

Rock Engineering and Tunnelling - a Nordic approach

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Summary

Execution of the tunnel work cannot be isolated from geological investigation, design requirements and planning. Excavation of the tunnel is a part of a chain exposed to a flow of information from the earlier stages of planning. Ability to interpret and handling the information is a prerequisite for successful tunnelling. In the paper, investigation and design strategy are discussed in order to handle the geological uncertainties. The connection between geological uncertainties and design tools, such as observational method and site specific classification system are important, as well as adaption of suitable tools to secure the quality of the tunnels based on the dualistic quality system and investigation during tunnel excavation.

The aim with the paper is more to give a holistic view of the tunnelling than to discuss the technology of tunnel excavation. Both parts are important, but focus needs to be directed upon the uncertainties and system to handle them in order to further improve and reduce the risks connected with rock tunnelling.

Keywords: Geological uncertainties, design strategy, quality assurance, observational method, grouting technology.

1. Introduction

Tunnelling is an old art, but is still under development. Excavation and rock support technology have been in focus and to large extent been a synonym to tunnelling. However, the problems of today are more connected to quality requirements related to risk and uncertainties than the excavation process. The geological risks are in focus. Execution of the tunnel work cannot be isolated from geological investigation, design requirements and planning. It is a part of a chain involving a flow of information from the earlier stages of planning. Ability to interpret and handling the information is a prerequisite for successful tunnelling. This is called risk management.

Geological investigation, tunnel design and planning, and risk management are all tools which can be grouped into rock engineering [1] and are linked together. The objective of this paper is to present and discuss some Nordic experiences of this flow of information and possibility for a successful management and execution of tunnels.

We discuss investigation and design strategy to handle the geological uncertainties, describe the connection between geological uncertainties and design tools, such as observational method and site specific classification system. We also discuss suitable tools to secure the quality of the tunnels based on the dualistic quality system and investigation during tunnel excavation. Material to this paper has been taken from our book Rock Engineering published by Thomas Telford in 2010 [1].

The aim is to give a more holistic view of the tunnelling than to discuss the technology of tunnel excavation. It is the authors' opinion that both parts are important, but we prefer to focus more upon the uncertainties and system to handle them to further improve and reduce the risks connected with rock tunnelling.

2. Investigation strategy and costs

2.1 Investigation

The main aim for the investigations for rock excavation is to provide sufficient information on the ground conditions and a basis to carry out the planning and evaluate consequences for the excavation in question, such as to:

- find the most optimal tunnel alignment or cavern location from the site conditions given;
- influence on environment and the nearby settlements;
- decide plan for and method for excavation and rock support;
- estimate cost and construction time for the excavation.

The main strategy is to carry out the investigations to such extent, that they give a net value compared to the costs of additional information at the actual stage of the project. This is called VOIA (Value of Information Analysis) [2]. In this paper, investigation costs for some projects are presented, which may be used as a guideline.

The geological conditions of the sites may vary within wide limits. Each site has its own characteristics, and there is no “standard investigation procedure”, or the only right set of investigations, which covers all site conditions. When it comes to engineering geological investigations, flexibility is a keyword, representing the potential of considerable cost saving advantages in geo-investigation practice.

It should be stressed that a provision for an appropriate volume of investigations is that *adequate investigations are performed efficiently and that the results are correctly interpreted and applied rationally in the design*. This is as important as to execute the investigations.

In practice, the aim is to select and locate investigations where the results can actively be used in the design. This has been illustrated in Figure 2.1. The additional investigations are selected or adjusted based on the results of the earlier results achieved.

2.2 Main elements influencing on investigation cost

Investigations for an underground opening in rock depend largely on the following important elements:

1. Local ground conditions (influenced by geology, access possibilities, topography, distance below surface, etc.)
2. Type of project and the requirements the project shall satisfy (regarding safety/stability, operating time, environment)
3. Actual stage of the project
4. Type of construction contract to be used (unit price, fixed price, total price, etc.)
5. Chosen excavation method(s) (drill & blast, TBM, roadheader, etc.)
6. Various other features, such as experience of those involved, national regulations and requirements.

The handling of these elements can be condensed into the following two main categories:

- A. The efforts needed to perform the field investigations, given in Table 2.1.
- B. The excavation requirement type or class, presented in Table 2.2.

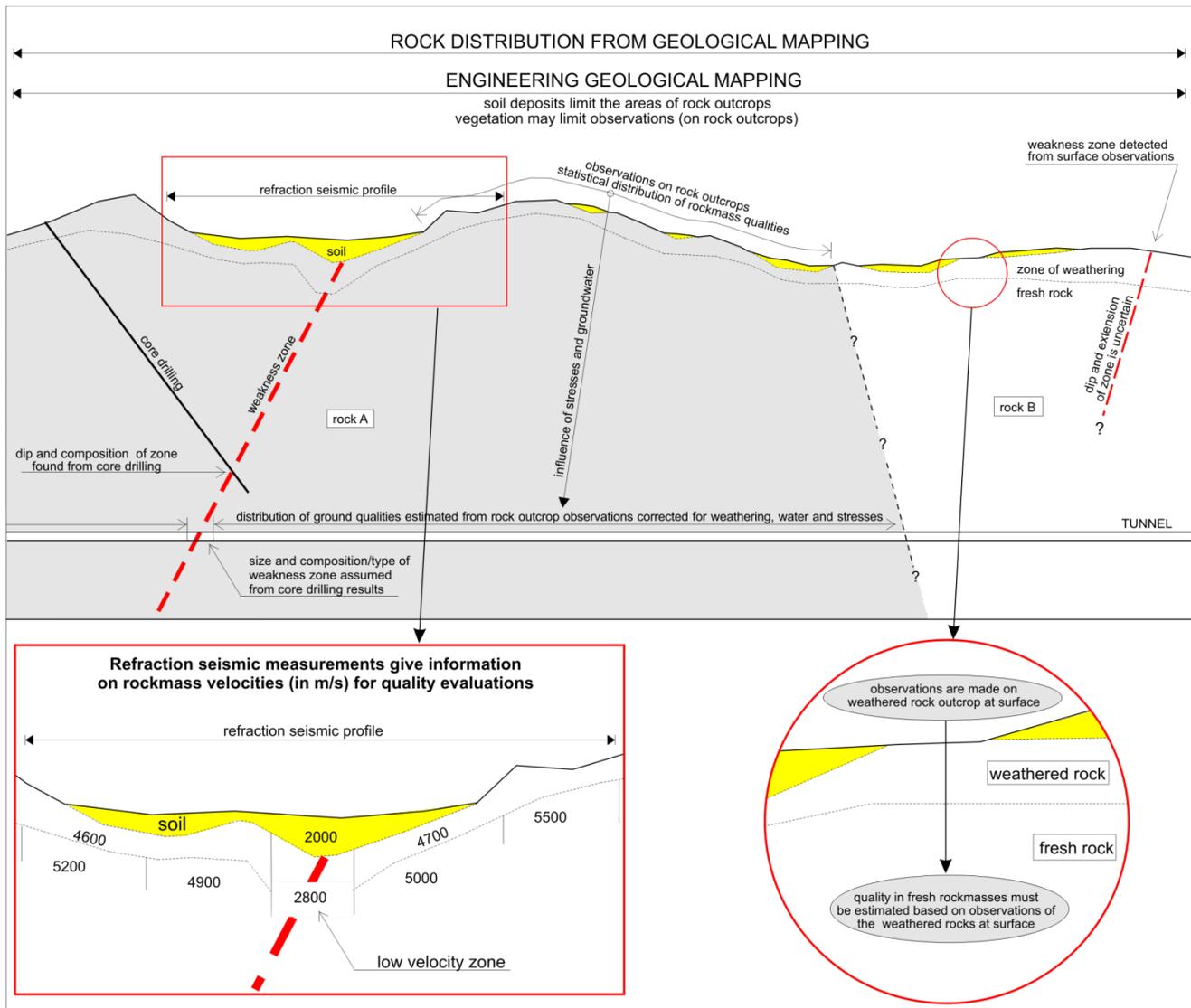


Figure 2.1 Geological information and investigation tools with interpretations.

