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RISK ANALYSIS AND MANAGEMENT IN TUNNELLING

Abstract: The concept of risk analysis and management has a big impact and application in various branches of society. Today in civil engineering, especially in infrastructure projects this concept represents a serious matter that should not be avoided or delayed. There are different approaches and definitions for a risk, but it is important every problem to be reviewed separately. In tunnelling the uncertainties and risks are always present, so appropriate measures and management should be considered and implemented.

Key words: Civil engineering, tunnels, risk analysis, risk management

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1. INTRODUCTION

Tunnels represent unique underground structures which are used for different purposes. Nowadays their application is bigger and more widespread throughout the world. Tunnel design and construction is a special area i.e. science discipline of the underground structures where the experience and knowledge from other areas are applied such as: geology, soil mechanics, rock mechanics, theory of structures, reinforced concrete, geodesy, organization and mechanization, etc. According to their purpose, the tunnels can be divided into several categories:

- Transportation tunnels (railway, roadway, pedestrian, metro);
- Hydrotechnical tunnels (water, sewage, diversion (outlet), meliorative);
- Communal tunnels (for placing electrical and telephone lines, gas, heating, etc.);
- Underground structures for special purposes (aircraft hangars, submarine shelters, bombing shelters, underground warehouses and garages, underground industrial plants, etc.).

In the modern era the construction conditions for the tunnels are getting more difficult, because they are placed under densely populated cities, under rivers, lakes, seas and tall mountains on large depths below the surface. In addition, the tunnel lengths in the world are increasing. All of this generates bigger risks, so more severe criteria is placed during the design, construction and exploitation phase.

Figure 1 – Gotthard Base Tunnel – Switzerland (The longest and deepest railway tunnel in the world, L = 57 km (single tube), H = 2,45 km (maximum depth))

2. RISK IN CIVIL ENGINNERING

The concept of risk and its management has application in various branches of society. One of the basic definitions for risk is probability of something negative happening, caused by an event or activity. Many engineers desire to define risk as the combination of failure and the probability of failure. The basic concept of risk managing is to accept risks that are reasonably small. In doing so, the risk of human injury and loss of life should be distinguished from the risk of economic loss. An example of a classification of consequences is given in table 1.

Table 1 – Example of Example of classification of consequences, Eskesen et al (2004) (left – consequences due to injury to third parties, right – consequences due to economic loss)

CLASS	DESCRIPTION	EXAMPLE FROM SERIOUS INJURY	CLASS	DESCRIPTION	ECONOMIC LOSS (MILION €)
1	Insignificant	No	1	Insignificant	< 0.003
2	Considerable	No, in general	2	Considerable	0.003 to 0.03
3	Serious	1	3	Serious	0.03 to 0.3
4	Severe	1 to 10	4	Severe	0.3 to 3
5	Disastrous	> 10	5	Disastrous	> 3

In civil engineering there are different approaches and definitions for risk, but it is important every problem to be reviewed separately. In some cases, different consequences with different probabilities may occur for a same problem. The overall risk in such case would be the sum of the risks associated with each possible consequence.

Risk assessment is an important part for the calculation of the project costs, so it should be implemented in every design phase, along with the general objectives of the project. The potential hazards and their consequences should be identified, and then the influence of the risk on the deadlines and costs should be evaluated. After this, the acceptable risk level should be determinated. This risk level will vary with the circumstances. The acceptable level of risk of total collapse of a structure may be different from acceptable risk level of malfunction.

The results from the risk assessment should be reviewed in consideration with the possibilities for avoiding, transferring or accepting each individual risk. The risk management can contribute to deviation of the main objectives of the project. In construction phase, the analysis of the uncertainties and risks is also an essential information for decision making, especially in the infrastructure projects. In general, the analysis and management of risks in civil engineering represent a serious matter, and should be approached with caution in every stage. For economic losses of ordinary projects, the ALARP concept can be used. This implies that all risks should be reduced to level as low as reasonable practicable. General scheme of the risk assessment and management is shown on figure 2.

