Geological Uncertainties in Tunnelling - Risk Assessment and Quality Assurance

Sir Muir Wood Lecture 2017

"There is no substitute for experience"

Professor Emeritus Håkan Stille
Division of Soil and Rock Mechnics KTH,
Royal Institute of Technology - Stockholm, Sweden

N° ISBN : 978-2-9701122-1-1

APRIL 2017

ASSOCIATION INTERNATIONALE DES TUNNELS ET DE L'ESPACE SOUTERRAIN
AITES
ITA
INTERNATIONAL TUNNELLING AND UNDERGROUND SPACE ASSOCIATION

Sir Muir Wood lecture 2017
GEOLOGICAL UNCERTAINTIES IN TUNNELLING - RISK ASSESSMENT AND QUALITY ASSURANCE
N°ISBN : 978-2-9701122-1-1 / APRIL 2017 - Layout : Longrine – Avignon – France – www.longrine.fr

Geological Uncertainties in Tunnelling - Risk Assessment and Quality Assurance

Sir Muir Wood Lecture 2017

“There is no substitute for experience”

Professor Emeritus Håkan Stille
Division of Soil and Rock Mechnics KTH,
Royal Institute of Technology - Stockholm, Sweden

Risk is always present in rock tunnelling. The uncertainties connected to design and execution, especially geological uncertainties, are larger and to some degree different from those in other types of civil engineering projects. This implies that systems for handing the uncertainties like ISO 31 000 “Risk management – Principles and guidelines” must be adapted to the special conditions prevailing in underground projects. Risk management is, consequently, closely connected to project management. The work can be carried out in different ways in relation to the complexity of the project. However, site organizations with teams responsible for the geotechnical and geological follow-up is an important part of risk management in tunnelling. The project manager must have the overall responsibility.

The uncertainties have to be treated as an integrated part with a set of activities within the project work and the ordinary project organization. Project models like Props, developed by Ericsson Infocom based on tollgates and milestones, are also very adequate.

The base for risk evaluation should be the epistemic nature of geological uncertainties. Updating by observation and investigation can reduce the uncertainties. Systematic approaches for collecting additional information should be implemented. Lead-time to make adequate decisions may be obtained by identifying and looking for warning bells. In many situations such an approach will prevent unwanted events, like tunnel collapse, high water ingress and similar problems from happening.

Rock design is affected by geological uncertainties. Models and material properties of the rock mass will have a much higher degree of uncertainty than other building material like concrete and steel. This implies that verification of the design cannot only be built on calculations as normal in civil engineering. The observational approach in tunnelling will therefore in most cases be mandatory and can be regarded as part of the risk assessment and quality control. A common approach in tunnel design is the adoption of prescriptive measures. Application of rock classification systems belongs to this category. The limitations of such approach need to be understood in order to achieve an adequate risk treatment.

The overall quality is governed by two factors “doing the right things” and “doing the things right”. The special focus on the first issue comes from the special uncertainties connected to underground works. The system is called “Dual quality system”. Geotechnical category as defined in the new Euro Code (EC7) is an essential part in applying a dual quality system but it has to be adapted to rock engineering problems.

The above described approach for risk assessments and quality assurance in rock engineering and tunnelling is based on experiences from tunnel projects and supported by theories of uncertainties.

1 >> Introduction

The art of tunnelling is partly the art of managing geological risks. This can easily be confirmed by studying both successfully and unsuccessfully completed underground projects. Geological risks are always prevailing since the variable rock mass is the building material for underground construction.

The geological uncertainties are not only an issue for the design of underground structures but also influence the construction work. Planning of underground openings and production methods for excavation has to be adjusted to the prerequisites emanating from the rock material. It is inescapable that the geological conditions will not be fully known before the tunnel is excavated, and even then mistakes can be done in estimation of the geological behaviour.

Underground construction work is carried out with heavy and noisy equipment, intense mass transportation and in most cases below the ground water level. In many urban areas the only available space for local traffic, metro and railways is the underground. Environmental and social impacts are therefore frequent. Many of them have their origin in the geological and hydrogeological conditions.

Studies indicate that failure costs in construction industry are in the order of 10 - 30% of the total production costs, (Avendo Castillo et al 2008). Similar results were obtained by Nylén (1996), who studied cost of failure in major civil engineering projects. It is also well established that underground projects have more problems with time and cost overruns, as well as claims, than ordinary building projects. Unexpected and unfavourable ground conditions are in many cases the cause (van Staveren 2006). Estimation of time and costs will be more uncertain for partly unknown geological conditions compared to building material because the latter can be purchased by specification. Figure 1.1 illustrates the impact of higher levels of uncertainties inherent in tunnelling compared to other types of construction. This figure shows that the surface-built projects with a relatively simple production process, such as pipeline projects, have less variability in the range of tenders than more complex underground projects: the spread between the mean tender value and the engineer´s cost estimate is also larger for tunnelling projects (Moavenzadeh and Markow 1976).

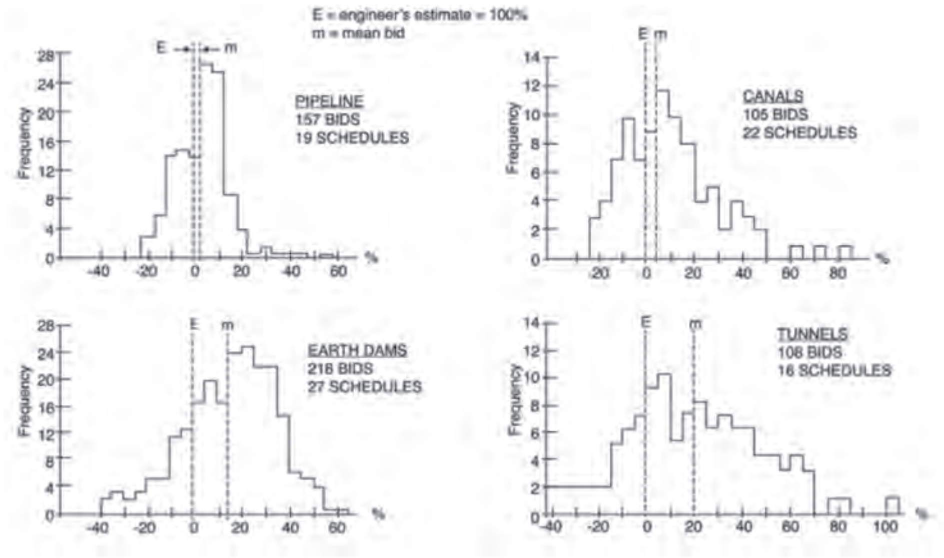

Figure 1.1 Tender data for four types of heavy construction projects (Moavenzadadeh and Markow, 1976)

The first tunnels were constructed more than several thousands of years ago. Mining as a special branch of underground construction started with underground excavation many hundreds of years ago. The art of tunnelling was based on the experiences of engineers and skill was based on craftsmanship. The complex structures of today's society with much larger population in combination with intense exploitation of the underground space imply that the risks connected to underground work have to be controlled in a more open, transparent and professional way that could be obtained by craftsmanship. Today´s tunnels have to be produced with experience and a much more stringent handling and risk awareness.

Rock mechanics as a scientific subject has been strongly developed during the last 40 years. Today calculations can be performed of the most complex geometry of any underground opening. The knowledge of the mechanical properties of the rock masses has increased and the behaviour of the ground can be better predicted. In spite of this strong development the basic geological uncertainties, connected to geological conditions that are not fully known have to be handled in a professional way.

The many issues of tunnelling can be broken down into rock design issues, rock engineering issues and rock excavation issues. Each issue entails risks, which have to be handled. Many of the issues have its origin in uncertainties about the geological conditions. Risk management processes have been developed, standardized and adopted in civil engineering. However, organisations, which have to deal with extensive risks, need to develop their own process (Chapman 2006).

With this lecture I want to give my personal reflections on the art of handling geotechnical risks in underground construction and to discuss the possibility to incorporate new philosophy and knowledge in handling of risks in tunnelling.

In Chapter 2 and 3 risks and risk management in civil engineering and underground projects are discussed from a general point of view. In chapter 4, 5 and 6 the geological uncertainties and related geotechnical risks are discussed and in chapter 7 aspects on quality assurance and tunnelling are presented. Material to this lecture is compiled from many books and papers. To some extent texts have been taken from the book "Rock engineering" by Palmström and Stille (2015) published by ICE.

2.1 INTRODUCTION

The concept of risk and risk management is applied for a large variation of contexts in society. Standards have been published all with the ambition to give general guidelines for risk handling, e.g. ISO 3100:2009. In the standards, risk is defined as an effect of uncertainties on objectives. However, there is a need to adapt the general definition to the conditions of rock engineering, especially to construction in partly unknown geological conditions. The general aspects on adaption of the guidelines for underground projects are discussed in this and the next chapter.

2.2 THE CONCEPT OF RISK IN CIVIL ENGINEERING

To be able to handle risks in civil engineering, a more unambiguous definition of the term risk must be applied. Objectivism is the basis for engineering science. In principle, facts can be objectively observed and analysed without subjective interpretation and judgment. Objectivism also implies that data, both regarding probability and consequences, are quantified and analysed. Many engineers desire to define risk as the combination of consequence of failure and the probability of failure. The probability of failure emanates from the underlying uncertainties. This definition describes the risks as expected consequences in the long run.

The basic concept of risk managing is to accept risks that are reasonably small. For every issue the probability of failure and the consequence of failure have to be evaluated and the related risk should be compared with a predefined risk criterion or acceptable level according to equation (1):

$$Risk = p_f \cdot C \leq R_{acc} \qquad (1)$$

where p_f is the probability of failure, C is the consequence of failure and R_{acc} is the acceptable level of the risk. In a linear diagram this will give a hyperbolic curve and a straight line in the risk diagram with logarithmic scales, see figure 2.1.

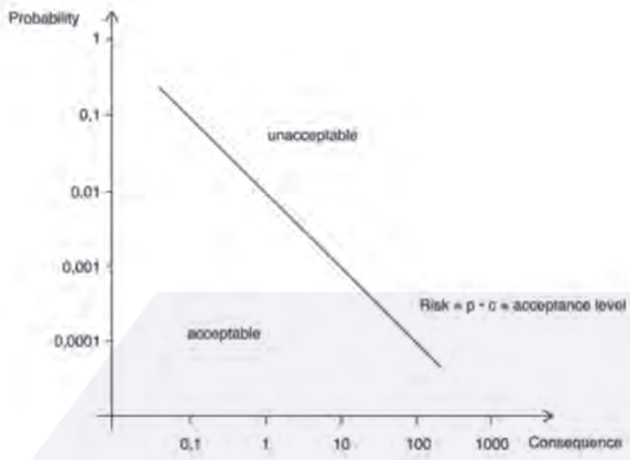

Figure 2.1 Risk diagram

However, in civil engineering there are many obstacles in following this strict definition and even more so in rock engineering, e.g. Kaplan and Garrick (1981) argued for using uncertainties in order to evaluate risks. Aven (2012) analysed different ways of defining risks. He concludes that risk is equal to the two dimensional combination of events / consequences of an activity and associated uncertainties. This definition is not as strict as the definition according to equation (1). The main difference is that the concept of uncertainty is used instead of probability.