2.2.1 A. Relevant efforts to investigate the ground conditions

Simple geology requires less investigation efforts than complicated geological conditions. Also weathering at and near the rock surface complicates the interpretations of surface observations, as well as when a large area is below water or the excavation is located in urban areas where the surface has been modified and rockmass conditions are hidden by houses and supplied materials in roads and gardens. The degree or class of bedrock difficulties can be found by giving ratings to certain parameters for geology, degree of weathering, rock cover and accessibility according to Table 2.1.

Table 2.1 includes all investigations necessary to acquire relevant data on the ground conditions for an underground excavation. Where geological information exists (good geological maps or similar) or material and/or experience from nearby earlier excavations is available, the estimated approximate cost for this should be deducted from the costs found from Figure 2.2.

Other methods for excavation than drill & blast, require generally more knowledge of the ground conditions and increased documentation of certain parameters.

Table 2.1 Ratings of the ground conditions related to the necessary investigation cost (mainly for drill & blast tunnels). The ratings are derived from Scandinavian tunnelling experience [3]

The efforts needed to investigate the ground conditions	Division with values			Comments
1. GEOLOGY (geological setting)	<u>simple</u> 1	<u>clear</u> 1.5	<u>complicated</u> 3	The distribution and composition of rocks, tectonic structures, foldings, etc.
2. DEGREE OF ROCK WEATHERING AT SURFACE	<u>minor</u> 0.5	<u>moderate</u> 1	<u>high</u> 2	The degree of weathering at the rock surface, making observations and interpretations of the rocks at tunnel/cavern level more difficult.
3. ROCK COVER (soil, lake/sea, vegetation, settlement)	<u>no or minor</u> 1	<u>moderate</u> 3	<u>comprehensive*</u> 5	Rock cover may reduce the possibilities to forecast the rockmass conditions underground. This will influence on the efforts to obtain sufficient information.
4. ACCESSIBILITY (to the terrain to execute investigations)	<u>easy</u> 0.5	<u>moderate</u> 1	<u>difficult*</u> 3	The access possibilities to the area and the topographical conditions may influence on the costs for performing the necessary investigations.
*) includes subsea tunnels and other excavations below lake or sea				
a. Ground investigation efforts (the efforts needed to achieve sufficient information on the geology and rockmass distribution)	CLASSIFICATION (sum (Σ) of the values for each topic)			
	a1. Small: $\Sigma < 5$		a2. Moderate: $\Sigma = 5 - 8.5$	
				a3. Large: $\Sigma > 8.5$

2.2.2 B. Requirements to the underground project during and after excavation

These requirements consist partly of conditions connected to safety requirements (stability and working conditions) in the underground opening during excavation and during its permanent use, partly to the potential damage it may impose to the environment in relation to the rules given, see Table 2.2.

2.3 Investigation classes and costs

The investigation class can then be found by combining the efforts to perform investigations (Table 2.1) with requirements to the excavation (Table 2.2), as has been performed in Table 2.3.

In a recent work on investigations for underground excavations in Norway [3] experience from 22 tunnels and shafts in Norway with lengths from 1km to 25km were analysed. All tunnels are located in crystalline, hard rocks and have been excavated by drill & blast, except one. The study includes 6 power/water supply tunnels (total length 228km), 14 traffic tunnels (total length 212km). The cost for the pre-investigations as a function of tunnel length and investigation classes A, B, C and D are presented in Figure 2.2. In other countries with different requirements to the documentation of the ground conditions, the investigation costs may be different.

Table 2.2 The requirements to the excavation during and after construction. The ratings are derived from Scandinavian tunnelling experience modified from [3]

Requirements and conditions connected to the excavation	Division with values			Comments
1. REQUIREMENTS TO USE OF THE EXCAVATION	<u>low</u> 1	<u>moderate</u> 3	<u>high</u> 5	Requirements to stability and durability during permanent use (depends on excavation type)
2. POTENTIAL RISKS DURING EXCAVATION	<u>minor</u> 1	<u>moderate</u> 2	<u>high</u> 4	Risk for collapse, large inflowing water problems and dangerous excavation conditions (rock bursting, etc.)
3. INFLUENCE ON ENVIRONMENT	<u>small</u> 0.5	<u>moderate</u> 1	<u>large</u> 3	Potential influence on vegetation (draining of ground water, etc.)
4. INFLUENCE ON NEARBY BUILDINGS	<u>small</u> 0.5	<u>moderate</u> 2	<u>large</u> 4	Potential for settlement of buildings founded on clay, mash, etc.
CLASSIFICATION (sum (Σ) of values from each topic)				
b. Requirements to the excavation (during construction and the final use)	b1. Minor: $\Sigma < 5.5$ b2. Moderate: $\Sigma = 5.5 - 11$ b3. Strict: $\Sigma > 11$			

Table 2.3 The investigation classes found from ground investigation efforts and requirements to the underground excavation modified from [3]

Definition of INVESTIGATION CLASS		a. GROUND INVESTIGATION EFFORTS (geology, zone of weathering, cover (loose materials, lake or sea, vegetation, settlements), and access to and within the area to be investigated, see Table 2.2)		
		a1. Small $\Sigma < 5$	a2. Moderate $\Sigma = 5 - 8.5$	a3. Large $\Sigma > 8.5$
b. REQUIREMENTS TO THE EXCAVATION (requirements to function and risks during excavation, influence to the environment and buildings, see Table 2.1)	b1. Minor $\Sigma < 5.5$	A	A	B
	b2. Moderate $\Sigma = 5.5 - 11$	A	B	C
	b3. Strict $\Sigma > 11$	B	C	D

Most Norwegian tunnels have low investigation costs because the ground conditions often are easily recognisable on the eroded, fresh rock surface, as observed in rock outcrops. Therefore, only one of the cases used in the study falls within investigation class D.

Fixed price and total price construction contracts require generally more information on the ground conditions and hence higher investigation costs than unit price contracts.

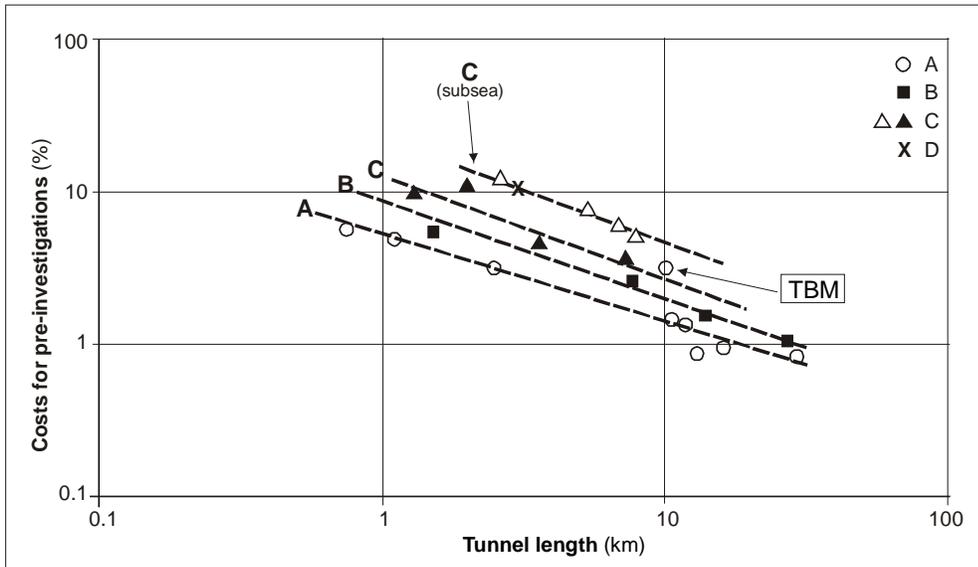


Figure 2.2 Approximate cost for pre-investigations (in Norway) as a function of tunnel length and investigation class [3]. Excavation costs here include only drill & blast (or TBM drilling), loading and transport out of the tunnel or cavern including rigging cost. A, B, C, and D are the investigation classes in Table 2.3.