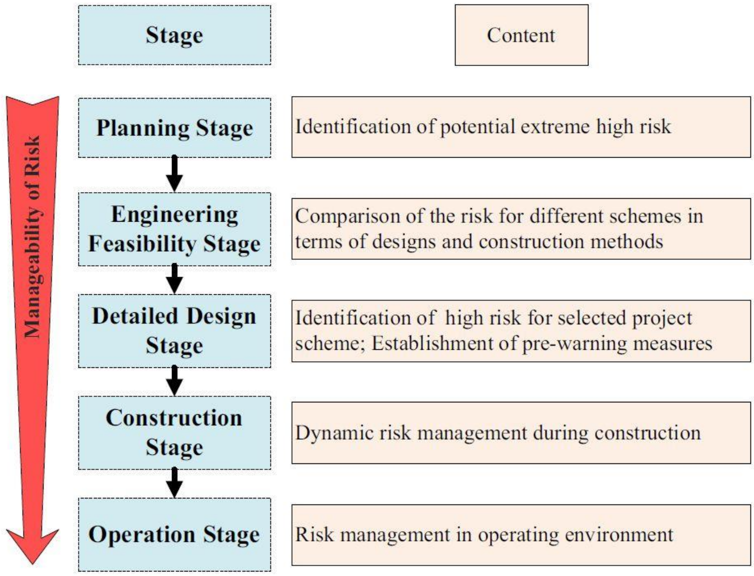

Figure 2 – General scheme for long-term risk assessment

3. GEOTECHNICAL UNCERTANTIES AND CONSEQUENCES

According to Muir Wood (1994), the prime source of uncertainty in geotechnical engineering is geology. Unidentified features of the ground may lead to unexpected behavior and identified features may not be expressible in quantified terms or its behavior is not fully know. The complexity of the geology may cause communication problems between the parties (human factors). This statement has been confirmed by many case histories of tunnel collapses and claim situations published in literature. The uncertainties can be divided based on their origin as the following:

- Geological scenario uncertainties for underground projects are related to limitations in ability to predict the scenarios in advance, future geological events, changes in engineered components with time and changes in the natural environment due to climate change;
- Model uncertainties may be related to the behavior of the rock mass at tunnel scale, the rock-structure interaction or description of the fracture system and faulting;

- Data uncertainties may be geometry related issues or connected to limitation in the scope of the tests as number of fault and fracture orientations, transmissivity of water-bearing structures and rock mass distribution and quality.

The nature of many underground projects implies that the level of confidence in the estimated ground conditions can be low based on the pre-investigation, especially in complex geological formations. Few geological uncertainties are shown in table 2.

Table 2 – Geological uncertainty found from various features influencing on geological and investigation conditions (Stille and Palmstrom, 2017)

SITE CONDITIONS INFLUENCING ON GEOLOGICAL AND GROUND UNCERTAINTY	DIVISON WITH RATINGS			COMMENTS
1 Geological setting[1)]	**Simple**	**Clear**	**Complicated**	The distribution of rocks, tectonic structures, foldings, etc.
	1	2	4	
2 Degree of rock weathering at terrain surface	**Minor**	**Moderate**	**High**	The degree of weathering at the rock surface, making observations and interpretations of the rocks at tunnel/cavern level more difficult.
	0.5	1	3	
3 Area of rock surface covered[2)] (by soil, lake/sea, vegetation, buildings, etc.)	**None or minor**	**Moderate**	**Comprehensive**	The rock cover reduces the possibilities to forecast the rock mass conditions underground.
	1	3	5	
4 Rock overburden. Distance from excavation to rock surface	**< 10 m / 10-50 m**	**50 – 300m**	**> 300 m**	Long distance from rock surface to the tunnel increases the uncertainties in forecasting the rock mass conditions. As limited (low) rock cover (< 10 m) is a risk, a rating = 2 is suggested. The same rating is set to surface excavation.
	2 / 0.5	1	4	
[1)] after information from investigations [2)] which has not been investigated				
	SUM (∑) OF THE VALUES FROM EACH TOPIC			
Degree of geological uncertainty	Low: ∑ < 5	Medium: ∑ = 5 - 8	High: ∑ > 8	

Usually the most unstable situation is directly after the excavation, and before the installation of the temporary (or permanent) support. In cases with weak rock, the geology and its properties are investigated, mapped and evaluated during tunnel excavation so the conditions of the next round can be predicted. In table 3 few geological factors related with risks during excavation are shown.

Table 3 – Example of geological factors related to risks connected to rock excavation

TYPE OF ISSUE	TECHNICAL RELEVANCE	GEOLOGICAL FACTOR
Damage of structures on ground	Damage of third part	Rock cover Rock quality
Environmental or social impact	Ground water lowering Pre and post grouting	Ground water pressure Rock mass permeability
	Vibration disturbance	Attenuation by the rock mass
Workers safety	Front stability	Rock mass quality Initial rock stresses Geometry of geological structures
	Time until initial support has to be installed	
Long term stability	Time before permanent support can be installed	Squeezing ground Swelling ground Raveling ground

The geotechnical consequences can be divided in three groups:

- Consequences due to design mistakes;
- Consequences due to rock engineering mistakes;
- Consequences due to rock excavation mistakes.