Neither is the probability concept unambiguous. There are two different definitions of probability. The classical approach (relative frequency) is to define the probability as the relative outcome from a long series of similar events. The other approach (degree of belief) has to do with the confidence in knowing the state of the world, Baecher and Christian (2003). No civil engineering projects or parts of projects can be repeated in the sense that it will be part of a long series of similar events. The degree of belief is the only possible approach but has to be connected to rules to avoid subjectivism.

Five classes with logarithmic scale have been proposed by Eskensen et al (2004) to describe the level of probability in rock engineering, see table 2.1

CLASS	DESCRIPTION	PROBABILITY INTERVAL
1	Very unlikely	< 0.0003
2	Unlikely	0.0003 to 0.003
3	Occasional	0.003 to 0.03
4	Likely	0.03 to 0.3
5	Very likely	> 0.3

Table 2.1 Classification of probability of occurrence (after Eskensen et al 2004)

However, probability of a failure related to loss of human life is using another scale according to EN 1990. They have three classes with probability of 10^{-5}, 10^{-6} and 10-7 for one-year reference period. The classes are all lower than the lowest class (0.0003 or $3 \cdot 10^{-4}$) according to table 2.1.

The code emphasises that the acceptable risk level for loss of human life must be much lower than other types of consequences. Such low probabilities are difficult to relate to and can only be understood in a mathematical context.

The span in probability of occurrence of different unexpected events in civil engineering will therefore be very large and with many orders of magnitude. Estimating the degree of belief by elicitation of experts has been discussed. However, no rules exist to cover this very large span. Most situations are not comparable. The term uncertainty is also to a large extent used by many rock engineers at applying the risk concept. The concept of uncertainty instead of probability will therefore better describe the problem in rock engineering.

The consequence will vary according to the issue and the nature of the project. It may be related to injury or loss of human beings, environmental issues, economic losses and loss of good will. Some of these issues are sensitive to discuss and difficult to evaluate.

The scale should reflect a division of the consequences, which in a logarithmic scale will be linear. Consequences related to structure failure are described by an absolute scale related to the number of fatalities. Eskesen et al (2004) proposed classes according to table 2.2. However, another scale and terminology is used by Euro code 1990, where the three classes are described as low, medium and high. Number of fatalities are not directly expressed but can

CLASS	DESCRIPTION	EXAMPLE FROM SERIOUS INJURY
1	Insignificant	No
2	Considerable	No, in general
3	Serious	1
4	Severe	1 to 10
5	Disastrous	> 10

Table 2.2 Example of classification of consequences due injury to third parties, Eskesen et al (2004).

be estimated from the set up examples to be respectively less than 1, 1-100 fatalities and more than 100 losses of human life. It is obvious that the classes proposed by Eskesen et al (2004) have to be updated and adapted to requirements according to Euro code.

An absolute scale for economic losses has also been proposed of Eskesen et al (2004), see table 2.3.

CLASS	DESCRIPTION	ECONOMIC LOSS (MILLION €)
1	Insignificant	< 0.003
2	Considerable	0.003 to 0.03
3	Serious	0.03 to 0.3
4	Severe	0.3 to 3
5	Disastrous	> 3

Table 2.3 Example of classification of consequences due to economic losses, Eskesen et al (2004).

Describing the consequence in terms like “disastrous” or “insignificant”, as Eskensen et al do, involves a judgement of what can be accepted, which may be confused with the formal acceptable risk level. The description ought to be more uncommitted.

The acceptable risk level will vary with the circumstances. The acceptable level of risk of total collapse of a structure may be different from the acceptable level of malfunction. The risk level connected to the budget or time constraints are normally much higher than the acceptable risk level for damage on third party or environment. In my opinion the classes of consequences for loss of human life and economic losses are not comparable. The level of probability as discussed above is also quite different and the acceptance criterion may also be different. The risk for loss of human life and economic losses should therefore be separately handled. In practise, the economic losses are normally related to the total project cost, (Duijn 2015) and a relative acceptance level is applied. Therefore a relative scale is to prefer for describing the economic losses. This is further discussed in chapter 6.

To manage risks effectively an organisation should define the acceptable risk level (criterion) in accordance with its risk management policy. Due to reluctance to accept extensive consequences the acceptance criteria will not be a straight line in the risk matrix diagram.

Some authors argue that there are risks just below the acceptable risk level where risk reduction is desired, see figure 2.1 and Versteeg (1987). However, such risks should in rock engineering not interfere with the decision to accept the risk or not. The decision to accept or not should always be related to the knowledge when the decision is taken. The uncertainties directly influence the probability of occurrence according to the more general definition as defined above in the concept of “degree of belief”. This implies that the probability of occurrence may increase or decrease with additional knowledge gained during later stages of the project and the decision has then to be reconsidered. Therefore I believe that the area just below the acceptable risk level should be looked upon as the area where additional efforts in further stages should be put to risk mitigation and to quality assurance work in order to reduce the likelihood of having to reconsider the decision.

Sometimes this area is also called ALARP, which implies that all risks should be reduced to a level as low as reasonable practicable, ANCOLD (1994). This means that no ultimate acceptable risk level can be defined and that the risk owner will accept the outcome as long as it can be shown reasonable. This is an issue for large and special projects where the benefit for society exceeds the risk, as I see it. Such projects are outside the scope of this lecture. However, the ALARP concept can be used for economical losses of ordinary projects where acceptance criteria cannot be stated.

Sometimes, equation (1) is extended to define the risk as the sum of the risks for a set of issues. Such an approach will give problems with the definition of acceptable level and should, therefore, not be used in rock engineering. Every issue ought be studied separately. In some cases different consequences may occur with different probability for the same issue. In such a case, the total risk will be the sum of the risks connected to each possible consequence.

The annual risks posed by a variety of civil activities and facilities are shown in figure 2.2 taken from Baecher and Christian (2003). In the figure the acceptance levels for buildings as reported from Versteeg (1987) and Hong Kong Planning department are shown. It is obvious and also understandable that society has more severe restrictions of the risks of building failure compared to many more commercial activities. The economic risk level for underground construction work caused by construction mistakes and delays will be around 10% of production costs according to Castillo et al (2008) and Nylén (1996) and is probably higher than for merchant shipping. Exact level is difficult to evaluate.

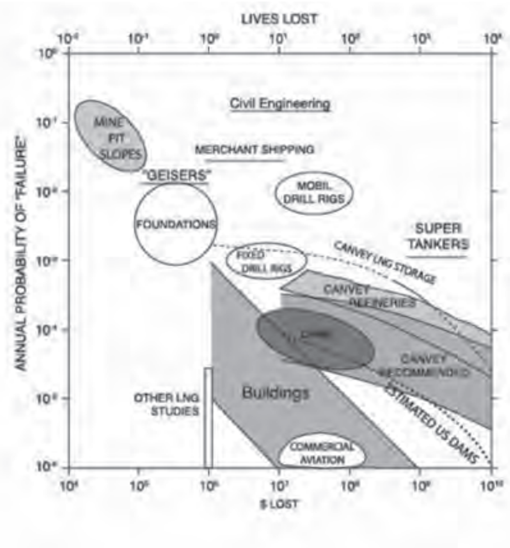

Figure 2.2 Annual risks for different activities and facilities compared with acceptable levels for buildings, after Baecher and Christian (2003)

Suggestions about how probability and consequence classes should be developed to be better adapted to the requirements and praxis of today will be presented in chapter 6.

2.3 RISK MANAGEMENT IN CIVIL ENGINEERING

Handling of risks is as we know an important part of civil engineering project management. The long period from feasibility study to completion of the construction emphasises that the process must be transparent and traceable. Standards have been developed for risk management in civil engineering projects, ISO 3100:2009 and for reliability for structures, ISO/FDIS 2394:2014 and ISO13824:2009.

Risk management can be defined as handling uncertainties that may prevent the objectives of the project from being obtained. The objectives can, in general terms, be expressed as the quality of the result. Quality is defined according to ISO 8402:1994 as: *"totality of characteristics of any entity that bear on its ability to satisfy stated and implied needs".*

In civil engineering, risk has always been prevailing and is a daily subject for consideration. Different projects are exposed to different levels of risk. The process of handling risks is, however, built up in a similar way, as follows:

1. Process initiation. The objective and context of the process must be established. Different stages and issues have to be treated in different ways.
2. Risk assessment containing risk identification, risk analysis and risk evaluation. The project manager must understand that risks are prevailing and have to be properly handled.
3. Risk treatment with planning and implementation. Every engineer involved must also understand that there are uncertainties that have to be treated.
4. Risk communication, monitoring and review. There must exist a system in each organisation and project for communication and reviewing the process.

The process of risk handling is illustrated in figure 2.3. The four basic stages and related requirements have always to be considered for enabling a strict risk management process. If any of these prerequisites fails, too large risks may be left untreated.