2.4 Other topics influencing on the amount of investigations

Other topics of importance for the execution of investigations, but which are difficult to include in any general estimate of investigation costs, are:

- Personnel and company to perform the investigation works, and the type of contract they have for their works;
- Quality and execution of the works;
- Documentation and presentation of the results;
- Interpretation and use of the results measured and/or collected (geological interpretations, engineering geological characterization);
- Deep tunnels require generally longer boreholes than shallow excavations; making stress measurements more difficult and costly.

These items should be included in the evaluations when the investigation company is selected.

At last it should be mentioned that it is not only the results from the investigations alone that may have a great impact on the construction costs, but also how they are interpreted and presented. It is important to emphasise that final and complete information of the geological conditions will not be achieved before the excavation is completed.

3. Design strategy for handling uncertainty

3.1 Introduction

Design strategy is very closely related to the uncertainties in the derived ground information from the pre-investigations. In general, uncertainty means 'lack of knowledge'. Still in many circumstances, uncertainty can be handled by quantification or other means so that useful decisions can be made despite the lack of complete knowledge. Handling uncertainties essentially aims at describing the geology or its components sufficiently well for the issue at hand. More general information about risk, uncertainties and rock design can be found in, for example, [4].

Uncertainties can be categorised into *aleatoric* uncertainty (natural variability) and *epistemic* uncertainty (uncertainty due to ignorance) [5]. The aleatoric type refers to the random distribution in parameters that influence the behaviour of a structure. This type of uncertainty cannot be reduced through extended measurements, only quantified. The other type of uncertainty (epistemic) can be attributed to a lack of knowledge. This includes insufficient knowledge of the actual geological conditions, including poor accuracy in terms of properties and geometries. This type of uncertainty may be reduced by means of obtaining more information, for example through investigation, monitoring or measurements.

A review of the problems in the design of geotechnical constructions with an emphasis on probability, statistics and risk analysis is provided by [6]. He confirms that geotechnical design problems primarily originate from a lack of knowledge. This lack of knowledge in the first instance contributes to uncertainties and difficulties to determine in advance the actual geology and the behaviour of a geotechnical structure. The lack of knowledge of the design conditions in the execution phase was also acknowledged by [7] when they formulated the observational method. This procedure has been accepted and formalized in the Eurocode for geotechnical problems.

Another way to categorise uncertainties depends on the origin or 'nature' of the uncertainty; it may be grouped into different categories. An often used division is:

- A. Uncertainty scenario
- B. Conceptual or model uncertainty
- C. Data uncertainty

This system is suitable to categorise geological uncertainties of the derived ground conditions. However, the uncertainties ~~is~~ are in all cases epistemic and depends on lack of knowledge and not on the inherent randomly behaviour of the geology.

In practice, the exact division into categories is not always clear-cut, but categorising uncertainties should be seen as a help to structure the uncertainty into parts that allow for quantification by e.g. stochastic models, and into parts which may need other treatment.

3.2 A. Uncertainty Scenario

Geological uncertainty scenario of a system, such as an underground excavation project, is generally related to uncertain future external events or uncertain boundary conditions. The evolution of external events is a continuous development, which cannot be predicted in full detail. In order to get a handle on this development, a number of future events or conditions, which can initiate chain of events – scenarios, have to be investigated.

Geological scenario initiators for an underground project may include the following, if not already considered as a part of the project description itself:

- Future *geological events* like earthquakes;
- *Changes in engineered* components (like weathering and degradation of the geological material);
- Changes in *natural environment* due to climate change (that may affect the ground water situation)

3.3 B. Model (conceptual) uncertainty

Model (or conceptual) uncertainty concerns the uncertainty originating from an incomplete understanding of the structure of the analysed project and the constituent interacting processes. The uncertainty is comprised both of lack of understanding of individual processes and the extent and nature of the interactions between processes. For underground engineering, the model uncertainty may be divided into:

- uncertainty in the basic principles for describing the rock, and
- uncertainty in the interaction between the rock and the different engineered components.

In this context, we are only discussing the uncertainties in describing the rock. Typical model uncertainties may be related to:

- Behaviour of the rockmass at tunnel scale;
- Estimation of water ingress to tunnels;
- Interaction between rockmass and installed support;
- Type of fracture/joint system and faulting.

3.4 C. Data uncertainty

Data uncertainty concerns uncertainty in the values of the parameters of a model. Data uncertainties may be caused, for example, by measurement errors, interpretation errors, or the uncertainty involved in extrapolation when the parameter varies in space or in time.

There exists an extensive arsenal of methods for describing and quantifying uncertainty, and the description can be made with different ambition levels. The approach and ambition level should be selected in relation to the importance in the system/project. Basic for all evaluation of geological data uncertainties is to understand the spatial variability of the geological structures studied.

Spatial variability concerns the variation in space of a parameter value. Spatial variability is not uncertainty per se, because it can well be recognised and understood, but it is often a cause for data uncertainty. Parameters with strong spatial variation are difficult to evaluate beyond the local region of their measurement.

Connected to spatial variation is the concept of 'scale'. The proper scale to use is problem specific. Usually, the performance of a mechanical system depends on rock properties averaged over a certain scale. If this scale is large, the resulting property variance is reduced, and if it is small, the variability from point estimates will directly affect performance, without any 'variance reduction'.

The scale of fluctuation will also have a practical application for the decision of spacing between the investigations holes. Holes closer to each other than the scale of fluctuation are more or less correlated and will probably give the same information and are in this respect less valuable. The scale of fluctuation is depending on the geological structure to be studied. If the investigation is directed

towards finding major faults, the scale could be hundreds of metres up to kilometres. On the other hand, if the issue is to establish the thickness of a fault or the quality, the scale is tens of metres.

Examples of data uncertainties may be:

- Geometrical related issues, like for example, fracture orientations, number of faults, width of fault zones.
- Strength and deformation modulus of rockmass and fractures.
- Number and transmissivity of water-bearing structures in rockmass.

3.5 Handling uncertainties

The various types of uncertainty have all implications on how to design and follow-up tunnel projects. Handling of the geological uncertainties is an important issue for all underground projects.

In the design process of an underground excavation, engineering parameters with varying degree of uncertainties must be taken into account. These uncertainties are in many cases related to sub-surface conditions and other site-specific requirements. Safety issues and providing underground structures with an economic design, taking the geological setting into account, were one of the key considerations when the basis for the observational method was formulated [7] and [8].

4. Important design tools in tunnel engineering

4.1 The Observational Method

There has been considerable discussion of what the observational method should include. At its simplest, it has been characterized as Terzaghi's "learn-as-you-go" method. However, this approach is not recommended, as used in many types of contracts, it often leads to time delays and claims related to unspecified and unforeseeable conditions. To avoid this, a more strict approach has been developed and the observational method is one of the designated design methods in the NATM (New Austrian Tunnelling Method) and in Eurocode, EN 1997. From an engineering point of view, this allows the designer to employ formal approaches towards design with uncertainties as well as towards results from monitoring and observations made during construction. An important part here is to apply sound engineering judgement.

Such observational approach relies on the review of the design during construction. Before excavation starts, an initial design is made, based on predictions of the rockmass behaviour, including plans for observations and a monitoring system and contingency plans for incremental support works. If, during construction, the monitoring records exceed the predicted behaviour, the pre-defined contingency plans will be triggered.

There are two fundamental features of the observational method. First, it must be able to observe the geotechnical behaviour during the execution of the excavation work by a set of control parameters, which also have to be quantified in the design. Secondly, it must be possible to reduce the uncertainties of the behaviour through an active analysis of observed values of the control parameters, see e.g. [9].

The code (EN) states that it may be appropriate to apply "the observational method" where prediction of the ground behaviour is difficult. But, in order to be allowed to use such a system, several requirements shall be met before construction. These include assessing the range of possible

behaviour and showing that there is an acceptable probability that the actual behaviour will be within acceptable limits. Monitoring plan and contingency plan shall also be written, see also [10].

