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MACEDONIAN ASSOCIATION FOR GEOTECHNICS

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# ENGINEERING PROBLEMS IN SOFT ROCKS

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# Application of failure mode and effect analysis for tunnel risk assessment

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## ABSTRACT

Modern tunnel engineering is a complex task. From planning, design to construction, tunnels represent great challenge for the engineers and everyone involved in the projects. Nowadays the „classic“ approach in design and tunnel construction alone, is not adequate for the intense and demanding tunneling projects. With greater dimension, complexed locations and geological conditions, modern tunnel engineering initiates greater risks. These risks generally can be associated with financial and time loss and in some worse cases with human injuries and losses. For better understanding and dealing with the hazards and risks, they should be assessed in a separate part of the project. The paper shows how the failure mode and effects analysis can be used for tunnel risk assessment. This type of approach represents a semi-quantitative risk analysis that identifies the parts of a project (uncertainties and hazards), which need greater attention or change. The presented assessment is an application of modified failure mode and effect analysis using information from the design phase, for predicting potential risks in the construction process. The results from the analyzed road tunnel show the advantages and disadvantages of this approach and how it can be used in tunneling.

## KEYWORDS

Tunnelling; Hazards; Risks; Assessment; Failure Mode and Effect Analysis.

## 1. INTRODUCTION

Tunnels and different undergrounds structures are always connected with some level of uncertainties. The potential hazards that can cause unwanted consequences represent the risks for the project. Conventional tunnel engineering approach, especially in big projects is not sufficient for determining, assessing and later managing the risks. This leads to the larger use of different methods, approaches and techniques for tunnel hazard and risk assessment and management.

## 2. HAZARDS AND RISKS IN TUNNEL ENGINEERING

The hazards and risks concept is a very valuable “tool” in many technical areas, whose beginnings can be linked to the military, nuclear and oil industries. Nowadays, such an approach is widespread and increasingly accepted in tunnels and other underground structures.

Terrain (field) features and characteristic have a very big role in determination of uncertainties, hazards and risks in tunnel engineering. Unidentified terrain features can lead to unexpected behavior of structures. On the other hand, the identified characteristics may not be expressed in quantitative terms or their behavior may not be fully determined. These uncertainties for underground projects are related to the limitation of the possibility to predict future geological events, changes in engineering components over time, changes in the environment caused by climate and changes that occur during the excavation itself. The volume and quality of investigations have a very large impact on the occurrence of geological (geotechnical) uncertainties. In tunnels, the primary source of uncertainty is usually the inappropriate approach in this segment. The typical components for examination of the construction location are:

- Collection of existing information (regional maps, satellite imagery, technical literature, studies and reports);
- Field investigations (direct investigations (boreholes and wells), indirect investigations (geophysical), geodetic surveying and monitoring);
- Laboratory tests - identification and classification of materials and determination of their geotechnical, hydraulic and other parameters;
- Field reconnaissance and mapping - geological, geomorphological and hydrogeological;
- Pilot tunnels or shafts - identification of complex geological environments, test fields for grouting, installation of primary lining, etc.

According to the research by Rita L. Sousa (2010), in “mechanized” methods (TBM and shields) hazards occur more often in soil materials, while in conventional methods the share of hazards is almost identical in soil and rock materials.

The reports from the world insurance industry contain information about large number of tunnels. In the period from 1993 to 2003, the main causes for hazards and risks in tunnels are:

- Natural events (50%);
- Construction methods (25%);
- Design bases (10%);
- Fires (10%);
- Unedified reasons (5%).

In professional literature, collapse (demolition) as a phenomenon is most often recorded due to the great consequences it causes on the construction process, the safety of workers and the environment. The collapse can be manifested in different ways such as: falling of the overburden, instability of the excavation face, collapse of the tunnel walls, etc. Usually, this phenomenon is caused by several factors, and some of them are other types of hazards.

Table 1. Main parameters that affect the manifestation of hazards during tunnel construction

| Hazards | Influential parameters |
|---|---|
| Rock burst | Rock type and strength, stress state, faults; tunnel geometry, construction method |
| Excessive deformations | Swelling, squeezing, construction method |
| Rock fall | Discontinuities, tunnel geometry, stress state, construction method, water inflow |
| Flooding | Location of water table, permeability (soil), water pressure, fracture conductivity (rock), faults, water bearing strata |
| Collapse | Ground type, faults, presence of other structures, overburden, water inflow, excessive deformation, construction method |

## 3. TUNNEL RISK ASSESMENT

Hazard and risk assessment is a process that uses knowledge from multiple areas. In addition to the engineering knowledge and skills for the specific problem, probability theories and statistics, decision-making methods, mathematical and graphical models are used in risk analysis.