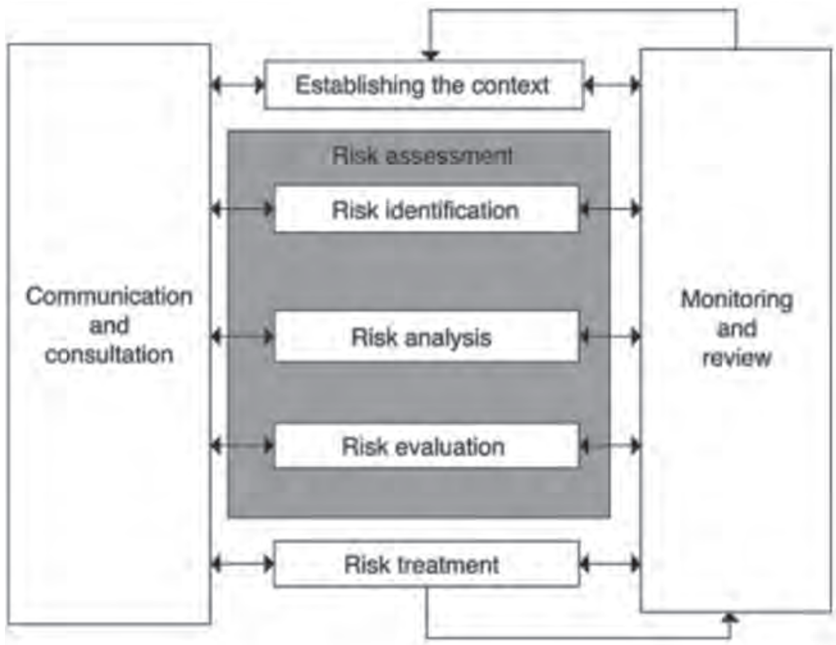

Figure 2.3 Risk management process (ISO 3100 : 2009)

Successfully completed civil engineering projects are characterized by the fact that the project manager understands his responsibility and that the involved personal has the knowledge and skill to handle the engineering issues including the risks. The work can be carried out in different ways depending on the complexity of the project. If the issues are complex a risk specialist may be needed, while for ordinary situations the considerations may be part of each engineer's work. The same can be said about the methodology used. The most complex projects may require a wide range of techniques for risk assessment, and also for communication. In ordinary projects common routines can be used like progress and project meetings for risk assessment, planning, implementation and communication.

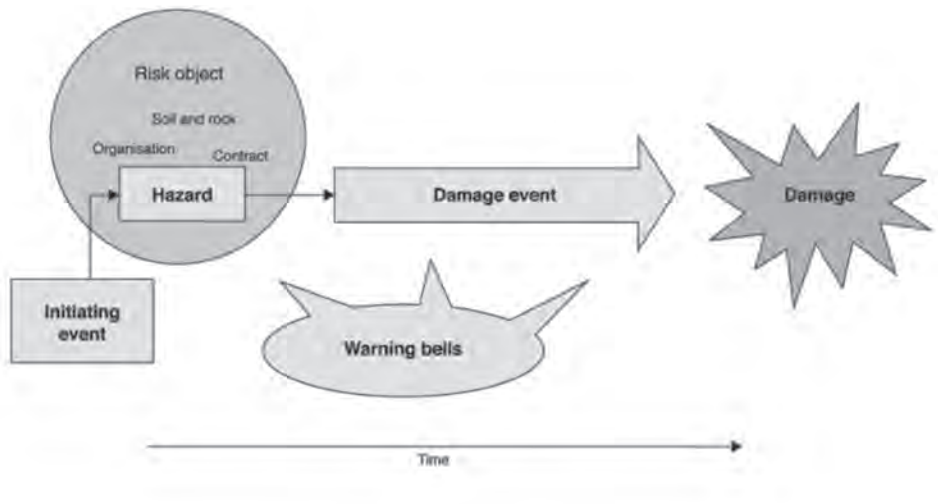

Figure 2.4 Illustration of time sequence and events between a hazard and damage (Sturk 1998)

The key element in risk management is evaluation of the risks. Risk evaluation contains four options; to retain, avoid, mitigate and transfer the risk. The choice depends on the circumstances.
Decisions have to be taken. In risk management it is important to understand that decisions have to be taken under uncertainties. There will always be a probability that the decision was wrong related to the outfall. However, this will not imply that the decision was wrong when taken. The way to take decisions can be described by the decision process. The decision alternatives have to be set up and ranked. Decision criteria have to be defined for choosing the best alternative. Risk evaluation, except what is required by legislation, is connected to costs and benefits (Kaplan and Garrick 1981).

Projects may fail in many ways. Some problems are so well known that they are not normally defined as risks although they have to be controlled. But strictly speaking, all issues controlled during the work can be regarded as risks. Thus, the normal quality control work is part of risk management.
Different types of hazards can cause risks. A hazard is defined as a potential source of undesirable consequences. Different risks can have different hazards, which have to be considered. It is important to emphasize that the hazard is not the risk or alone gives the damage. It is the weakness in an object, which can give negative impact on the quality of the project.

In order to avoid unwanted events it is essential to understand the chain from hazards to damages. Damage is an outcome of a process caused by a damage event that is initiated by an event that triggers a hazard contained in a risk object (figure 2.4). From a risk perspective damage can be regarded as the consequence. The probability of occurrence becomes the probability of a complex chain of events.

In order to achieve the required quality, i.e. fulfilling both stated and implied needs, two aims must be met at the same time, namely:

1. to identify the hazards and initiating events and
2. to use a manufacturing process that eliminates or reduces the probability or consequences of potential damage.

The objective of avoiding damage must be built up by an understanding of the process of getting damage. The quality assurance work should therefore focus upon:

- Eliminating or reducing hazards
- Reducing the probability of getting initiating events
- Reducing the consequences of possible damage events

There are always indications, here called warning bells that damage events are about to occur. Sudden changes of geology, poor production, malfunction of installed rock support are all examples. In the quality assurance work identifying warning bells is important. Such a function can let the engineers avoid both damage events and damage. Working actively with warning bells will reduce the probability of occurrence.

Processes where initiated events lead to damages are associated with uncertainties. The uncertainties have different sources. They may depend on the random nature of a factor or limited knowledge of the factor. They may also be related to human influences and human errors. A major task in quality assurance work is to describe and handle these types of uncertainties and obstacles.

3.1 INTRODUCTION

The fundamental objective of clients and contractors involved in underground projects is to complete the work in time and at budget without damage and loss of goodwill. Most risks can be related to this issue.

The risk level in underground construction is normally higher than in other types of construction why the managing of risks has to be more pronounced. The main difference is related to the building material. In structural design suitable material should be specified. In geotechnical design, the soil and rock material is not chosen but has to be adequately investigated and described. The full knowledge of the actual geological conditions will first be revealed after excavation and even not then. This implies that the final design cannot be established in advance. In rock mechanics, the terms preliminary and final design are used to describe the time-related procedure to obtain adequate information of the ground and the adapted design.

This main difference can be explained by studying the nature of uncertainties involved. The term aleatory uncertainty reflects that the uncertainties are related to underlying physical randomness and is also called natural variability. Epistemic uncertainty reflects the lack of knowledge and is also called knowledge uncertainty. These are useful terms; the distinction is important. The aleatory uncertainties can only be described while the epistemic one can be reduced with further investigations. The probability concept of degree as a belief is a prerequisite for dealing with epistemic uncertainties. Material like concrete and steel are regarded to be aleatory. The properties are specified and the expected variation comes from limited randomness in manufacturing. In rock engineering, the uncertainties about the building material (rock) are mainly epistemic and depend on the level of information. In principle, there will be no randomness of the properties when the geology is revealed. However, from practical reasons some uncertainties may be remaining, which can be interpreted as aletoric.

General aspects on risks in geotechnical engineering have been given by many authors, see e.g. Blockley (1994). Guidelines for tunnelling risk management have been elaborated by the International Tunneling Insurance Group (2012). The British Tunnelling Society prepared a report (2003), in which fundamental principles was set up regarding code of practise. Many of these aspects, guidelines and principles have been indicative of forming my opinion how risk management for underground projects should be applied.

3.2 GENERAL ASPECT ON RISK HANDLING OF UNDERGROUND PROJECTS

Process initiation and establishing the context will build up the framework of risk management, but different stakeholders will have different objectives concerning risk assessment, Palmström and Stille (2015). Clients are interested in function of the structure and strive for no risk for cost overrun and time delays. Contractors have their focus on production, cost and time implications and workers safety. Risks can primarily be related to function, geology, environment and production. The type of contract between client and contractor is of great importance for defining the risk owners. The risk sharing between contractors and clients for different construction contracting methods and for different types of risks are shown in Figure 3.1.

Each stakeholder has to carry out his own risk assessment. An important part is to define risk criteria in accordance with the risk management policy of the organization.

In practical work the level of risk of each hazard, as defined by the vector R (Probability class; Consequence class), is compared with the acceptable level for the position of the vector. Three levels are normally used; (i) unacceptable risk (Red), (ii) acceptable risk that should be mitigated if reasonably practicable (yellow) and (iii) acceptable risk without any mitigation (green). This is illustrated in the risk matrix in figure 3.2.

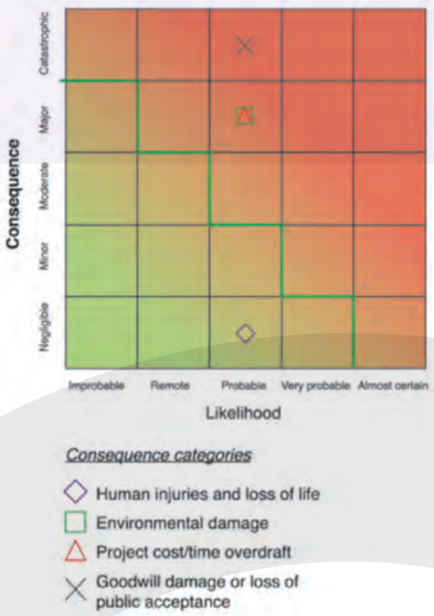

Figure 3.2 Example of risk matrix used in rock engineering, (Olsson 2013)

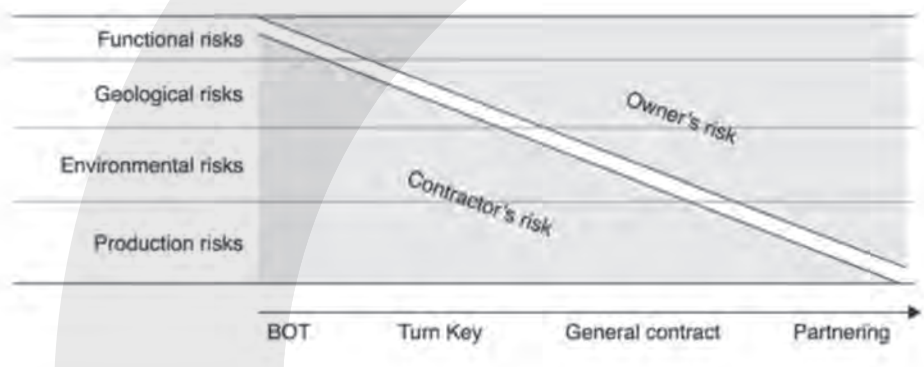

Figure 3.1 Risk sharing and type of organization (Palmström and Stille, 2015)

3 >> Risk in rock engineering

However, there are many arguments against the use of risk matrices. Cox (2008) argued that there may be no objectively correct way to fill out the risk matrix and that there are the difficulties in comparing risk levels. However, the use is widespread and the risk matrix is easy to communicate, so carefully used I believe it has its place. To overcome some of the problems with application of risk matrixes, it is recommended to put not all risks into one large risk matrix or register. The risks should be separated and grouped into categories based on engineering issues. Design issues related to consequences to third parts like loss of human life, environmental and social impacts defined by legislation should be handled separately. Rock engineering issues with origin in geological uncertainties could preferably be grouped together. This will give a good overview of the risks related to geology (geotechnical risks).