The overall objective of the observational approach is to reduce the uncertainties about the behaviour and structural stability of the underground opening and thus establish the final design. The final design of the underground opening must be able to fulfil all standard requirements of stability, serviceability and durability.

In principle, the framework of reliability analysis has to be linked with the framework of the observational method into one system. The acceptance criterion for such a system is the probability of failure or some other related measure like the safety index (β) for the studied underground opening. This requires reliability analysis using information from observations as well as employing random variables and acceptance criteria.

The procedure is illustrated in Figure 4.1. The results from the analysis is either that the actual structure has to be observed during construction or alternatively redesigned, or the structure can be accepted as it is. The basis for this study follows the design methodology guidelines described by [11], [12] and [13], which include determining rockmass type, ground behaviour and system behaviour. To the general flow charts, the reliability analysis and checking against acceptance criterion have been added.

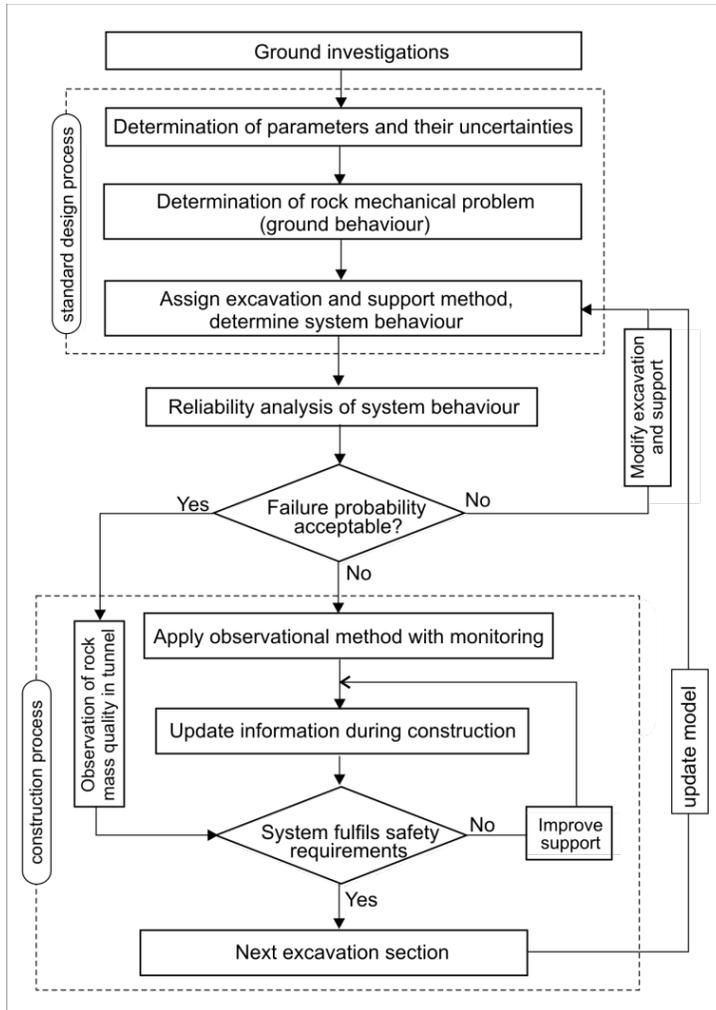


Figure 4.1 The combined design process of reliability analysis and observational method

Design of underground excavations with the observational method fits well within the framework of current design practices and procedures. The implementation of the observational method is not considered to be a significant problem, but will definitely be a positive development of today's design practices.

4.2 Rock engineering and site specific classification systems

The uncertainties to estimate in advance the measure to be taken in order to carry out a safe excavation have implied that a preparedness of different actions is mandatory. Pre-defined actions based on the use of classification systems have been shown to be an economic option in many cases. Some examples are:

- A common situation during the tunnelling process is to take the decision whether or not to use forepoling or spiling. This is a typical choice between two classes (alternatives).
- Another example is when to reduce the length of the blast holes drilled to advance a tunnel. It is not very practical to use a continuous reduction; instead, classes are used like full round length, half round length or a quarter round length.
- Even for rock support, it is very common and convenient to use classes with a stepwise increase in levels of support measures. Often, choosing between pre-defined classes has been found to speed up the tunnel works. One reason for this is that it has often been found practical to use

multiples of the thickness of a single shotcrete layer instead of a continuous variation. The inaccuracy in the site characterization is in many cases so high that it is not meaningful to discuss the difference in support between, for example, 2.1m or 2.2m rock bolt spacing. In such cases, stepwise-defined classes will be adequate.

Figure 4.2 gives examples of two common situations where classification is used in rock engineering.

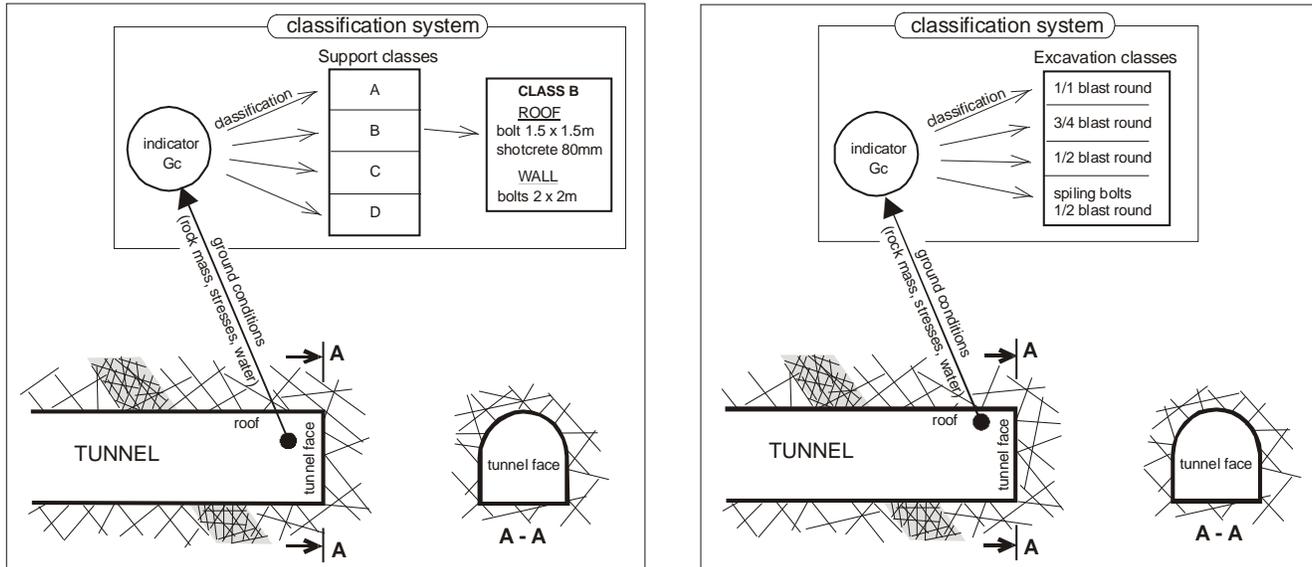


Figure 4.2 Examples of classification into support classes (left) and excavation classes (right) from [14].

In principle, there are two ways that can be used in order to establish the classes:

- One way is to use classes based on existing classification systems. Better or more correctly, pre-defined actions are selected, based on the existing empirical design methods. However, as pointed out in many recent publications, such systems are not perfect and can sometimes lead to the selection of inadequate ground support or an inappropriate design.
- The other way is to develop a specific system tailored for the site in question, based on adequate site information. It is the authors' experiences that, in many cases, this approach will give the optimum design. See also [15] and [16].

Every tunnel project is unique. A tailor-made system can take into account the actual conditions and local construction experience in a more accurate way. This approach has more chance of creating the best solutions than the application of a general system developed to meet universal conditions. It also implies that a combination of empirical design rules and refined rock mechanics models can be used, both serving as input to the prescribed support classes.