Some of the consequences classes are given in the next few tables.

Table 4 – Consequences classes due to design mistakes

CLASS	RELATIVE ECONOMIC LOSS TO PROJECT COST	CONSEQUNCE CLASS EN 1990:2002	EXAMPLE OR LOSSES
1	< 0.1 %	Small or negligible	Negligible
2	0.1 to 1 %		Minor costs due to construction mistakes
3	1 to 10 %	Considerable	Reparations costs for inadequate design
4	10 to 100 %	Very great	Cost for reparation of local tunnel collapse
5	> 100 %		Rebuilding of the project due to malfunction

Table 5 – Example of relative losses (productivity disturbance) due to rock engineering mistakes

CLASS	CLASSIFICATION	RELATIVE ECONOMIC LOSS TO PRODUCTION COSTS	EXAMPLE OF DISTURBANCE OF PRODUCTIVITY
1	Negligible	< 0.1 %	Negligible
2	Minor	0.1 to 1 %	Minor disturbance of the productivity
3	Moderate	1 to 10 %	Medium disturbance
4	Major	10 to 100 %	High disturbance
5	Extensive	> 100 %	Excavation method is not applicable

Table 6 – Consequences classes due to unwanted events during excavation

CLASS	FATALITY	CONSEQUNCE CLASS EN 1990:2002	EXAMPLE OF PROJECT
1	No, in general	Low	Deep tunnels
2	< 1		Shallow tunnels in rural areas
3	1 to 10	Medium	Shallow tunnels below parks, streets and roads
4	10 to 100	High	Shallow tunnels bellow buildings and crowded places
5	> 100		Shallow tunnels below residential buildings

4. RISK ANALYSIS IN TUNNELLING

With proceeding urbanization and increasing demands on life-quality, the importance of underground infrastructure, including tunnels, is likely to increase in the future. Tunnels minimize the impact of the infrastructure (e.g. road or railway) on the environment, they allow placing the infrastructure in the cities underground and thus improve the life quality of the inhabitants. Tunnels also help to fulfil the increasing demands on the technical parameters of the infrastructure, the modern roads and railways, to comply with the requirements on high design speed, sweeping curves and gentle elevation. In a complicated terrain, this can often be gained only through designing tunnels.

The objectives of a tunnel construction (measurable performance parameters) are as follows:

- Completion of the construction on time;

- Completion of the construction within the budget;
- Fulfilment of the technical requirements;
- Ensuring safety during the construction;
- Minimization of impact on operation of adjacent structures;
- Minimization of damage to third party property;
- Avoidance of negative reaction of media and public.

Generally, there are two approaches to risk analysis:

- Deterministic method

Based on engineering experiences and observations. This method is preferred for simpler projects.

- Probabilistic method

The approach of this method is with mathematical models. The risk is estimated with statistical distribution of the probability, consequences and the possible interdependence.

4.1. Qualitative risk analyis

The qualitative risk analysis (QlRA) aims at identifying the hazards threatening the project, to evaluate the consequent risks and to determine the strategy for risk treatment. The QlRA serves as a basis for preparation of contracts, for management of the project and for allocation of responsibilities amongst the stakeholders or their employees and representatives.

The hazards are identified and collected in the so-called risk registers. The risk registers should cover all thinkable events and situations, which can threaten the project. Therefore, experts from many different areas and with varying experiences should participate on the hazard identification. To evaluate the risks, varying classification and rating systems describing the probability of occurrence of a hazard and expected consequences in verbal form are used.

Based on evaluation of the risks, the strategies for their treatment and the responsibilities are determined. All information (causes and consequences of the hazards, risk classification, responsibilities, treatment strategies) is collected in the risk register, which should be actively used and updated in all phases of the project.

4.2. Quantitative risk analyis

The quantitative risk analysis (QnRA) aims to numerically evaluate the risk. Compared to the QlRA, the QnRA requires a clearer structuration of the problem, detailed analysis of causes and consequences and description of the dependences amongst considered events or phenomena. The QnRA provides valuable information for decisions-making under uncertainty such as for the selection of appropriate design or construction technology and it allows efficiently communicating the uncertainties with stakeholders.