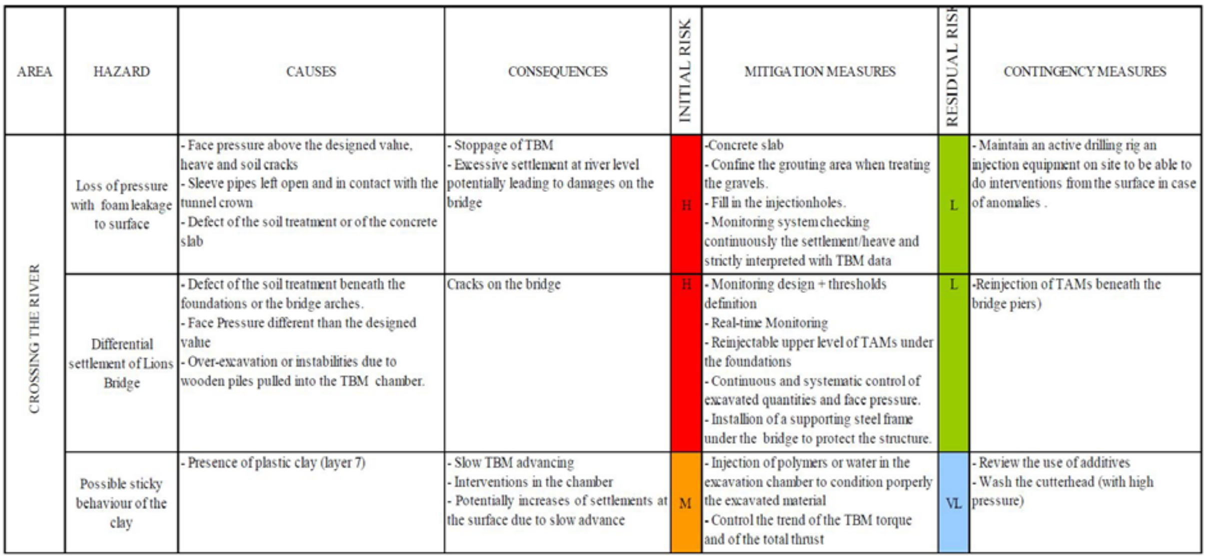
During the early design stages the qualitative risk analysis is an appropriate approach for identification of hazards that represent a threat for the activates during construction. Qualitative analysis should be carried out while major design changes are still possible.

Probability and consequence ratings are usually combined in a risk index or risk matrix (Table 2) in order to assess it. The risk matrix can also be used in quantitative analysis, when the probabilities and consequences are followed by appropriate numerical values.

Table 2. Example of risk matrix

| Probability | Consequence | | | | |
|---|---|---|---|---|---|
| | Disastrous | Severe | Serious | Considerable | Insignificant |
| Very likely | Unacceptable | Unacceptable | Unacceptable | Unwanted | Unwanted |
| Likely | Unacceptable | Unacceptable | Unwanted | Unwanted | Acceptable |
| Occasional | Unacceptable | Unwanted | Unwanted | Acceptable | Acceptable |
| Unlikely | Unwanted | Unwanted | Acceptable | Acceptable | Negligible |
| Very unlikely | Unwanted | Acceptable | Acceptable | Negligible | Negligible |

Most regulations and manuals in this area recommend the use of a risk register (Figure 1). These registers should cover all possible events and situations that pose a threat to the project. In order to be able to make them properly, experts from many different fields with experience in the field of hazard identification are needed.



| AREA | HAZARD | CAUSES | CONSEQUENCES | INITIAL RISK | MITIGATION MEASURES | RESIDUAL RISK | CONTINGENCY MEASURES |
|---|---|---|---|---|---|---|---|
| CROSSING THE RIVER | Loss of pressure with foam leakage to surface | - Face pressure above the designed value, heave and soil cracks<br>- Sleeve pipes left open and in contact with the tunnel crown<br>- Defect of the soil treatment or of the concrete slab | - Stoppage of TBM<br>- Excessive settlement at river level potentially leading to damages on the bridge | H | -Concrete slab<br>- Confine the grouting area when treating the gravels.<br>- Fill in the injectionholes.<br>- Monitoring system checking continuously the settlement/heave and strictly interpreted with TBM data | L | - Maintain an active drilling rig an injection equipment on site to be able to do interventions from the surface in case of anomalies . |
| | Differential settlement of Lions Bridge | - Defect of the soil treatment beneath the foundations or the bridge arches.<br>- Face Pressure different than the designed value<br>- Over-excavation or instabilities due to wooden piles pulled into the TBM chamber. | Cracks on the bridge | H | - Monitoring design + thresholds definition<br>- Real-time Monitoring<br>- Reinjectable upper level of TAMs under the foundations<br>- Continuous and systematic control of excavated quantities and face pressure.<br>- Installion of a supporting steel frame under the bridge to protect the structure. | L | -Reinjection of TAMs beneath the bridge piers) |
| | Possible sticky behaviour of the clay | - Presence of plastic clay (layer 7) | - Slow TBM advancing<br>- Interventions in the chamber<br>- Potentially increases of settlements at the surface due to slow advance | M | - Injection of polymers or water in the excavation chamber to condition porperly the excavated material<br>- Control the trend of the TBM torque and of the total thrust | VL | - Review the use of additives<br>- Wash the cutterhead (with high pressure) |

