparing the obtained code with judgment criteria of risk, the primary risk analysis was performed to determine the necessity of implementing the controlling measures.

## 3 Results and Discussion

Among 7 parts of TBM, 51 hazardous energy resources were identified in six energy groups. While 29.4% of the identified energy resources were related to the physical energies, 19.6%, 41% and 8% of the identified energy resources were related to chemical, mechanical, and electrical energies, respectively. However, only 2% of those resources were natural.

It was found that 60% of physical energies were related to noise and vibration while 13% of those were related to weather condition and 27% were related to electromagnetic fields; in chemical energy group, 40% of energies were categorized as flammable materials and 60% were identified as harmful materials. Hazards were identified and categorized in 5 subgroups for mechanical energies, which has the highest number of hazardous energy resources; falling with 27%, throwing with 18%, stumbling and collision both with 14%, under pressure tanks and dragging both with 9% and sharp and keen edges and hot and cold surfaces both with 4.5% are of highest contribution in mechanical energy resources.

In the current study, noise and vibration in erector, crane, pea-gravel and grouting and noise in car mover are of highest rank in the primary risk analysis. The secondary risk evaluation, assuming that the recommended controlling measures for each part is implemented, was shown that risk is in an acceptable level.

In cutter-head, shield, erector, pea-gravel/tanks, grouting and car mover harmful material subgroup of chemical energy group is of highest rank of risk while in crane, flammable materials is of highest rank in the primary risk analysis. Dust induced by excavation operation and emissions from exhausts are the most important reasons for chemicals emission in the environment. The secondary risk evaluation, assuming that the recommended controlling measures such as installing appropriate filters on the exhausts and providing water sprinkling system on the wagons during material removing is implemented, was shown that risk is in an acceptable level.

Mechanical hazards were identified in all investigated parts of TBM. The identified hazards were included falling, stumbling and dragging, under pressure tanks, throwing, sharp and keen edges and collision. Among various parts of TBM, falling is of most amplitude. Pea-gravel/tanks and grouting are of the highest rank risk of 1A among all parts of TBM.

The electricity was identified in all parts except that erector, cotter-head and shield and the primary risk rank was evaluated more than acceptable level. In secondary evaluations, assuming that controlling measures such as using connecting system to the earth and accurate maintenance and repair of equipment are implemented, risk levels were reduced.

Energies related to natural sources are of the lowest amplitude. Due to the possibility of instability in face of tunnel, cutter-head was the only part of TBM which presented in this group. In order to avoid from the occurrence of such accident, some measures such as visual assessing of ground, ground stabilizing with crowbar and performing probe drilling investigations can be considered before each period of excavation to reduce risks down to acceptable level.

The crane with 19.5% and the cutter-head and shield with 10% of total hazardous energy resources were the most and the least dangerous parts of tunneling process with TBM. Car mover and erector, pea-gravel/tanks and injection and grouting have 17.5%, 13.5% and 12% of hazardous energy resources, respectively.

## 4 Conclusion

As mentioned above, most of the identified energy resources were related to mechanical energies. In mechanical energy subgroup, the highest identified risk was falling with 27% amplitude since there are various activities related to relocating and transporting of materials and equipment in tunnel excavation operation. Falling from height is one of the most frequent accidents in construction projects. Falling is a major risk factor in construction industry as well as other industries.

Throwing also was identified as the second most important mechanical hazard. It was shown that throwing is involved in activities such as pea-gravel injection and grouting as well as excavation operation. Gravel and soil particle throwing may be led to eye injuring.

Further, it was found that both collision and stumbling has 14% of hazardous energy resources. Going the soil wagon off the rails in the tunnel, stucking body organs in segment feeder (erector), and stucking body organs when locomotive and soil wagons are moving are the activities in which, collision and stumbling were identified. In order to control the mentioned risks, some measures such as continuous inspection of equipment, ensuring soundness of speakers, continuous education of personnel and compilation of working specifications were recommended. The difference between percents of various industries is due to the differences in type and nature of the work as well as different amount of implementing the controlling measures in each industry.

In addition to accidents induced by work, construction workers are subjected to pathogenic factors such as smoke and fumes, noise and vibration. The results of the current study also demonstrates this issue. In the present study, 60% of the identified physical energy resources were related to noise and vibration; the presence of equipment such as compressors and pumps in excavation operation and high level noise induced by such equipment as well as confining the working environment of tunnel led to emergence of these harmful factors. The secondary risk of this problem was reduced by performing some controlling measures on the noise and vibration resources and on the workers such as installing silencer on the fans and pea-gravel compressor and proper isolating of car mover cabin. Bad weather condition and encountering with electromagnetic fields also were identified as physical energy resources. The most important reasons of these hazardous energies were working in depth of tunnel, high humidity level, high temperature and working adjacent to high voltage power lines.

Electricity and electrocution risk were identified in 57% of investigated TBM parts. The importance of electrocution hazard is very high due to presence of numerous electric equipment and high level of humidity in working environment.

In chemical group, 60% of the identified hazardous energy resources were related to harmful materials. Such high level is due to the fact that a wide range of chemicals are placed in this subgroup. Emissions from exhaust of locomotive, aerosol and dust induced by excavation operation and underground gases such as hydrogen sulfide and methane all contain these hazardous factors.

Factors relating to the earth were the only identified natural energy resources. Since segments installed on tunnel walls when tunneling is performed by TBM, instability of walls is reduced to the lowest possible amount and the only possible risk is burying the head of machine in the soil during excavation which has not offered any risk to workers. In an investigation performed by Jafari et al. about risk analysis of TBM by failure mode analysis and its effects, they were concluded that cutter-head stoppage is of highest risk, which can be led to TBM stoppage.

Safety education, inspection, maintenance, and repair of equipment are suggested in controlling recommendations as effective factors for reducing hazard level. It has been widely recognized that education of safety issues and compilation and implementation of inspection, maintenance and repair programs are very effective in promotion of safety culture and reduction of hazards.

A strong side of the current study is using the common sense in all steps of the project, which led to lower error in data collecting and analysis as well as allowing the use of the results in other similar projects. When using ETBA, human errors and deficiencies of equipment, which are not directly related to energy resources, may be ignored. This is one of the disadvantages of the method. Lack of similar studies limits comparing the results. According to the obtained results, it can be said that Energy Trace and Barrier Analysis technique, with its logical approach, can be utilized as an effective risk analysis method for automated excavation operation of tunnel.

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