The hazards of rock engineering projects can be grouped under following headlines:

- Contractual hazards
- Design hazards
- Organisation hazards
- Geological Hazards
- Construction technology hazards
- Environmental hazards
- Human hazards
- Political hazards

These hazards are not mutually exclusive. The geological uncertainties will in many cases be the underlying factor for many of the other hazards. Hazards connected to design, construction technology and environment are in many cases emanating from geological uncertainties. According to my experiences many claims and construction mistakes have their roots in the fact that the contract and organisation have not been adapted to prevailing geological uncertainties.

Despite of the many hazards and geological uncertainties, many projects are completed in time and at budget. Successful projects are characterised by following factors (Stille et al, 1998):

- Comprehensive view of the risk situations
- Knowledge and competence of the involved personal
- Clear objectives common by the parts
- Adequate management and information systems
- Quality assurance based on dual quality systems

Bles et al (2009) have come to a similar conclusion in their study of five selected major infrastructure projects in Netherlands. They emphasised the importance of risk driven site investigation and field monitoring and a clear focus on the geotechnical risks.

In the coming chapters the handling of the risks emanating from geological uncertainties will be in focus and related to rock design, rock engineering and rock excavation.

4 >> Geological uncaertainties

4.1 GENERAL CONCEPTS

Muir Wood (1994) argues that geology is the prime source of uncertainty in geotechnical engineering. Unidentified features of the ground may lead to unexpected behaviour (incompleteness). Identified features may not be expressible in quantified terms or its behaviour is not fully known (system uncertainty). The complexity of the geology may cause communication problems between the parties (human factors). His statement has been confirmed by the many case histories of tunnel collapses and claim situations published in literature.

The uncertainties can be subdivided based on their origin. An often-used division is:

- 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 behaviour 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.

This characterisation is suitable for geological uncertainties of derived ground conditions. In addition to this, quality assurance work must take into account the division of nature of the uncertainties.

Geological uncertainties are related to the assessment of the conditions. They include insufficient knowledge of the actual geological conditions as well as poor accuracy in terms of properties and geometries. The geological uncertainties are related to the extent of ground investigations, and also to the fact that rock mechanics and rock engineering are to a large extent empirically based. 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. The geological uncertainties can in most cases be categorized as epistemic, as discussed in chapter 3.1. This implies that the level of the geological uncertainties will decrease during excavation when actual geology will be revealed.

4.2 IDENTIFICATION AND ASSESSMENT OF GEOLOGICAL UNCERTAINTY

4.2.1 Introduction

Conceptually every issue related to geological uncertainties to be studied in the risk assessments can be described by a behaviour variable, *P.* This variable may be a function of many basic variables, X_i, that includes not only the data uncertainties but also model and scenario uncertainties. Tunnel deformation may be a behaviour variable related to tunnel stability. The underlying basic variables may be several, like rock mass modulus, rock mass strength and quality of installed tunnel support. Penetration per revolution can be a behaviour variable for estimation of the productivity of TBM. Underlying variable may then be rock strength, degree of jointing and thrust. Another example of a behaviour variable is block sizes or fragmentation at quarry blasting with rock strength, brittleness and rock fracture spacing as the underlying variables.

The term geological conditions can therefore be regarded as a collection name of different behaviour variables. Geological uncertainties can be seen as a measure of the possible spread of the variables and is thus closely connected to the coefficient of variation of stochastic variables. The geological uncertainties have to be specified in order to enable more adequate descriptions of the studied behaviour. For example specification of the geological uncertainties could be related to rock mass quality or estimation of the fragmentation or drill ability.

Until recently identification and assessment of the geological uncertainties were purely empirically based. The estimation was subjectively and qualitatively described in the engineering geological report. The practical handling included an active follow-up during construction by the engineering geologist, often based on an observational approach. All this has to be based on geotechnical knowledge and skill in order to enable a meaningful risk assessment.

As previously established the nature of the geological uncertainties is based on Bayesian theory. The prior estimation based on general knowledge and information is updated with information from investigations. The investigations are stopped when it is assumed that the value of further information does not exceed the investigation costs. It is recommended that the investigations be based on a geological model, see chapter 7.2.

Guidelines and rules for investigation and normal investigation costs can be found in literature.
A more mathematical approach based on Bayesian statistics has been presented. Both updating of additional information and evaluation of value of the information have been presented (Stille and Holmberg 2005 and Zetterlund et al 2015). In both cases, elicitation of expert knowledge is essential. Different systems exist and have been applied. However, there is no substitute for experiences.

Some aspects on the approaches for estimating the geological uncertainties are presented below. Further developments are foreseen in order to improve the tools.

4.2.2 Estimation by empirical methods

Based on experiences from many rock engineering projects Stille and Palmström (2017) have proposed a method for evaluating the geological uncertainties in quantitative measures.

Simple geology requires less investigation effort than complicated geological conditions. Simple geology can be areas with fresh, exposed crystalline rocks in a surface created by ice erosion during the Quaternary, where the various geological features, such as faults and joints can be easily observed on the surface. From simple surface observation and aerial photographic studies, a fairly good interpretation of the geological and ground conditions can be provided at low cost.

Complex geology may be the case when there is a mixture of rocks normally connected to intense faulting and folding. Large areas along the tunnel covered by soil increase uncertainties of the rocks below. Other features that complicate the interpretation of ground conditions can be deep surface weathering, areas below water or cover by urban development. The risk of encountering geological features, which have not been detected from the field investigations and therefore may appear unexpectedly during the excavation, is larger in complicated ground and where rock outcrops are not found.

The degree or class of ground condition uncertainty can be found by giving ratings to certain parameters for geology, rock cover, and weathering of the rocks at the terrain surface (Table 4.1).

In rock excavation, there will always be some degree of uncertainty. The geological uncertainties connected to tunnels are larger than for surface rock excavations. More field investigations will generally lead to less uncertainty. The table is based on experiences from case histories with small or moderately investigation efforts. By additional geological investigation the uncertainties related to geological settings will be refined by dividing the area or tunnel alignment into reaches where the settings may be simple or clear. Further investigation will also reduce the areas of not investigated covered rock surface and thus the related uncertainties.

SITE CONDITIONS INFLUENCING ON GEOLOGICAL AND GROUND UNCERTAINTY	DIVISION WITH RATINGS			COMMENTS
1 Geological setting[1]	**simple**	**clear**	**complicated**	The distribution and composition of rocks, tectonic structures, foldings, etc.
	1	2	4	
2 Degree of rock weathering at the 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 the 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 – 300 m**	**> 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 (Σ) OF THE VALUES FROM EACH TOPIC		
Degree of geological uncertainty	Low: $\Sigma < 5$	Medium: $\Sigma = 5 – 8$	High: $\Sigma > 8$

Table 4.1. Geological uncertainty found from various geological features influencing on geological and investigation conditions (Stille and Palmstrom, 2017)

4.2.3 Estimation based on Bayesian statistics

Two cases of uncertainties can be distinguished. One is when the behaviour variable, P, can directly be observed and measured. The other case is when the basic variables, X_i, are the observable factor and the function describing the behaviour is known. In both cases elicitation of expert knowledge is needed to determine the statistical parameters of the variables since in most cases these parameters cannot be determined by ordinary statistic testing.

It is reasonable to assume that P follows a normal distribution. This is a conservative approach also supported by the Central Limit Theorem. The obviously impossible negative values have, however, very little effect on the calculation results, Baecher and Christian (2003). The advantage of using normal distribution is obvious. It simplifies the calculations since there are analytical solutions for many of the issues discussed here. This simplification will not change the theoretical concept, only the computational effort. The main effort will then be directed to evaluate the mean value and standard deviation of the behaviour variable. With the assumed distribution the variable can then be described.

For the cases when the behaviour variable is directly observable, the Bayes theorem can be applied to update the statistical parameters, see for example Ang and Tang (1984). The theorem may also be applicable for the basic variables. Application of Bayes theorem to rock engineering issues has been presented by Stille and Holmberg (2005). In many cases it is appropriate to describe the total uncertainty consisting of both the variation in the random variable itself and the unknown mean value. The best estimation of the variable can then be described by the Bayesian prediction distribution.

Prior information of the total uncertainty can be estimated by experience or design calculation. The estimation of the standard deviation of the underlying population must normally be based on experience. For example, the coefficient of variation can be used if this is known or accepted. This means that a *à priori* perception of the statistical parameters can be obtained.

Observational data of the behaviour make it possible to update the statistical parameters of the behaviour variable by using Bayes' theorem. What can be updated and reduced by observation is the uncertainty of the mean values. Updating would be carried out of the prior assessed values of the statistic parameters of the unknown mean. The updated prediction distribution can then be estimated.

An interesting feature is that the reduction in the variance can be calculated without using monitoring data. The variance will only depend on the number of observations. The mean value will, however, depend on monitoring data. The result shows that the uncertainties expressed by the standard deviation will always be less with further observations. The reduction of uncertainties will be more pronounced if there is a greater uncertainty about the mean value than in the underlying process. The benefit of observation is then as largest. It is also interesting to notice that single observations give a substantial reduction and that a more massive effort will only give minor additional contribution.

The described approach is based on the concept that no spatial variability exists. In many cases there is a correlation between the actual behaviour measured close to each other. The problem can be analysed by geostatistical methods like Kriging. This, however, lies outside the scope of this paper.

The behaviour variable can be directly calculated if the function and the basic variables are known. If the function is complex, an acceptable estimation of the mean and variance of the behaviour variable can be found by applying error propagation theory.

Tunnel wall deformation is an example of behaviour variables. The underlying variables are all the variables to be used at applying the ground reaction curve concept. The statistical parameters of many of them like rock mass strength and modulus have to be evaluated based on elicitation of expert knowledge. The results of measurements of deformations can be used to reduce the uncertainties as described above.

4.3 SPECIAL CONSIDERATIONS FOR EVALUATION OF THE GEOLOGICAL UNCERTAINTIES

The scale, for which the behaviour variable will be estimated, will influence the evaluation of the risk. Two groups can be distinguished:

- The behaviour variables describe events related to the total tunnel length.
- The behaviour variables describe events related to a part of the tunnel.