Figure 1. Example of a risk register for tunnelling underneath a bridge in Sofia

Most regulations and manuals in this area recommend the use of a risk register (Figure 1). These registers should cover all possible events and situations that pose a threat to the project. In order to be able to make them properly, experts from many different fields with experience in the field of hazard identification are needed.

Quantitative risk analysis such a deterministic and probabilistic assessment approaches can also be used for tunnel projects. There are various advantages in relation to the qualitative approach, such as better description of the hazards and risk, explanation of the dependencies between the considered events and phenomena and more specific results from the analysis. There are many methods and models for quantitative risk assessment worldwide: failure mode and effects analysis (FMEA), fault tree analysis (FTA), event tree analysis (ETA), decision tree analysis, bayesian networks, Markov process, etc.

### 3.1. Failure mode and effect analysis (FMEA)

The failure mode and effects analysis allows to assess the relative impact of different types of failure in order to identify the parts of a process (system, construction) to which the greatest attention should be paid. (or who need change the most). This process developed by the US army, should answer two questions "what could happen wrong?" and "how can this happen?". The method is also found under the name "Failure mode, effects and criticality analysis" (FMECA) where additional criticality analysis is performed. In civil engineering, these techniques can be applied in the design, construction, operation and maintenance phase for various types of structures. To use this analysis it is necessary to have a well-defined system and detailed information and data on the components in the system.

Show in this paper is a semi quantitative modified approach where each type of hazard is ranked according to three parameters: severity, occurrence and detection. Each rank is a numerical rating assigned to the parameter and then the product of all three ratings give the risk priority number (RPN). Elements with a higher RPN are more critical than those with lower values. The number of ratings and interpretations of the RPN can be found in different variants in the literature. Often in software containing this method, the three main parameters are ranked on a scale of 1 to 10, so that the RPN can vary from 1 to 1000. This paper shows modification of this method in terms of ratings, in order to obtain a more efficient model for use in tunneling. Each parameter is ranked or graded on a scale of 1 to 5 (Table 3,4 and 5).

Table 3. Ratings for severity of failure

| Rating | Effect | Severity of effect |
|---|---|---|
| 1 | Minor | < 0,1 % impact on project costs and time |
| 2 | Low | 0,1 - 1 % impact on project costs and time |
| 3 | Moderate | 1 - 10 % impact on project costs and time |
| 4 | Major | 10 – 80 % impact on project costs and time |
| 5 | Extreme | 80 % impact on project costs and time |

Table 4. Ratings for occurrence of failure

| Rating | Probability of occurrence | Possible failure rate |
|---|---|---|
| 1 | Very low | < 1/500 |
| 2 | Low | 1/500 – 1/100 |
| 3 | Moderate | 1/100 – 1/10 |
| 4 | High | 1/10 – 1/2 |
| 5 | Very high | > 1/2 |

Table 5. Ratings for detection

| Rating | Detection | Criteria |
|---|---|---|
| 1 | Very high | Very high chance for detection of potential cause/mechanism for failure |
| 2 | High | High chance for detection of potential cause/mechanism for failure |
| 3 | Moderate | Moderate for detection of potential cause/mechanism for failure |
| 4 | Low | Low for detection of potential cause/mechanism for failure |
| 5 | Very low | Very low for detection of potential cause/mechanism for failure |

Multiplying the ratings from all three parameters gives the risk priority number for each hazard (failure) separately. The presented FMEA analysis gives the RPN in range from 1 to 125. In addition to the RPN ranking, which analyzes the most critical hazards, a qualitative risk assessment based on the obtained values is often made (Table 6).