The key question is to use a classification system that covers the actual ground conditions and has an acceptable level of uncertainties. This is the basic question for all rock engineers. The accuracy of the

classification system and the risk for mis-classification must therefore always be evaluated. When working with rockmass classification systems, it is important to be aware of the structure of the system and its input parameters and the many limitations rockmass engineering classification systems have [17].

The existing rockmass classification systems for design are based on experience from older projects. In all the best known systems, simplifications have been introduced in order to arrive at both a manageable and a simple procedure. No distinction is made between:

- structural resistance,
- lifetime of the project,
- safety requirements, and
- serviceability.

The classification systems of today are only appropriate for the design of structural resistance. This is a serious shortcoming, especially when related to the requirements in modern design codes. Therefore, as discussed by [14], none of the best known systems can be regarded as a true classification. They may better be characterized as *empirical rock design tools*.

Furthermore, they do not allow the user to quantify the degree of safety achieved by the design. Other factors not assessed in the systems are connected to the influence from vibrations from earthquakes or from nearby blasting or other impacts from human activity.

Being statistically based, a support chart or table can never replace or accurately represent the ground conditions at a specific site. A main reason is that all the actual compositions and textures of the rocks together with the many geometrical features of discontinuities cannot be included in such a chart.

The influence from single seams (filled joints), shears and similar discontinuities will to a great extent, often depend on site-specific geometrical and structural features, and also here the use of support charts may give inaccurate results if not the seam(s) is especially included in the system. For swelling and slaking rock, the stability may be strongly influenced by local conditions. In such cases the rock support should be evaluated separately for each case.

It is also important to keep in mind that most empirical methods in rock engineering give averaged values, and that there may be significant variation between the lowest and highest value. All empirical systems based on experience have similar inherent inaccuracies. Their support selection tables are based on cases where often the installed support was determined by the tunnel workers, and/or the use of varying contractual conditions, which may have caused the amount of installed support to vary significantly (Figure 4.3). Most users easily forget the large variation/inaccuracy when using classification systems for support design.

The different excavation and rock supporting practices in various countries, as well as the requirements to the permanent support, may also cause that the methods and amount of rock support can vary largely from one tunnel to another.

The two most popular classification systems, RMR and Q originally developed for rock support, have severe shortcomings according to [18]. One of the main deficiencies is that the classification parameters are universally applied to all rockmass types. In heterogeneous and poor ground conditions, these classification methods may provide misleading results, whilst their other shortcomings include the lack of consideration for different rockmass failure modes and for the ground-support interaction.

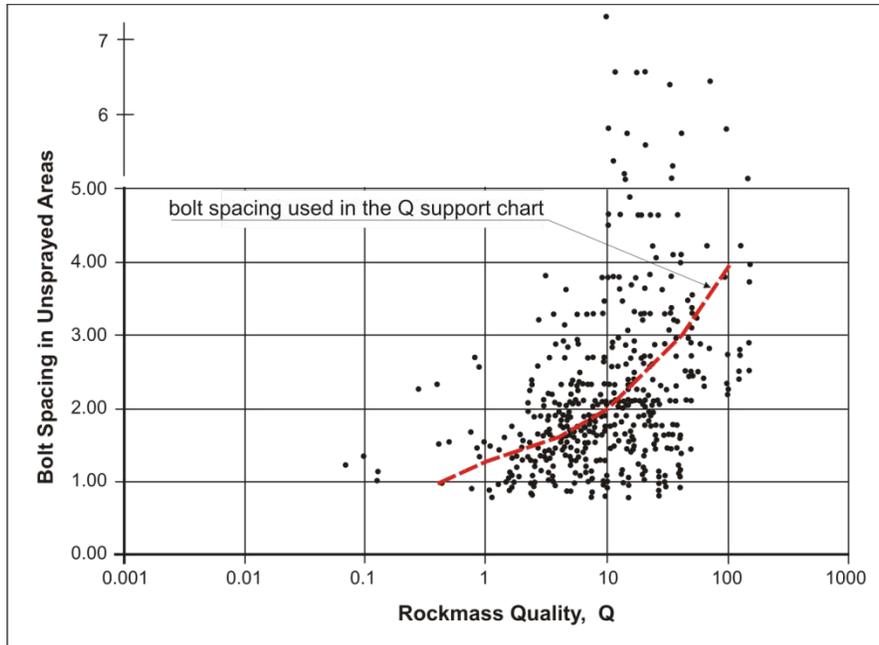


Figure 4.3 The data basis used in the Q system for rock bolt spacing where shotcrete is not installed from [17]

From the most interesting paper of [19], the following requirements of classifications systems are summarized:

- They should promote economic, yet safe designs or action.
- They must be correctly calibrated against test cases, and those test cases must be representative of the field of application.
- They should be complete in that all relevant factors are included, yet they must be practical.
- They should have general applicability and robustness to the varieties of use.

5. Underground projects and quality

5.1 Introduction

In the light of the discussion of the uncertainties involved in underground projects, it is obvious that the need for a quality system is large. Quality control is from a risk perspective to reduce the probability or consequence of an unwanted event by using some kind of quality system.

According to European Standard EN ISO 8402:1994, quality is defined as *"totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs"*. Looking at this definition, it is interesting to note that not only stated, but implied needs shall be satisfied. This is easily forgotten and today not fully done in the underground construction industry. The stated and implied needs are related to a certain acceptance for malfunction with a certain probability. The level of risk acceptance may vary from one project to another as long as it fulfils the demands set by the society in the building codes.

Insufficient quality is an outcome of a process and may be considered as a damage (often: economic loss) caused by an accident. The accident is initiated by an event that triggers a hazard contained in a risk object. Quality assurance [20] should in this respect be concentrated on:

- (i) reducing the consequences of a potential accident,
- (ii) reducing the possibility of getting an initiating event, and
- (iii) identifying and eliminating or reducing the hazard itself.

Quality work should always focus upon important factors and problems. The most important factors for most owners and contractors are to complete a project that fulfils customer demands, within the scheduled time and cost frames, without loss of goodwill. The opposite is to be considered as a severe damage.

Insufficient quality may be related to every phase of a tunnel project, like during excavation and after completion. It may also be related to the tunnel itself and its function, as well as to the environment. Most underground projects are, however, constructed without any damage, even if the hazards have been substantial.

5.2 Important factors influencing quality

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

- 1) to identify the hazards connected to the project, and
- 2) to use a manufacturing process, which eliminates or reduces the probability of potentially damaging initiating events.

If damage is unacceptable, or if it is impossible to eliminate or reduce the probability of initiating events, it is important to reduce the consequence of possible accidents and still achieve an acceptable quality in a broad sense. Insufficient quality due to failure of meeting the above aims within a project, depends on several different obstacles.

Most of the quality systems used today that are certified according to European Standard EN ISO 9001, have an intention of reducing organisational and human obstacles. This is basically due to the fact that the standard ISO 9001 was developed to improve suppliers manufacturing process and product quality. However, such quality systems are not directly developed to eliminate things like lack of competence and insight. As an underground project is a complex process including a high degree of uncertainty, it cannot be treated as a manufacturing process as a whole (even if there are single parts that can be described as such). Consequently aspects, such as competence and insight, as well as assessment of implied needs, become important.

5.3 The dualistic quality system

In order to reach the goal, the supplier (for example a contractor) must finding out the expectations of the customer (a client), i.e. ensuring that the right thing is done or built. It is also important that the quality is acceptable by doing and building right. The overall quality is governed by both these factors, "*doing or building the right thing*" and "*doing or building these things right*" and they must both be handled by the quality system [20].

In many aspects, the idea of TQM [21] 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.

5.3.1 Doing the right thing

The client must at an early stage specify his requirements on the underground structure, starting from the use for which it is intended. These concern:

- function,
- aesthetics, and
- economy; for instance initial investment, or still better LCC (Life Cycle Cost), which includes maintenance and completion time.