The first group can, for example, contain risk for encountering flowing ground. Flowing ground is an event that will occur very seldom. Its probability is evaluated based on experience from other projects with similar conditions of geology and tunnel length. The second group can be exemplified with the risk related to what can happen in each excavation round like encountering poor rock. In this case the hazard will be repeated for each round and will thus occur many times. Both the probability of occurrence of an unwanted event and the consequences must be related to the scale.

Another issue that influences the probability levels is the process behind the behaviour. In some cases the behaviour is directly related to the basic variables and can be described and estimated by the above set up rules. Such cases depends on the outcome of the populations itself. In other cases the process behind the variable is a mean value process. This implies that the event will be related to the variation of the mean value. Larger and lower outcome of the variable will equalise the result. Time requested to drill a borehole will be such a mean value process. The variance of the mean value is much smaller than the variance of the population itself (Ang and Tang 1984).

Many issues in tunnelling can be seen as a series system. It is called the system of weakest link. The probability of breaking a chain of many independent links will be much higher than for a single link to break. Sedimentary rock with single layers of very hard rock can be such a system for the case when road header is used for excavation.

In chapter 5 some more examples of the behaviour variables belonging to the above-described categories are given.

5 >> EXEMPLES OF GEOLOGICAL UNCERTAINTIES

5.1 INTRODUCTION

In this chapter I strive to categorize the many different issues that rock engineers face. The examples of behaviour variables presented are not comprehensive. Each project is unique. The list of actual behaviour variables should be established for each project and geological domain.
The issues can be divided into three main groups:

- Geological uncertainties related to design
- Geological uncertainties related to rock construction engineering
- Geological uncertainties related to execution of rock excavation

5.2 GEOLOGICAL UNCERTAINTIES RELATED TO DESIGN

The issues to be considered in the design work are related to relevant behaviour types of the rock mass. Due to geological complexities of a site, more than one ground behaviour type has to be considered. The structural resistance of the ground has to be analysed both locally and totally. The various types of ground behaviour require different assessments or methods (rock engineering tools) for a proper design that can be relied on to cover the actual case. Therefore, it is necessary to understand the actual type of behaviour, as a prerequisite for estimates of rock support and other evaluations.

Behaviour type is an important concept in rock mechanics. Many researchers have contributed like Terzaghi (1946), Hoek et al (1995), Martin et al (1999), Schubert et al (2001) and Palmström and Stille (2008). Different behaviour types may be occurring in the same tunnel section. They can be put into three groups: gravity driven, stress induced and water influenced. A list of types is given in Table 5.1.These phenomena are in general not mutually exclusive and can therefore be occurring at the same time and location.

Depending on the geology, some behaviour types can cause local instability in some situations but in other they may affect the total stability. Some will only be prevailing during excavation and others may only influence the permanent stability.

<table>
<tr><th colspan="2">BEHAVIOUR TYPE</th><th>DEFINITION</th><th>COMMENTS</th></tr>
<tr><td colspan="4">Group 1: Gravity driven</td></tr>
<tr><td colspan="2">a. Stable</td><td>The surrounding ground will stand unsupported for several days or longer</td><td>Massive, durable rocks at low and moderate depths</td></tr>
<tr><td rowspan="2">b. Block fall(s)</td><td>of single blocks</td><td>Stable, with potential fall of individual blocks</td><td rowspan="2">Discontinuity-controlled failure</td></tr>
<tr><td>of several blocks</td><td>Stable, with potential fall of several3blocks (slide volume <10 m³)</td></tr>
<tr><td colspan="2">c. Cave-in</td><td>Inward, quick movement of larger volumes (>10 m³) of rock fragments or pieces</td><td>Encountered in highly jointed or crushed rock</td></tr>
<tr><td colspan="2">d. Running ground</td><td>A particulate material quickly invades the tunnel until a stable slope is formed at the face. Stand-up time is zero or nearly zero</td><td>Examples are clean medium to coarse sands and gravels above groundwater level</td></tr>
<tr><td colspan="4">Group 2: Stress induced</td></tr>
<tr><td colspan="2">e. Buckling</td><td>Breaking out of fragments in tunnel surface</td><td>Occurs in anisotropic, hard, brittle rock under sufficiently high load due to deflection of the rock structure</td></tr>
<tr><td colspan="2">f. Rupturing from stresses</td><td>Gradually breaking up into pieces, flakes or fragments in the tunnel surface</td><td>The time-dependent effect of slabbing or rock burst from redistribution of stresses</td></tr>
<tr><td colspan="2">g. Slabbing</td><td>Sudden, violent detachment of thin rock slabs from sides or roof</td><td>Moderate to high overstressing of massive hard, brittle rock. Includes popping or spalling*</td></tr>
<tr><td colspan="2">h. Rock burst</td><td>Much more violent than slabbing, and involves</td><td>Very high overstressing of massive hard, brittle rock considerably larger volumes (heavy rock bursting often registers as a seismic event)</td></tr>
<tr><td colspan="2">i. Plastic behaviour (initial)</td><td>Initial deformations caused by shear failures in combination with discontinuity and gravity-controlled failure of the rock mass.</td><td>Takes place in plastic (deformable) rock from overstressing. Often the start of squeezing</td></tr>
<tr><td colspan="2">j. Squeezing</td><td>Time-dependent deformation, essentially associated with creep caused by overstressing.
Deformations may terminate during construction or continue over a long period</td><td>Overstressed plastic, massive rocks and materials with a high percentage of micaceous minerals or of clay minerals with a low swelling capacity</td></tr>
<tr><td colspan="4">Group 3: Water influenced</td></tr>
<tr><td colspan="2">k. Ravelling from slaking</td><td>Ground breaks gradually up into pieces, flakes or fragments</td><td>Disintegration (slaking) of some moderately coherent and friable materials.
Examples: mudstones and stiff, fissured clays</td></tr>
<tr><td rowspan="2">l. Swelling</td><td>of certain rocks</td><td>Advance of surrounding ground into the tunnel due to expansion caused by water adsorption. The process may sometimes be mistaken for squeezing</td><td>Occurs in swelling of rocks, in which anhydrite, halite (rock salt) and swelling clay minerals, such as smectite (montmorillonite), constitute a significant portion</td></tr>
<tr><td>of certain clay seams or fillings</td><td>Swelling of clay seams caused by adsorption of water. This leads to loosening of blocks and reduced shear strength of clay</td><td>The swelling takes place in seams having fillings of swelling clay minerals (smectite, montmorillonite)</td></tr>
<tr><td colspan="2">m. Flowing ground</td><td>A mixture of water and solids quickly invades the tunnel from all sides, including the invert</td><td>May occur in tunnels below the groundwater table in particulate materials with little or no coherence</td></tr>
<tr><td colspan="2">n. Water ingress</td><td>Pressurised water invades the excavation through channels or openings in rocks</td><td>May occur in porous and soluble rocks, or along significant openings or channels in fractures or joints</td></tr>
</table>

Table 5.1: Behaviour types in underground excavations. (Data taken from Stille and Palmström (2008) based on Terzaghi (1946), Schubert et al. (2001)

* This term was often used by Terzaghi (1946) as synonymous with the falling out of individual blocks, primarily as a result of damage during excavation

The three discussed types of uncertainties (scenario, model and data) are all prevailing. Scenario uncertainties are normally so large that final design cannot be defined before excavation. Model uncertainties are also in many cases large. In order to adequately describe the behaviour an observational approach must be applied for verifying the design. The same is also true for the data uncertainties, which will be large until actual conditions are revealed after excavation. Mandatory is, therefore, that the geology and its properties are investigated, mapped and evaluated during tunnel excavation. This is a necessary part of the quality assurance work and cannot be carried out without the supervision and cooperation of the designer in charge.

TYPE OF BEHAVIOUR VARIABLE OR ISSUE	TECHNICAL RELEVANCE	GEOLOGICAL FACTOR
Drill ability	Penetration rate (m/min) Penetrability (mm/ rev) Wear	Degree of fracturing Abrasive minerals Strength of rock Brittleness
Energy to break up rock	Consumption of explosives Trust and moment of the machine Fragmentation of the rock	Toughness Degree of fracturing Brittleness Residual stresses
Stand up time	Time until initial support has to be installed Time before permanent support can be installed	Rock mass quality Squeezing or swelling behaviour Initial rock stresses Flowing ground
Initial support	Amount of initial support to be installed before next round can be taken	Rock mass quality
Ground water conditions	Ingress of water to be pumped out Conditions for workers Conditions of carry out work Pregrouting to be carried out	Ground water pressure Rock mass permeability Erodibility of fracture filling Ravelling ground behaviour

Table 5.2 Example of behaviour variables related to rock construction engineering

5.3 GEOLOGICAL UNCERTAINTIES RELATED TO ROCK CONSTRUCTION ENGINEERING

The choice of construction method and technology has to be based on expected ground conditions. The basic concerns are related to estimation of time and costs. Many different geological conditions have to be considered, see table 5.2.

The three discussed types of geological uncertainties are also prevailing here. The behaviour variables will vary along the tunnel alignment. Scenario uncertainties are normally so large that no value can be determined in a specific location. Many issues are governed by the mean value of the variable. This is the case when the outcome can be formulated as the sum of many realisations, for examples the drill ability. In such cases, the uncertainty is described by the uncertainty to estimate the mean, and not the variation of the variable itself. In some cases, occurrence of a single very unfavourable realisation can stop the production and require change of excavations method. For example when there is flowing ground condition that cannot be passed by open TBM.

Model uncertainties are also in many cases too large to make adequate predictions of the behaviour in advance. An observational approach must then be applied to adapt the tunnel excavation to the actual condition. For example, plans for drilling and blasting must be adapted to real conditions by observation of the results from the blasting rounds.

The same is true for the data uncertainties, which will be large until actual conditions are revealed after excavation. Mandatory is therefore that the geology and its properties are investigated, mapped and evaluated during tunnel excavation. It is a necessary part of the quality assurance work. This cannot be carried out without the supervision and cooperation of the designer in charge.

Many of the behaviour variables related to rock engineering issues can be seen as an outcome from a mean value process. Variables for describing the productivity are such. Low and high values will both occur and will equalise the result. The behaviour will describe how well the mean value can be estimated. For example, drill ability and energy to break up the rock will vary from round to round but the issue is to estimate what the outcome is for the sum of efforts along the total tunnel length. Ingress of water to the tunnel is the sum of water ingress along very meter of the tunnel. Single minor ingress will in most cases not be of any interest.

However, single events that can stop the production completely must be identified and the risk evaluated. Such issues can be flowing ground and catastrophic ingress of water.

5.4 GEOLOGICAL UNCERTAINTIES RELATED TO EXECUTION OF ROCK EXCAVATION

Rock excavation is the critical moment when the geological conditions will be revealed. Issues related to the risk of damage on third party have to be studied in the design phase and criteria have to be set up for the excavation team.