Some of the methods and models for quantitative risk analysis during tunnel construction are: Fault tree analysis, Event tree analysis, Bernoulli process, Binomial distribution, Poisson process, Markov process, Bayesian networks and dynamic Bayesian networks.

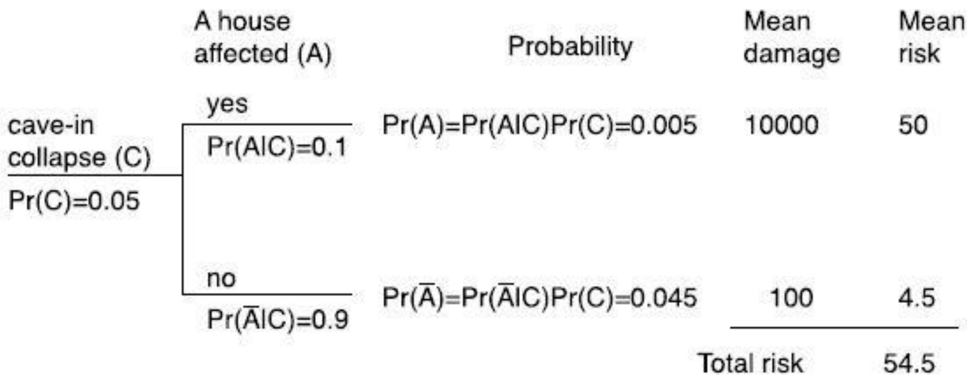

Figure 3 – Example of an Event tree analysis (cave-in collapse)

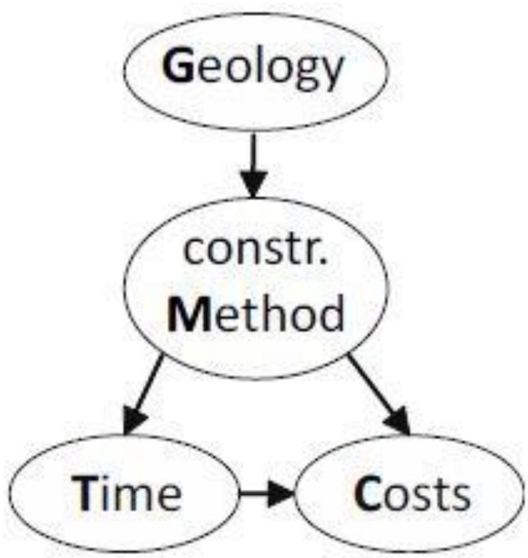

Figure 4 – Example of Bayesian network

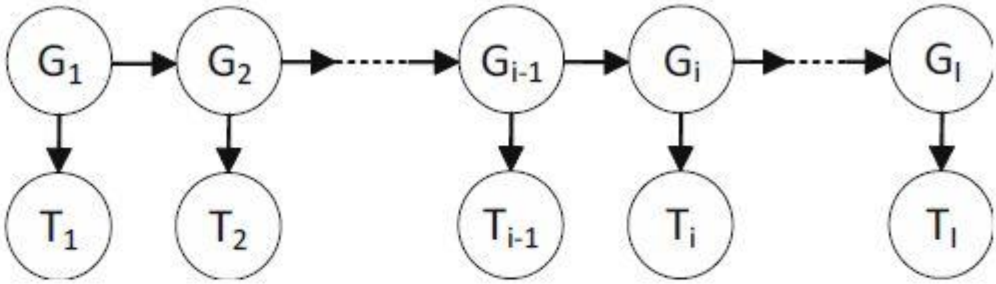

Figure 5 – Example of dynamic Bayesian network

5. RISK MANAGEMENT AND QUALITY ASSURANCE

The treatment of unacceptable risks can be done in different ways. Risks can be avoided, mitigated and transferred. Risk mitigation can be seen as part of the quality assurance work.

Optimal methods for mitigating the risks are directed toward the epistemic nature of the uncertainties, which implies that the risk can be reduced by obtaining further information about the geotechnical conditions. This may be achieved by further geological investigations in the preconstruction stages or during excavation. In some cases, adoption of an observational approach will be required. The level of investigation, control and monitoring has to be adapted to the chosen design process and risk level.

5.1. Ground investigation and ground model

The degree of uncertainty depends on the site conditions such as depth of excavation, ease of access to perform investigations, the nature and extent of the investigations, degree of weathering of rocks, and complexity of the geology. The geological conditions of a site may vary within wide limits. Therefore, there is no „standard investigation procedure“, which covers all cases. The objective is to perform „appropriate investigations“, which means right pre-investigations performed at right time.