Other demands can be implied through laws and regulations, for instance environmental regards. It is necessary, but not a sufficient prerequisite for the contractor to receive these specified demands from the client. First, some of the functional demands must be specified in technical detail (for example diameter of tunnel, demands on lightning etc.). One must remember that civil engineering works are one of a kind, and that once construction is underway, it is difficult to change the design. Secondly, a construction procedure must be chosen, that will give the finished object the demanded properties. When making this choice, rock properties and the uncertainties inherent in them must be considered and it may well happen that one has to find a suitable ranking of the demands, if all cannot be fulfilled. This phase of the design work is very important, as it will determine whether the quality goal will be reached or not.

Although the ISO standards specify that the requirements, on which to base the design, shall be specified and that the resulting design shall be verified, it is not specified how to find the correct requirements and how to rank them in light of the uncertainties and the possible construction methods. One of the reasons is that this work calls for engineering creativity, professional skill, and good communication between all involved parties. One cannot specify how to be creative or how not to misunderstand each other, but rules can be given on how to arrange a team that has a good probability of achieving the goal.

To summarise, it may be concluded that Quality tools as precise project models, risk analyses, system analyses, technical audits and team qualification are helpful in the work of securing that the *right things are done*. It should also be emphasised that these tools could and should be used within all project phases. This is further discussed below.

5.3.2 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 flaws or errors. The overall understanding of quality work as an integrated part of the production process has also increased significantly.

Consequently, the ISO standards do help in *doing things right*, i.e. to plan, control and document the work (see quality tools below). But this is not quite enough. By applying a project model and thereby creating opportunities for good relations and clear communication, the possibility of *doing the things right* will be further increased.

5.4 Quality tools

5.4.1 Project model

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. A useful tool for making both project work and quality work structured and clear, is to employ a precise project model. One applicable model is PROPS, developed and used by [22]. 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. Quality work is then carried out using suitable quality tools, further described below.

The quality assurance should also be carried out using a distinction between the model for quality work and the quality work itself, similar to the project model. The quality work is then connected to the activities within the project. Important features in the project plan are the milestones and tollgates. Milestones imply that a certain work has to be carried out at specific situations. Tollgates are gates, which are not allowed to be passed before responsible managers give their permissions. These features have to be identified in advance based on project risk assessment.

5.4.2 Risk analysis and system analysis

There are tools to help structuring problems, making communication easier, finding demands and the threats against them. One such tool is the application of risk analysis (and decision analysis) methods. Which tool(s) to use depends on the problem and on personal preferences [23]. By applying risk analysis, it is possible to help the client focusing on what he thinks is desirable in the product. One can also find factors that can make a certain construction principle more desirable than another, based on the fact that it has a greater potential of fulfilling the demands.

If it is necessary to make trade-offs between different demands, there are techniques of ranking them, for instance, the Analytic Hierarchy Process (AHP), which has been applied to underground construction projects.

Within underground projects, it is necessary to adjust the working procedures to get acceptable performance from a quality point of view. Statistical methods can for example help in the prediction of geological conditions and in the choice of possible adjustment to the construction and working procedures [23].

One concept that can be applied to civil engineering is that of robustness [24], i.e. the ability to handle variations in geological conditions and construction procedures based on system analysis. The concept may be used both on the design phase and on the construction phase. A robust design method will find a design that can adapt to (reasonable) modifications of the client's demands during construction and that can be built using different methods. A robust construction method can handle different geological conditions that can arise with adjustments within the method, but without change of the main construction principles [25].

5.4.3 ISO 9001

ISO 9001 is a standard dealing with quality system requirements and is intended to be used as a base for design and implementation of quality systems. It should be emphasised that the quality assurance models set out in ISO 9001 constitute good tools for making a production process systematic, effective

and well documented, i.e. to "*do things right*". Key elements particularly important for underground construction, included in most quality systems based on ISO 9001, are

- description of responsibilities and authorities,
- formulation and implementation of organisation goals,
- handling of nonconformity,
- preventive and corrective actions,
- training and education, and
- quality audits.

ISO 9001-based systems definitely serve a purpose within a more holistic quality system, but it must be remembered that they do not guarantee good quality.

In the introduction to ISO 9001, it is emphasised that the quality system requirements specified in the standard is complementary (not alternative) to the technical requirements specified for a product. Consequently, identification and definition of important problems and demands, i.e. "*doing the right things*", discussed above are not included in ISO 9001.

5.4.4 Technical audits

An important tool in quality work is the audit. Audits should be considered as an investigation into various aspects of a project. It is important not only to carry out quality audits, but also technical audits. The investigation should preferably be performed by an independent party consisting of experts in relevant areas. These experts must be competent within their professional field of work, have high integrity and preferably a developed capability for holistic viewing.

5.4.5 Team qualification

It may be difficult to define demands for certain critical and unique activities within a project, especially in early stages. In order to secure sufficient quality, it is important that such activities are executed by a competent team. This necessitates team qualification. Team qualification should be carried out in order to assure the overall competence of the team and that the team will work well together. It is important to note that team assessment should not only rely on scrutinising formal knowledge and operational skills. Personal attitudes and the ability of the individual to communicate and interact in a group should also be assessed.

6. Investigations and observations during tunnel excavation

6.1 Introduction

Investigations performed during the tunnel excavation can be performed in addition to, or as a part of the ground investigations. They should always be related to the geological uncertainties. The main purpose can be to check the conditions just ahead of the tunnel working face for possible unexpected conditions, such as open water channels and/or occurrence of faults and very poor rock masses. This enables the contractor to install or plan appropriate measures to meet the conditions detected.

Observations and measurements is a part of the design process. Tunnel design and observational method are strongly linked to each other. Geological follow up, visual inspection and deformation measurements are all tools to be used. Where prediction of ground behaviour is difficult, it may be appropriate to apply the observational method. The application of a site specific classification system belongs also to this category. It is very seldom that the exact rock class encountered at a certain

chainage of the tunnel can be predicted in advance. The geological follow-up and the classification will then give the relevant support and excavation procedure to be carried out.

All investigation, observation and measurements performed during the tunnel excavation must be planned and communicated with the contractor in advance. It must be a part of the contract and described in the Bill of Quantities. If not, it is a definite risk that the measures will not be carried out to the extent the designer has proposed, with risk of failure, accidents and claims.

6.2 Probe drilling ahead of the face

Exploratory or probe drillings from tunnel face are carried out to obtain information on the rockmass conditions ahead of the tunnel working face, such as potential water conveying structures, faults and major weakness zones. It is important that such features are discovered sufficiently far from the face, so that appropriate measures can be taken for safe tunnelling through them.

Sometimes, exploratory drillings are used also to check the rock cover (distance to the rock terrain surface) especially for shallow tunnels in urban areas.

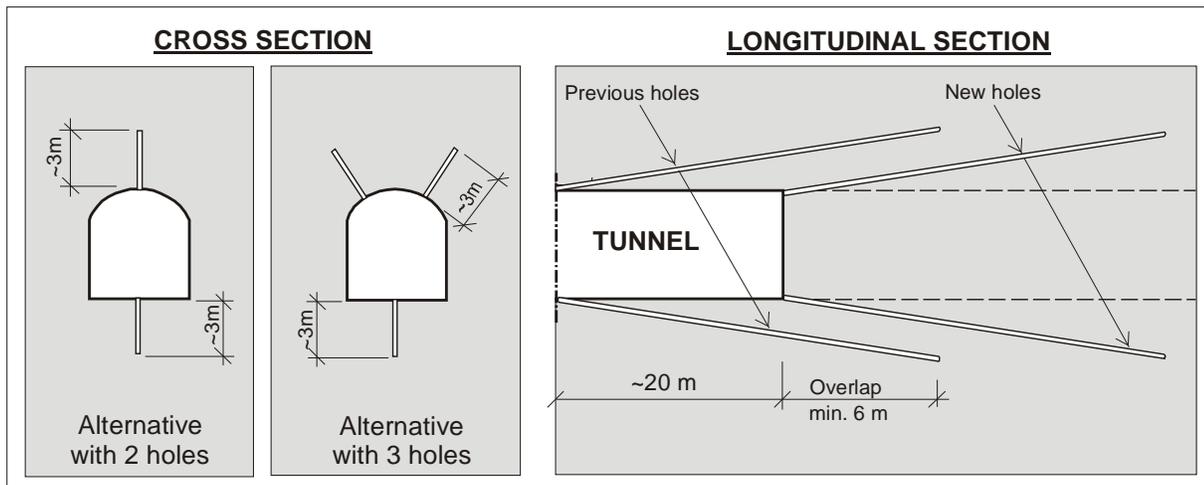


Figure 6.1 Exploratory drilling from tunnel working face during excavation modified from [3]

There are many types of equipment for drilling holes for probing. A main requirement is often that the holes can be drilled quickly and that the drilling can start at short notice. The length of the holes will often be selected based on the capacity of the drilling equipment to be used.