5 >> Exemples of geological uncertainties

Other issues are for the contractor to decide. Example of engineering issues can be found in table 5.3.

The three discussed types of geological uncertainties are prevailing also here. The most unstable situation will in most cases be directly after excavation of a round and before temporary support has been installed. In cases with low rock cover this situation will also be a risk for damage on third party and not only an issue for the workers safety and project economy. Mandatory is, therefore, that the geology and its properties are investigated, mapped and evaluated during tunnel excavation to enable prediction of the condition of next round. At higher risk levels, the production must be subordinated the need to achieve additional information of the geology by investigation ahead of the tunnel front. This is a necessary part of the quality assurance work.

Model uncertainties are in many cases too large to enable adequate description of the behaviour, which implies that an observational approach must be applied in order to adapt the work to actual condition. For example attenuation of vibration and ground water impact together with grouting have to be evaluated during execution.

Front instability will delay the production and also be a risk for the safety of the workers. What is the probability to get one front or more collapse during the excavation? This can be regarded as a weakest link problem. Grout take for a whole tunnel, on the other hand, is a result of the sum of the takes of each round and will therefore be an outcome of a mean value process.

TYPE OF ISSUE	TECHNICAL RELEVANCE	GEOLOGICAL FACTOR
Damage of structures on ground	Damage on third part	Rock cover Rock quality
Environmental or social impact	Ground water lowering Pre and post grouting	Ground water pressure Rock mass permeability Fracture geometry
	Vibrations 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 Ravelling ground

Table 5.3 Example of geological factors related to risks connected to rock excavation.

6.1 INTRODUCTION

For each rock engineering issue the risks associated with the geological uncertainties have to be evaluated. Risks associated with geology and with issues related to the behaviour of the permanent structures or the construction work are called geotechnical risks.

Conceptually every hazard related to geological uncertainties has to be studied in the risk assessments by estimating the probability of occurrence of unwanted events and the correlated consequence. This implies that the limit state of the event has to be defined. The consequences will be defined in an absolute scale regarding damage on third part. For project risks a relative scale should be used and related to a zero option based on expected conditions.

The resistance, durability and serviceability of the permanent tunnel structure are issues that have to be handled in the geotechnical design like in all other building projects.

Stability issues and environmental impact during construction have to be covered by the design work to avoid consequences comparable to failure of permanent structures. The first category of risks is mainly related to the uncertainties from estimation of ground properties of identified geology. The second category is also related to uncertainties from assessment of actual geological conditions ahead of the tunnel front.

Geotechnical risks are also a serious factor in cost and schedule control on all major engineering projects, see e.g. Hoek and Palmieri (1998). They all have to be handled in the rock engineering work connected to planning and execution of the tunnel work.

6.2 GEOLOGICAL UNCERTAINTIES AND PROBABILITY OF OCCURRENCE

6.2.1 Estimation based on experiences

Geological uncertainties are strongly correlated to the general knowledge of the geological conditions. Therefore normal practise is to relate the degree of geological uncertainties directly to probability of occurrence without considering any special performance limits for all rock engineering issues. Implicitly, the prerequisite is that it is assumed that the work is carried out professionally. Such approach is applicable for defining the degree of geological uncertainties before excavation and all related decisions. However, in many cases this will give an unacceptable risk for loss of human life if not an observational approach is applied in order to reduce further the probability of failure to the low levels, which building codes can accept. After excavation when the geology has been revealed the degree of uncertainties will be substantially reduced.

Even a low degree of geological uncertainties implies that occasionally the real conditions will imply unwanted occurrence. High degree will give very likely occurrence, see table 6.1. This is the nature of underground construction. To distinguish levels lower than 1 to 100 is difficult and uncertain. The lowest class has, therefore, been set up to this level. The degree of the geological uncertainties is based on engineering judgement. The table 4.1 may give some guidance.

6.2.2 Estimation based on statistics

Probability of occurrence of an unwanted event can be estimated if the behaviour variable is described and known and the limit between unwanted and acceptable behaviour can be defined. In this respect the issue is in principle the same as limit state design in the modern building codes.

The performance function, here described as safety margin, SM, has to be rewritten as

$$SM = A - P \qquad (3.13)$$

where *A* is the variable, that describes limit of acceptable behaviour and P is the behaviour variable. In principle, both factors can be regarded as stochastic variables even if the acceptance function is normally given as a deterministic parameter. The probability of occurrence of unwanted events can be calculated as

$$P_f = p(SM = (A - P) < 0) \qquad (3.14)$$

By assuming normal distribution and with the usual definition of the index, β, the probability of occurrence can be estimated according to equation (3.15 and 3.16).

$$\beta = \frac{\mu_{sm}}{\sigma_{sm}} \qquad (3.15)$$

$$p_f = 1 - \Phi(\beta) \qquad (3.16)$$

where μ_{sm} is the mean value of the safety margin and σ_{sm} is the standard deviation.

CLASS	DESCRIPTION AS LIKELIHOOD OF OCCURRENCE	PROBABILITY INTERVAL	DEGREE OF ASSOCIATED GEOLOGICAL UNCERTAINTIES
1	Very unlikely	< 0.01	Very low
2	Unlikely	0.01 to 0.05	Low
3	Occasional	0.05 to 0.20	Medium
4	Likely	0.20 to 0.5	High
5	Very likely	> 0.5	Very High

Table 6.1 Relations between probability and degree of geological uncertainties.

The calculated probability is a result of the level of knowledge at the time of estimation. The level may decrease with further information revealed during the progress of the project. A beta value of 2.3 corresponds to a probability of failure of 0.01, e.g. very low.

6.3 GEOTECHNICAL UNCERTAINTIES AND CONSEQUENCES

6.3.1 Design mistakes

Consequences due to design mistakes can be divided into two groups. One group corresponds to the consequences that are preliminary connected to third party and thus is a responsibility of society. They can be divided into loss of human life and social or environmental consequences. The other group is connected to economic losses and is mainly related to the losses of the owner and the contractor, see table 6.2 a, b and c.

Consequence class regarding loss of human life (fatality) during operation of the facility is related to the type of project and collapse due to instability of the cavern. Consequence class due to environmental or social impact is related to the level of impact if there is occurrence of an unwanted event. Frequently, impact due to groundwater lowering and settlement due to over-excavation have occurred. Classification of consequences due to economic losses is related to the cost for reparation and the total project cost. Deficiencies in function (serviceability) and durability related to the service life period belong to this category.

In all these three cases the probability of occurrence depends on the quality of the design work and of the quality assurance.

Since the different types of consequences are related to different behaviour variables and thus different types of underground openings and probability of occurrences, the issues must be treated separately. For the same issue the highest consequences class should be applied.

CLASS	FATALITY	CONSEQUENCE CLASS EN 1990:2002	TYPE OF PROJECT
1	No, in general	Low	Oil and gas storage, no people can enter
2	< 1		Hydro Power tunnels
3	1 to 10	Medium	Low to medium traffic tunnels
4	10 to 100	High	Heavy traffic tunnels
5	> 100		Underground stations

CLASS	ENVIRONMENTAL OR SOCIAL IMPACT	CONSEQUENCE CLASS EN 1990:2002	EXAMPLE OF IMPACT
1	Negligible	Small or negligible	-
2	Minor		Drainage of single wells
3	Moderate	Considerable	Significant changes of the conditions of living
4	Major	Very great	Settlements in urban areas causing major damages
5	Extensive		Flooding due to dam failure

CLASS	RELATIVE ECONOMIC LOSS TO PROJECT COST	CONSEQUENCE CLASS EN 1990:2002	EXAMPLE OF LOSSES
1	< 0.1%	Small or negligible	Negligible
2	0.1 to 1 %		Minor costs due to construction mistakes
3	1 to 10 %	Considerable	Reparation 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 6.2 a, b and c Consequence Classes due to design mistakes related to different types of impact

6.3.2 Rock engineering mistakes

The risk owner of rock engineering issues can be the client or the contractor or jointly both of them depending on the type of organisation and contract. The issues are mainly related to economic losses, see table 6.3. The main issue is production capacity, which may be divided in sub-issues such as suitable equipment, drillability, and installation of temporary support. All are closely connected to geological information. The geological uncertainties will therefore influence the probability of unwanted performance and give raise to many contractual claims. There may be a specific probability that a certain consequence class may occur.

The risk will then be the mean value of the risk of each consequence class. It is required that the sum of probability of the occurrence of the consequences classes is one.

6.3.3 Rock excavation mistakes

Normally the contractor is the risk owner. The third party may be affected by the excavation work both due to loss of human life and environmental or social disturbance. The loss of human life due to tunnel instability during excavation will be negligible for deeper tunnels but may be substantial for shallow tunnels in urban areas. The tunnel is regarded to be deeply situated if the rock cover is larger than twice the span.

Classification of consequences from environmental or social impact is related to the degree of impact from occurrence of the unwanted event, see table 6.4 a and b. Disturbance from rock excavation is in most cases due to noise, vibration or air pollution. Temporary lowering of ground water and pollution of ground water also belongs to this category. Some of them are not due to geological uncertainties and will not be further discussed in this paper.

All issues related to mandatory legislation like the safety of the workers are not part of the risk assessments.

Mistakes during excavation that only gives consequences for the cost of the project can be classified according to table 6.3

6.4 RISK HANDLING

All risks related to the requirements from society must be treated separately. Even if they can be regarded as a measure of expected consequences or costs (consequence times probability) the treatment of the risks must be separate and absolute. However, the nature of the geological uncertainties may imply that additional information is required to reduce the risk to an acceptable level. This may be obtained by using a flexible design method like the observational method, but the final requirements from society could no be negotiated or changed.

Geotechnical risks connected to other types of rock design issues, rock engineering and rock excavation issues are related to expected additional costs. This implies that a zero option must be defined to which additional costs have to be related. The geological prerequisites and the related geological uncertainties for this zero option must be defined. Consequences in terms of additional cost at occurrence of cost increasing events have to be estimated. A prerequisite is that all requirements from society regarding design (loss of human life, economic, social or environmental impact) and other issues defined by legislation are satisfied.

CLASS	CLASSIFICATION	RELATIVE ECONOMIC LOSS TO PRODUCTION COST	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 6.3 Example of relative losses

CLASS	FATALITY	CONSEQUENCE 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 below buildings and crowded places
5	> 100		Shallow tunnels below residential buildings

CLASS	ENVIRONMENTAL OR SOCIAL IMPACT	CONSEQUENCE CLASS EN 1990:2002	EXAMPLE OF IMPACT
1	Negligible	Small or negligible	-
2	Minor		Drainage of single wells
3	Moderate	Considerable	Vibration
4	Major	Very great	Pollution of ground water
5	Extensive		-

Table 6.4 a and b, Consequence Classes due unwanted events during excavation.