Table 6. Risk assessment in relation to the risk priority number (RPN)

| Risk assessment | Risk priority number (RPN) |
|---|---|
| “Low” < | 16 |
| “Moderate” = | 16 – 36 |
| “High” > | 36 |

## 4. APPLICATION OF FMEA FOR ROAD TUNNEL RISK ASSESSSMENT

The failure mode and effect analysis has been used for risk assessment of a road tunnel in the construction phase with data and information for the design phase. Located in the west part of North Macedonia as a part of the future highway, the two tunnel pipes (for each direction) have width of 9,60 m and height of 6,83 m. The length of the pipes are 622 and 705 m with maximum overburden around 60 m. The planned construction method is with Cut & Cover for the portals and drilling with mining for the underground part. A lot of different information regarding existing data, investigations, faults, state of groundwater, tunnels support and construction technology have been used for the risk analysis.

The three most relevant hazards for this tunnel are the unpredicted groundwater inflow, instability of the excavation face and block instability. For the hazards, different risk priority number has been obtained, from which the risk assessment can be made (Table 7).

Table 7. Results from the failure mode and effects analysis for a road tunnel

| Number | Hazard | Severity | Occurrence | Detection | RPN | Risk assessment |
|---|---|---|---|---|---|---|
| 1 | Groundwater inflow | 3 | 2 | 2 | 12 | Low |
| 2 | Instability of the excavation face | 4 | 2 | 2 | 16 | Moderate |
| 3 | Block instability | 4 | 3 | 4 | 48 | High |

The highest value of RPN arises from the instability of blocks, which belongs to the high risk zone according to the proposed limits (Table 6). The reason for this result is the lack of analysis of potentially unstable blocks. The instability of the excavation face belongs to the moderate risk zone or ALARP region, and the groundwater inflow to the low risk zone or the generally acceptable area (Figure 2).

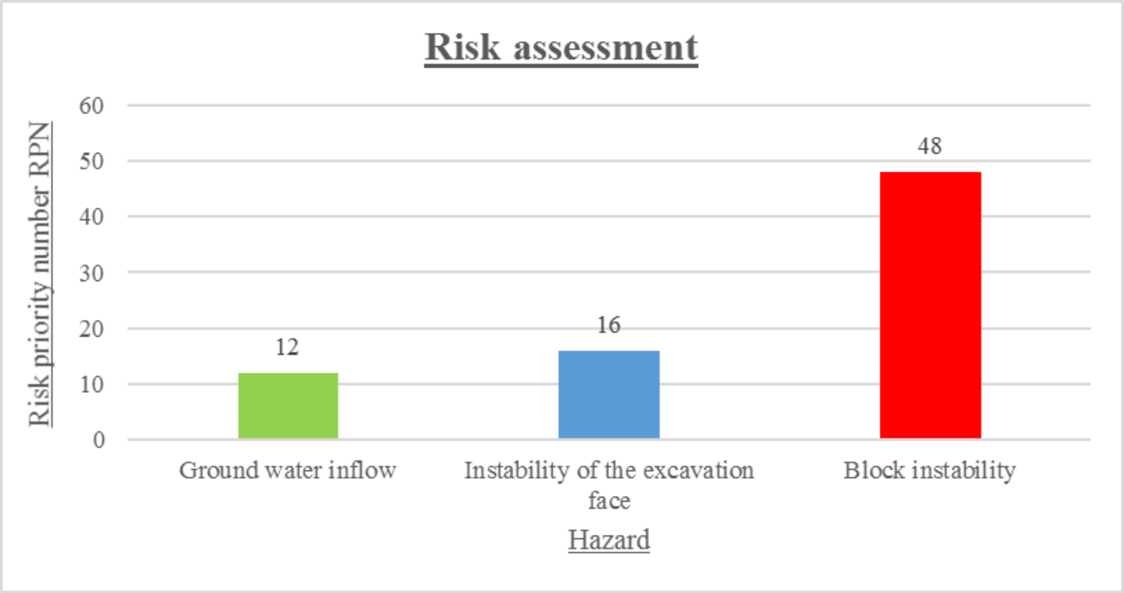


Figure 2. Graphical representation from the risk analysis of the road tunnel

Because this tunnel has a high risk i.e. a risk that belongs to an unacceptable region, it needs to be reduced, regardless of the costs. In addition, to confirm or disprove this assumption, another type of quantitative analysis is recommended.

## 5. CONCLUSIONS

New tunnel challenges require greater and more advanced approach in the area of hazards and risks. Qualitative and quantitative methods offer different examination and results for the problems that may occur in the planning, design and especially in the construction and exploitation phase. The failure mode and effects analysis (FMEA) offers basic risk assessment for different project phases. The biggest advantage of this method is its simplicity of use and the possibility for modification, where satisfactory results can be obtained without the use of specialized software. For better results the modified FMEA analysis shown in this paper should be used along (before) another more advanced quantitative analysis. This process can help in the determination of the most relevant hazards and risks to the tunnel project.

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