Figure 6.1 shows the use of up to 30m long holes drilled by the tunnel jumbo. This method is suitable in most types of blocky ground conditions. Drill holes of this type are to be considered a pinprick, which main purpose is to determine the distance to a certain geological phenomenon, such as channels with flowing water, altered zones or noticeable shears or joints. The drilling is very quick.

If the drill rig is equipped with MWD (measuring while drilling) device, additional information on the penetration rate, torque, etc. can be collected. Equipment with MWD and software (Rockma or similar) register and compare and from this present graphs with different sets of data from the drilling. When using such equipment and programs, a calibration must take place utilising a simultaneous geological mapping.

In some cases, *Lugeon testing* is carried out in the probe drill holes. From the results of this test, the decision to perform grouting is taken. In most cases the decision on when to grout is, however, based simply on the measurement of the volume of water flowing out from the holes. Grouting is carried out when the water flow exceeds a pre-defined limit. For sub-sea tunnels, this limit is in Norway often 5 l/min for one hole of 20 to 25m length. For tunnels in urban areas that are more sensitive to changes in the ground water level, the limit may be as low as 0.1 – 0.5 l/min in a 20m long borehole. The development of grouting technology the last ten years has given a possibility to seal the rock mass down to 0.1 to 0.3 Lu (Lugeon) compared to old rule of thumbs of 1 to 3 Lu. Pre-grouting is therefore a standard method in Nordic tunnelling in order to not to cause an undesirable lowering of the ground water table.

6.3 Excavation follow-up and tunnel mapping

The best observations can be performed at the tunnel working face before the initial work support is installed. In drill and blast excavation, this is preferably done after or better during scaling and just after the tunnel spoil has been mucked out. The main features influencing on stability are normally:

- Rock type (often mainly for information, except where high stresses occur)
- Alteration or weathering of the rock material
- Degree of jointing (block size, density of joints, etc.)
- Orientation of joints with respect to the tunnel, – of special importance here are sub-horizontal joints influencing on roof stability and steep joints striking parallel or at a small angle to the tunnel walls
- Joint characteristics (roughness, filling material, etc.)
- The occurrence of weakness zones and their size and composition (faults with crushed rock, or with alteration to clay, or content of clay shears). Weakness zones should be given special attention and description, as well as close follow-up
- Water, especially when large inflows may occur.
- Influence of stresses, especially where rock slabbing/bursting or squeezing may take place.

It is not rational to map all these items in every location in the tunnel. The mapping should be tailored to actual geological conditions in the location. Thus, the observations should be concentrated on the main features influencing the short-term as well as the long-term stability in the tunnel. In this connection it is generally the following types of conditions:

- Blocky ground where stability is governed by potential block falls. The joints normally present a chaotic pattern. It should be recognized by the geologists already during the observations that it is impossible to make a complete presentation of such a complex material. Therefore, the registration should be directed towards the degree of jointing (block size) and the orientations of the main joints with respect to the tunnel. It takes a long time to map all joints with orientations, size, location etc., therefore it is quicker and generally sufficient, to only observe/measure the block size.
- Slabbing or bursting rock. It is important to observe and characterize the main features of the rockmasses: the type of rock and how it behaves.
- Squeezing ground (in schists or in particulate or highly jointed clay-containing rockmasses), similar observations should be made as for blocky ground. Later, the behaviour should be followed-up by convergence measurements or similar measures.

- Weakness zone, faults, which require much attention during the observation and mapping. The weakness zones may often fall outside the limits of classification systems. A close follow-up with observations using photos supplied with frequent informal sketches during excavation through the zone may be a means to produce a map of the zone.

Additional to the geological follow-up is the visual inspection of the tunnel behaviour. Cracks in the shotcrete support and bending of washer of the bolts are clear indications of undesired behaviour. Plaster fill can be installed over cracks to observe if there are any further deformations going on in the sprayed concrete or in the in-situ concrete. A 1 to 2cm deep and 5 to 10cm wide cut across the crack should be filled with gypsum plaster. Further deformation will be revealed by cracks in the plaster.

6.4 Monitoring during and after excavation

6.4.1 Introduction

Modern tunnel design is to a large extent based on the observational method. An important part of the method is the monitoring plan. It means that the designer in advance has to decide which observations to be carried out during the excavation. The uncertainties and risk involved should be the base for the evaluation of the monitoring program.

It is important to establish representative control parameters that expose significant events having influence on the geotechnical behaviour during construction. In many cases, the deformation constitutes a robust parameter as it can be quantified in design and monitored during construction [26]. Two different cases can be assessed:

1. The first aims to assess the final deformation in one tunnel section based on the early monitoring data before the deformations have come to a halt (see Figure 6.2). Theoretical models have been developed to be able predict the structural behaviour based on curve fitting methods.
2. The second case is directed to assess the final deformation between two measuring sections (Figure 6.3). In this case both Kriging models, which take spatial variance into account and Bayesian theories can be applied.

In these types of application of the observation method, the actions to be taken when certain limits (thresholds) are reached, should be determined in advance. These types of thresholds may be called "design thresholds" since they are related to changes in the design and has nothing to do with advert danger.

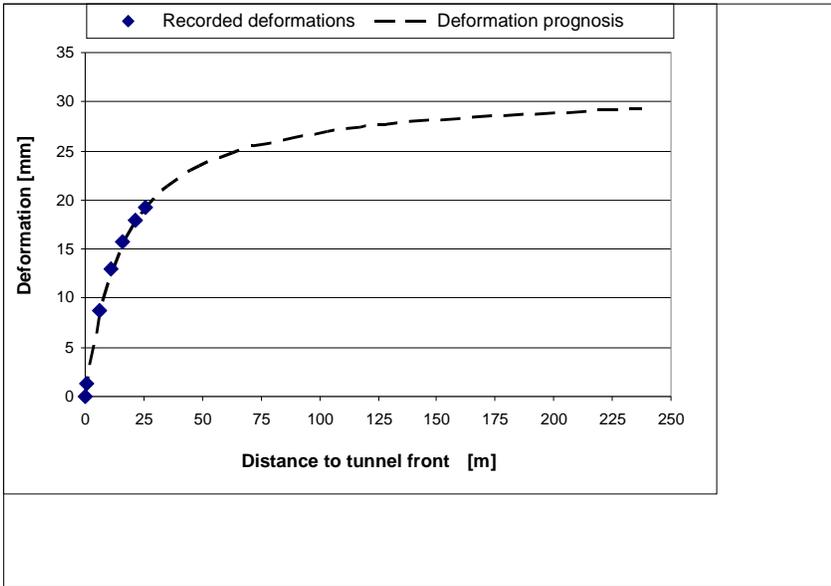


Figure 6.2 Reference case 1 aims at providing an assessment of the final deformation which can be updated with new information from during the on-going excavation [26]

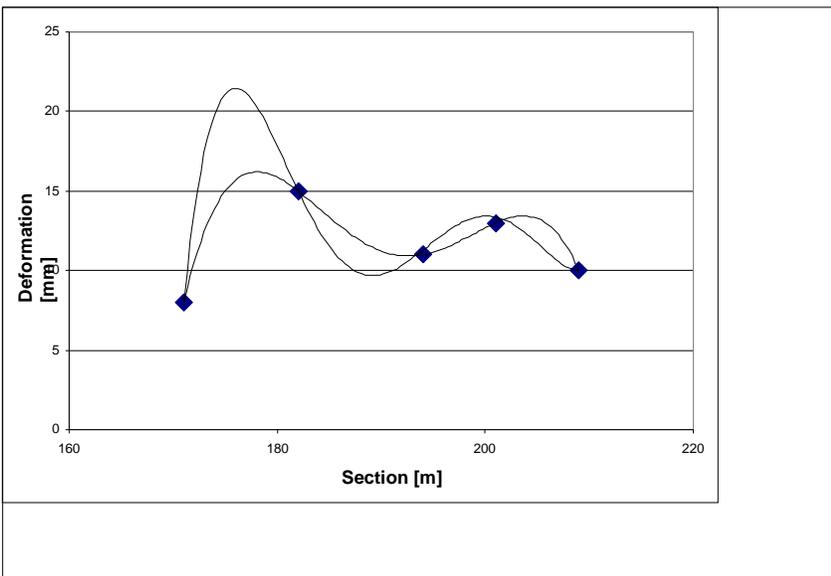


Figure 6.3 Reference case 2 aims at assessing final deformations between the measuring sections. The two lines represent different assessments of deformations between measuring sections [26].