6 >> Evaluation geotechnical risks

Geotechnical risks could be evaluated according to figure 6.1 by applying linear classes for both uncertainties and consequences with the above set up terminology. Three risk levels are proposed. Levels and criterion for acceptance are to be defined for each project and company policy. All risks exceeding the acceptable risk level have to be mitigated or avoided. Acceptable risk level should be defined in the risk policy. Mitigation of all other risks should be based on cost-benefit analysis. The type of contract and organisation will influence which risks should be included in the analysis.

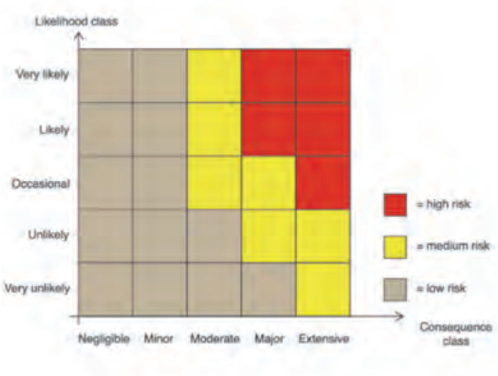

Figure 6.1 Proposed risk matrix for geotechnical risks with three risk levels

By applying cost-benefit analysis an optimal solution can in theory be obtained. In principle the optimal solution is the one with the smallest expected cost, C:

$$C = \min\,(\text{construction cost} + \sum \text{risk})$$

The construction cost can also be regarded as a stochastic variable influenced by the geological conditions. The geological uncertainties will then also imply a positive effect on the cost estimation in the case better rock conditions are prevailing. This is further discussed in chapter 7.7.

However, issues which have not been identified and studied in the risk handling, will never be reflected in the calculation results. The quality assurance work must be directed to discover such hidden risks.

7.1 INTRODUCTION

Treatment of unacceptable geotechnical risks can be done in different ways. Risks can be avoided, mitigated and transferred.

Some risks can be avoided by adapting a more robust excavation method. Some risks can be transferred to insurance companies. However, the majority of the geotechnical risks have to be mitigated. Risk mitigation can be seen as part of the quality assurance work.

As established in previous chapters the geological uncertainty has an obvious connection to design hazards. It is also to large extent the decisive factor for contractual and construction technology hazards. Mitigation of the geotechnical risks must be seen in a broad perspective. A clear focus on the geotechnical risks is mandatory. The way of communicating the geological uncertainties and organise the construction and quality control work are important parts of the risk mitigation. Estimation of time and costs based on understanding of the geological uncertainties can also be regarded as a mitigation of the geotechnical risks.

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 geological 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. Level of investigation, control and monitoring has to be adapted to the chosen design process and risk level.

The construction technology and design must be robust enough to be applicable in the range of the geological conditions that are reasonably to be expected. The know-how of the personal in the site organisation must be adequate for dealing with this range of geological conditions and have clear instruction of how to act at unforeseen conditions. Investigation of the ground conditions and monitoring of the ground behaviour are important. The quality system must also be adapted to the different uncertainties and related risks.

7.2 GROUND INVESTIGATION AND GROUND MODEL

Geotechnical investigations are performed to reduce the geological uncertainty. The degree of uncertainty will depend 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* (Stille and Palmström 2017).

The starting point, in order to achieve appropriate investigations, is to use a geological model to guide site characterisation and hazard identification as suggested by many authors e.g. Fookes et al (2000), Hoek and Bray (1977) and Palmström and Stille (2015). This will reduce the risk associated with geological uncertainties. My experiences is that a top down approach should be applied in order to enable focus on relevant issues in order to decide which geological uncertainties preferably should be mitigated by further investigations during construction.

7.3 GEOTECHNICAL BASELINE REPORT

A transparent communication of the geotechnical uncertainties is essential. 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. For general contracts the focus should be on construction issues. For design and built contracts the basis for design should also be established. As discussed above geological conditions and uncertainties will have different impacts on construction and design. This must be recognised at the presentation of the baseline conditions. 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.

In writing the GBR an approach for handling actual uncertainties must be set. The client and the consultant must be aware of the geological uncertainties and the limits for the contractor’s bid. Preparation of GBR is a qualified task and must be carried out by experienced, knowledgeable people. An independent review of the document should be considered to be an essential element of the process to develop an adequate report.

7.4 PROJECT MODEL

Geological uncertainties are always prevailing. Information of the ground conditions is obtained during construction. Large organisations are involved, which complicates communications. Underground projects should therefore be seen as a development project with clear objectives but unknown means to reach the goal. A useful tool for making both project work and quality work structured and clear is the *precise project model*. One applicable model is PROPS, developed and used by the Ericsson company (1997). This model makes a clear distinction between the general project model, the project work model valid for a specific object, and the actual project work. The use of a project model contributes to quality by making the project and its activities well planned, structured and clear. Important features in the project plan are the milestones and tollgates. Milestones imply that certain work has to be carried out in specific situations. Tollgates are not allowed to be passed before the responsible managers give their permission, see figure 7.1

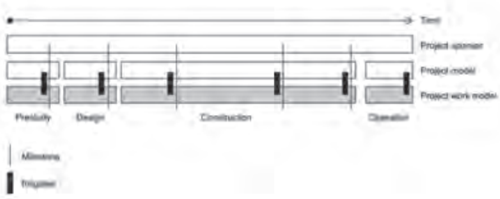

Figure 7.1 Project model after Ericson (1997)

Quality assurance within a construction project should not be carried out as a control function parallel to the actual project work, but be seen as a set of activities within the project work itself. The uncertainties have to be identified in advance, based on risk assessment together with measures to be taken in order to mitigate the actual risk. The milestones and the tollgates will be built up by these measures and also their locations in the chain of production.

7.5 THE DUALISTIC QUALITY SYSTEM

Quality is to give the customer what is needed, wanted and hoped for, and more, i.e. to fulfil the stated and implied needs. In order to reach this goal, the supplier (e.g. a contractor or designer) must begin by finding out what the customer (a client) really 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. Otherwise, there is a probability of handing over a substandard product, with heavier requirements on maintenance than what the customer expected. There is also a probability of handing over a more expensive product, or of handing it over later than the customer expected, or some combination of these. The overall quality is governed by both these factors, *'doing or building the right thing'* and *'doing or building these things right'*. They must both be handled by the quality system, which has been called the dualistic quality system by Stille et al (1998)

Experience from underground project has shown that it is difficult to achieve satisfactory quality only using quality systems limited to the ISO 9001 standard. This is basically due to the fact that the standard ISO9001 was developed to improve suppliers manufacturing processes and product quality and not for doing the right thing. The process of making sure of the issue *"doing or building the right things"* should be established in the early project stages, and should continue throughout the whole project.

In many aspects, the idea of total quality management (TQM; TQM International, 1994) is applicable to an underground project and its actors. The suggested *"dualistic quality system"* can be seen as a development and adaptation of TQM to the special conditions typical of an underground project.

Doing the right thing

The client must, at an early stage, specify the requirements for the underground structure, starting from the use for which it is intended. These concern issues like function, aesthetics and economy including life cycle cost (LCC), maintenance and completion time. Other demands can be implied through laws and regulations, for instance environmental concerns. The design work has to put these demands in perspective to the geological conditions. A construction procedure must be chosen that gives the finished product the required properties. When making this choice the geological uncertainties must be considered.

The scenario uncertainties will imply that the rock design cannot be established beforehand. The large model uncertainties connected to rock design require expert judgements for managing the related risks. This is very important, as it will determine whether the quality goal will be reached or not.

The ISO standards, ISO 9001, specify that the requirements, on which to base the design should be defined and that the resulting design should be verified. It is not, however, specified how to find the correct requirements and how to rank them in the light of the geological uncertainties and the possible construction methods. This work calls for engineering creativity, professional skill and good communication between all involved parties. Quality tools helpful in the work of ensuring that the right things are done should therefore be used within all project phases.

Doing the thing right

For the underground industry, the introduction of formal quality systems, based on ISO 9001, has improved the ability of *doing/building things right.* Contractors have, for example, put much effort into reducing mistakes, making the construction process more effective and turning over products without faults. The overall understanding of quality work as an integrated part of the production process has also increased significantly. Normal quality control belongs to this category.

Consequently, the ISO standards do help in doing things right, i.e. to plan, control and document the work. But this is not enough. Applying a project model and thereby creating opportunities for good relations and clear communication will further increase the possibility of doing things right.

7.6 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 has 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. In many cases an engineering geologist working in the field has the knowledge to handle ordinary design issues. But there are also examples when the engineering geologist has not the full overview and knowledge to understand the complex loading conditions account for the final design of the tunnel. On the other hand, an engineering geologist may have better possibility to understand the geology and thus will be able to interpret the geological warning bells, which are always prevailing.

The use of a board of experts or independent reviewers addresses on the geotechnical risks, which are connected to doing the right thing. This has been found to be very useful for reducing occurrence of unwanted events. Especially for Design/Build and EPC contract the review team should be involved already from the pre-bid stage (Bröchner et al 2006). The requirements regarding design issues as stated in Eurocode for structures belonging to geotechnical categories 3 (GK3) will be best fulfilled by using independent reviewers. The use of such a board or group of reviewers should be based on trust, and shall not change the responsibility of the client, consultant or contractor. Monitoring and review of issues defined as more risky should also be part of the responsibility of the board of experts or the independent reviewers.

7.7 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. Safety issues and providing underground openings with an economic design taking the geological settings into account was the key considerations when the observational approach was formulated by Peck (1969). The basic elements comprises following:

- Prediction of possible behaviour
- Plan for contingency measures in case of unexpected conditions
- Observations of performance during construction
- Execution of final design by adaption of observation

The approach has been one of the designated methods for design in Euro code 1997 and is called the Observational Method. The method has been found useful especially for rock design, see e.g. Stille and Holmberg (2005) and Spross and Johansson (2017). However, the approach with its basic elements is also applicable for many other rock engineering issues.

7.8 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 cost or the time for a project can then be regarded as a stochastic variable with an associated distribution curve. Decisions can be made based on the result of the calculations for example tunnelling method, budgeting and tender pricing.

A distinct approach based on the uncertainties will clarify the involved risks much better than cost and time estimation based on deterministic parameters with fixed risk premium. This will mitigate the risk to take wrong decisions, see e.g. Einstein et al (1987), Lichtenberg (1990), Isaksson and Stille (2005) or Spackova et al (2013). 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.