The starting point, in order to achieve appropriate investigations, is to use a geological model to guide site characterization and hazard identification.

5.2. Geotechnical Baseline Report

The Geotechnical Baseline Report, GBR, as proposed by Essex et al (1997), is an excellent tool to set the baseline for the geotechnical conditions anticipated to be encountered during construction.

Ground characterisation has therefore to be divided into construction considerations and design considerations. If a general characterisation of the ground is presented, it must be applicable on both issues. The preparation of GBR is a qualified task and must be carried out by experienced, knowledgeable people.

5.3. Site organisation for monitoring and review

Having a geotechnical team on site is necessary in order to follow up the encountered geological conditions but also for investigating and detecting conditions that have not been predicted and foreseen. A close cooperation is also required both with the designer in charge and the contractor in order to adequately implement the findings in the design work and the rock engineering planning.

The use of a board of experts or independent reviewers addresses on the geotechnical risks, which are connected to doing the right thing.

5.4. Observational approach

For many underground projects it is not practical and sometimes even impossible to adequately investigate all ground conditions in advance. Further information is needed in order to be able to perform the final design. In such cases observational approach can be implemented.

5.5. Time and cost estimation

The definition of risk as the effect of the uncertainties on the objectives is adequate for the purpose of a correct estimation of time and cost for budget or tendering. Therefore the estimation should be based on a probabilistic approach, which clearly can evaluate the effect of the geological uncertainties. The budget of clients has to cover costs connected to geotechnical risks. It has been found that it is a good strategy to use some of the risk allowances to pay for precaution arrangements. This will increase the risk awareness in the project and can be seen as risk mitigation measures.

5.6. The dual quality system

For achieving a certain quality level, first it must be clear what the investor (client) wants, i.e. see to it that the right thing is done or built. It is also important to ensure that the thing is done or built right. If this is not considered and carefully done there is a probability of handing over substandard product that can increase the maintenance costs which the client didn’t predict, or handing over a more expensive product or breaking the deadline.

The overall quality is governed by both these factors:

- „Doing or building the right thing“;
- „Doing or building these things right“.

6. CONCLUSION

The uncertainties and risks are always present in underground construction. In every phase of a project from design, planning to execution, the uncertainties, especially the geotechnical will affect the decisions. The effect of the uncertainties on the objective is called the risk. These risks can affect function, construction productivity and environment. The competence with a comprehensive view of the risk situation is mandatory for a successful handling of the risks.

The focus of the risk management process should be to mitigate the risks. Depending on the problem, different approaches can be implemented. The risk management process according to the International Organization for Standardization is shown of figure 6.

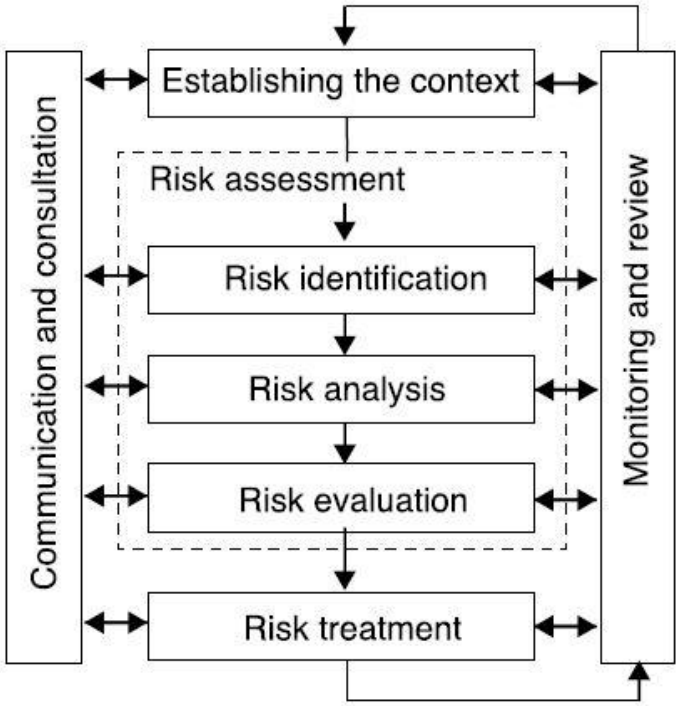

Figure 6 – Risk management process according to ISO 31000: 2009

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