8 >> Concluding remark

Geological uncertainties are always prevailing in underground construction. In every phase of a project from design, planning to execution, the geological uncertainties will affect the decisions to be taken. The effect of the uncertainties on the objective is called the geotechnical risks. These risks can affect function, construction productivity and environment. Experiences from both problematic and successful projects show that competence with a comprehensive view of the risk situation is mandatory for a successful handling of the geotechnical risks.

Human obstacles like lack of knowledge, conservatism, ignorance and prestige can prevent a good communication that can be devastating for the project. Respect of the fact that the different parties have different objectives is important to facilitate the communication.

Different stakeholders will have different objectives. Clients are interested in good function of the built project without any risk for cost overrun and time delays. Contractors have their focus on production issues, cost and time implications and workers safety. The owner of the risks depends on the contract. By using a risk management process integrated with the project management the underground construction industry will reach a quality level satisfactory to the client and customer.

The focus of the risk management process should be to mitigate the geotechnical risks since they cannot be avoided or transferred. Depending on the issue different mitigation tools should be applied. Geotechnical Baseline Report is a tool to communicate the geological uncertainties between the parties. The risk of disputes and claims concerning the geological conditions will be reduced. Applying a project model with tollgates and milestones will reduce many of the risks connected to execution. The model will secure that all available geological information is used before passing critical reaches or sections. Having focus on doing the right thing should strengthen quality control. This is preferable done by using a board of experts or independent reviewers. This in combination with a strong geotechnical team on site will mitigate the risks that the actual geological conditions are not realised or understood. However, the geological conditions cannot be fully understood until the tunnel has been excavated, if then. Both the design and the excavation method must be adapted to the actual conditions. An observational approach can mitigate the geotechnical risks of faulty design or poor production. Applying a probabilistic approach can mitigate risks connected to time and cost estimates due to geological uncertainties. Addressing and managing all these aspects of risks are necessary to achieve a successful underground project.

9 >> Acknowledgement

First of all I want to thank ITA for the opportunity to give a Sir Muir Wood lecture. Many have contributed. In particular the contributions from Dr Johan Spross, Dr Fredrik Johansson, Dr Lars Olsson and Dr Arild Palmström are gratefully acknowledged.

10 >> References

ANCOLD (1994), "Guidelines on risk assessment 1994" Australia-New Zealand Committee on large dams.

Ang H-S and Tang W (1984), Probability concept in Engineering Planning and Design, Vol1, New York, John Wileys &Sons.

Aven T (2012), The risk concept. historical and recent development trends, Reliability Engineering and System Safety 99 , 33-44.

Avendo Castillo J. E, Al-Jibouri S:H, Halman J.i.M, (2008), Conpetual model for failure costs management in construction, Proc, 5th Int. Conf. on innovation in Architecture, Engineering and Construction(ACE), Antalya, Turkey, 23-25

Baecher G and Christian J (2003), Reliability and Statistics in Geotechnical Engineering. John Wileys &Sons.

Bles T, van Staveren M, Litjens P and Cools P, (2009), Geo Risk ScaGetting grips on geotechnical risks, Proc of the 2nd Int symposium on Geotechnical Safety & Risk, Gifu, Japan, 2009

Blockley D.I. (1994), Uncertain ground; on risk and reliability in geotechnical engineering. Ground Engineering (March 1994) 27 (2): 29-34.

The British Tunnelling Society and Association of British Insures, (2003), The joint code of practice for risk management of tunnel works in the UK.

Bröchner J, Håkansson U and Hässler L, (2006) Contractors and deign risk in major civil works Design/Build projects, 1st Int. Construction Speciality Conference, Calgary, Alberta, Canada

Chapman C, (2006), Key points of contention in framing assumptions for risk and uncertainty management. Int. Journal of project management 24 (2006), 303-313

Cox T, (2008), What´s wrong with risk matrices? Risk analysis Vol. 28, No.2

Duijm, N. J. (2015), Recommendations on the use and design of risk matrices. Safety Science, 76, 21–31. 10.1016/j.ssci.2015.02.014

Einstein H.H., Dudt J.-P., Halabe V.B. and Descoeudres F. (1996), Geologic uncertainties in tunnelling. Proc. Uncertainty in the Geologic Environment: from Theory to Practice.

Ericsson Infocom. (1997), Project handbooks PROPS [in Swedish]. Ericsson Infocom AB, Sweden.

EN 1990, Eurocode - Basis for structural design. 97 p.

EN1997-1:2004, Eurocode 7: Geotechnical design-Part1: General Rules.

Eskensen S, Tengborg P, Kampman J, Veicherts T.H, (2004), Guidelines for tunnelling risk management International Tunnelling Association, Working group No. Tunnelling and Underground Space Technology 19 (2004) 217-237.

Essex R, (editor), (1997), Geotechnical Baseline Repports for underground construction, American Society of Civil Engineers.

Fookes PG, Baynes FJ and Hutchinson JN (2000), Total geological history. Int. Symp.; GeoEng 2000, Melbourne, Australia

Hoek E and Bray JW (1977), Rock Slope Engineering. Inst. of Mining and Metallurgy, London, UK

Hoek E., Kaiser P.K. and Bawden W.F. (1995), Support of Underground Excavations in Hard Rock. Balkema, Rotterdam.

Hoek E and Palmieri A. (1998), Geotechnical risks on large civil engineering projects. Key note lecture, Int Association of Eng. Geologists Congress, Vancouver, Canada.

ISO 31000:2009 (2009), Risk Management –Principles and guidelines.

ISO/FDIS 2394:2014 (2014), General principles on reliability for structures.

ISO13824:2009 (2009) Bases for design of structures-General principles on risk assessment of systems involving structures

ISO 8402:1994 (1994), Quality management and quality assurance

ISO 9001, Quality management

IS0 9000, Quality management systems-Fundamentals and vocabulary.

Isaksson T. and Stille H. (2005), Model for estimation of time and cost for tunnel projects based on risk evaluation. Int. J. Rock Mech. Rock Eng., 38(5): 373—398.

10 >> References

Kaplan S, Garrick B.J, (1981), On the quantitative definition of risk. Risk Analysis, Vol. 1, No. 1.

Lichtenberg S. (1990), Project Planning — In a Changeable World [in Danish]. Polyteknisk Publisher, Copenhagen.

Martin C.D., Tannant D.D., Yazici S. and Kaiser P.K. (1999), Stress path and instability around mine openings. In Proc. 9th, ISRM Congress on Rock Mechanics, Paris (Ed. G. Vouille and P. Berest), vol. 1, pp. 311–315. A. A. Balkema, Rotterdam.

Muir Wood A.M. (1994), Control of uncertainties in geotechnical engineering, special publication on Geotechnical Eng. ISSMFE, New Delhi, India.

Moavenzadeh F. and Markow M.J. (1976), Simulation model for tunnel construction costs. J. Contr. Div. ASCE, CO1: 51—66.

Nilsen B., Palmström A. and Stille H. (1999), Quality control of a sub-sea tunnel project in complex ground conditions. ITA World Tunnel Congress '99, Oslo, pp. 137 – 145.

Nylen K-O. (1996), Cost of failure in quality in a major civil engineering project. Lic.thesis. Royal Institute of Technology, KTH, Dept. of Real Estate and Construction Management, Stockholm, Sweden, pp 1-96.

Olsson L, (2013), Tools to be used in rock engineering for managing uncertainties (in Swedish) BeFo, Stockholm.

Palmström A. and Stille H. (2007), Ground behaviour and rock engineering tools for underground excavations. Tunnelling Underground Space Technol., 22 (2007): 363—376.

Palmstrom A. and Stille H. (2015), Rock Engineering. 2nd edition. Book published by ICE Publishing, London, 444 p.

Schubert W. and Goricki A. (2004), Probabilistic assessment of rock mass behaviour as basis for stability analyses of tunnels. Proc. Rock Mechanics Meeting, Stockholm. SveBeFo, Swedish Rock Engineering.

Spackova O, Novotna E, Sejnoha M and Sejnoha J, (2013), Probabilistic models for tunnel construction risk assessment, Advances in Engineering Software 62-63, 72-84

Spross J, Johansson F. (2017), When is the observational method in geotechnical engineering favourable? Structural safety 66 (2017): 17-26.

Van Staveren M, (2006), Uncertainties and ground conditions: A risk management approch, Elsevier Ltd

Stille H., Sturk R. and Olsson L. (1998), Quality systems and risk analysis-new philosophy in underground construction industry, Int. Congress of Underground Construction in Modern Infrastructure, Stockholm, Balkema.

Stille H, Holmberg M, 2005, Observational method in rock engineering, Keynote lecture, Int conf. ASRM08, Tehran, Iran.

Stille H. and Palmström A. (2008), Ground behaviour and rock mass composition in underground excavations. Tunnelling and Underground Space Technology 23 (2008), pp. 46–64

Stille H, Plamström A, (2017), PRACTICAL USE OF THE EUROCODE 7 in rock engineering, Submitted for publication in Tunnelling and Underground Space Technology

Stille H., Sturk R. and Olsson L. (1998), Quality systems and risk analysis — new philosophies in underground construction industry. In: T. Franzen and S.-G. Bergdahl and A. Nordmark (eds), Int. Congr. Underground Construction in Modern Infrastructure. Rotterdam, Balkema.

Sturk R. 1(998), Engineering geological information — its value and impact on tunnelling. Ph.D. thesis, Royal Institute of Technology, Stockholm.

Terzaghi K. (1946): Rock defects and loads on tunnel supports. Introduction to tunnel geology. In Rock tunneling with steel supports, (eds. R. V. Proctor and T. L. White) 1, 17-99. Youngstown, OH: Commercial Shearing and Stamping Company. pp. 5 – 153.

The International Tunnelling Insurance Group (2012), A code of practice for risk management of tunnel works.

TQM International (1994), Total Quality Management — Your Handbook. TQM International Ltd, Manchester.

Versteeg M (1987), External safety policy in the Netherlands: An approach to risk management. Journal of Hazardous Materials 17:215-221

Zetterlund M, Norberg T, Ericsson, L.O NOrrman J and Rosén L (2015), Value of information analysis in rock engineering: a case study of a tunnel project in Äspö Hard Rock Laboratory, Georisk 2015 vol.9, No.1,9-24

ITA Secretariat c/o EPFL - Bât. GC - Station 18 - CH - 1015 Lausanne - Tel. : + 41 21 693 23 10 - Fax : + 41 21 693 41 53
Email : secretariat@ita-aites.org - Web : www.ita-aites.org