The use of observational systems with alarm thresholds that are set in advance, have been increasingly used in underground construction work. One reason for this is that underground building projects are getting more and more complex with an increased focus on safety, and at the same time, automatic measurement systems with computerised data logging, processing and display have been developed. The alarm threshold is a pre-determined value of one, or of a combination of several observation results, which if exceeded, will trigger pre-determined measures in order to avoid damage.

A very clear distinction should be made between:

- The design threshold, often called target value, which is a guide to efficient and at the same time, safe work. It might, for instance, be vibrations when blasting is set such that it can be carried out with as large salvos as possible, but at the same time with a sufficiently low probability of exceeding the alarm threshold.
- The alarm threshold. The chosen threshold is the limit set in relation to the level of the critical limit and the system for monitoring.
- The critical limit. This is the limit where damage is expected to occur with an unacceptable probability.
- The expected value, which is the most likely value that will occur for a given design and building process.

It takes time to carry out and to take effect of the counter measures. It is thus necessary to have some lead time between the alarm is given by its threshold value and the movements etc. reach a critical limit, see Figure 6.4. This lead time depends on the type of counter measures to be taken, equipment availability and not least the organisation. This means that not only purely technical factors must be considered when determining the alarm threshold, but also human errors etc. The same type of considerations has to be applied also for target value, but is not as critical.

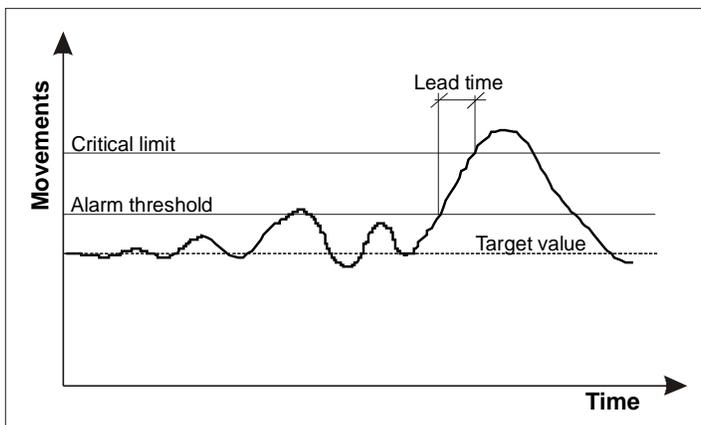


Figure 6.4 Alarm threshold and lead time after [27]

6.4.2 Choice and implementation of instrumentation

Robust and practical methods are required for monitoring and visualising monitoring results. The instrumentation must fulfil requirements of necessary precision, low noise level and stability and also of ease of operation (to avoid gross errors).

All necessary manuals and operating instructions are a part of the quality system and shall be included in the quality control manual. It is important that the total monitoring system is designed with the human error aspects in mind. An alarm should be given in such a form that it is immediately observed and that it needs confirmation from the user.

6.4.3 Deformation measurements

Beside visual inspection, deformation measurements are the most frequently used monitoring method. Such measurement in a cavern can be carried out in different ways. In principle the deformations can be measured at the cavern surface or inside the rockmass.

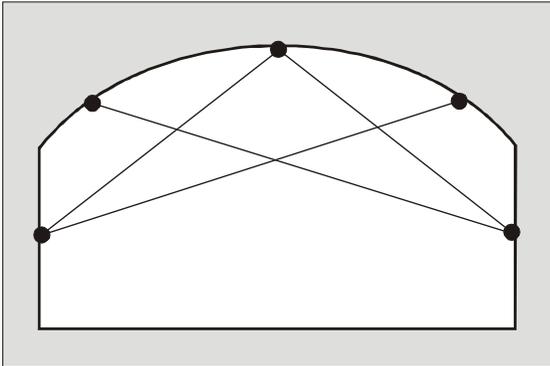


Figure 6.5 Example of placing measuring points for convergence measurements

Deformation measurement is also called convergence measurement with the intention to monitor the deformation of the opening. It is advisable to place the measuring points covering the roof and other critical parts of the tunnel cross section. For convergence measurements, it is important to have a sufficient number of measuring points all over the profile. The installation of the measuring points and the measurements itself can only take place after excavation. The deformations occurring before the front cannot be measured. In order to follow the development of the deformations, the measuring points should be placed as close to the front as possible.

An example of placing the points is shown in Figure 6.5.

Up till today, relative deformation monitoring has been the dominating method and is carried out with measuring tape. It means that the relative displacement between two points is measured. The use of measuring tapes is a quick method that requires little planning. However, it will block the opening during the measurement and also require sky lifts to reach the points in the roof and abutments. The results are only relative and will give no information of the absolute deformations.

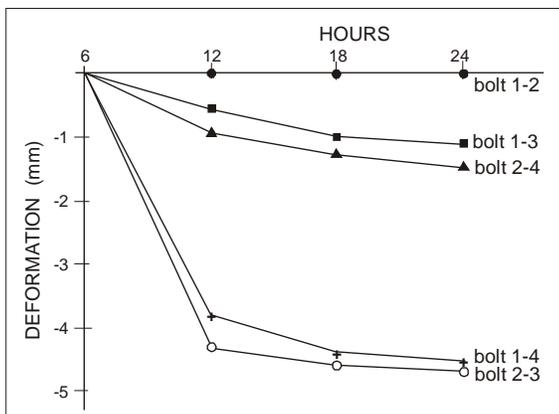


Figure 6.6 Example of set-up and results from convergence measurement in a road tunnel [28]

The development of the measuring technique has given fast and accurate measurement methods based on the use of a theodolite. The accuracy can be around 1mm per measurement, which normally is acceptable. The system of today is computerized. It means that the absolute deformations may be established in relation to some fixed points. Normally the same equipment as used for setting the tunnel alignment and the boreholes for the blasting can be used. It is important for accurate measurements to establish fixed points.

In Figure 6.6 an example of results from convergence measurements are given.

6.5 Presentation of the ground conditions and installed support in tunnels

The documentation of the ground conditions encountered in the underground excavation is worked out from the descriptions and characterizations made. This is an important part in the long term maintenance and repair work.

Efforts should be made to work out a documentation system, which clearly shows the main features influencing on stability, rock support and excavation performance. For instance, the often large amount of chaotic lines in the tunnel map representing the joints, tend to hide the most important

features. This means that local joints should only be shown in principle, i.e. as the degree of jointing (block size distribution) and as presented trends of joint orientation.

To show the trends of the joint orientations, especially unfavourably oriented joint, a simplified joint rosette can be used as indicated in Figure 6.7.

In blocky ground, the block sizes, together with joint condition, especially the occurrence of clay, are the most important parameters influencing on stability. The occurrence of weakness zones or highly jointed, altered or clayey rock will often require special descriptions and sketches to be appropriately presented. Mapping of water ingress is especially important in urban areas where lowering of ground water table must be avoided.

Figure 6.7 shows an example of such a presentation. In addition, files of the observations made in the tunnel should be stored.

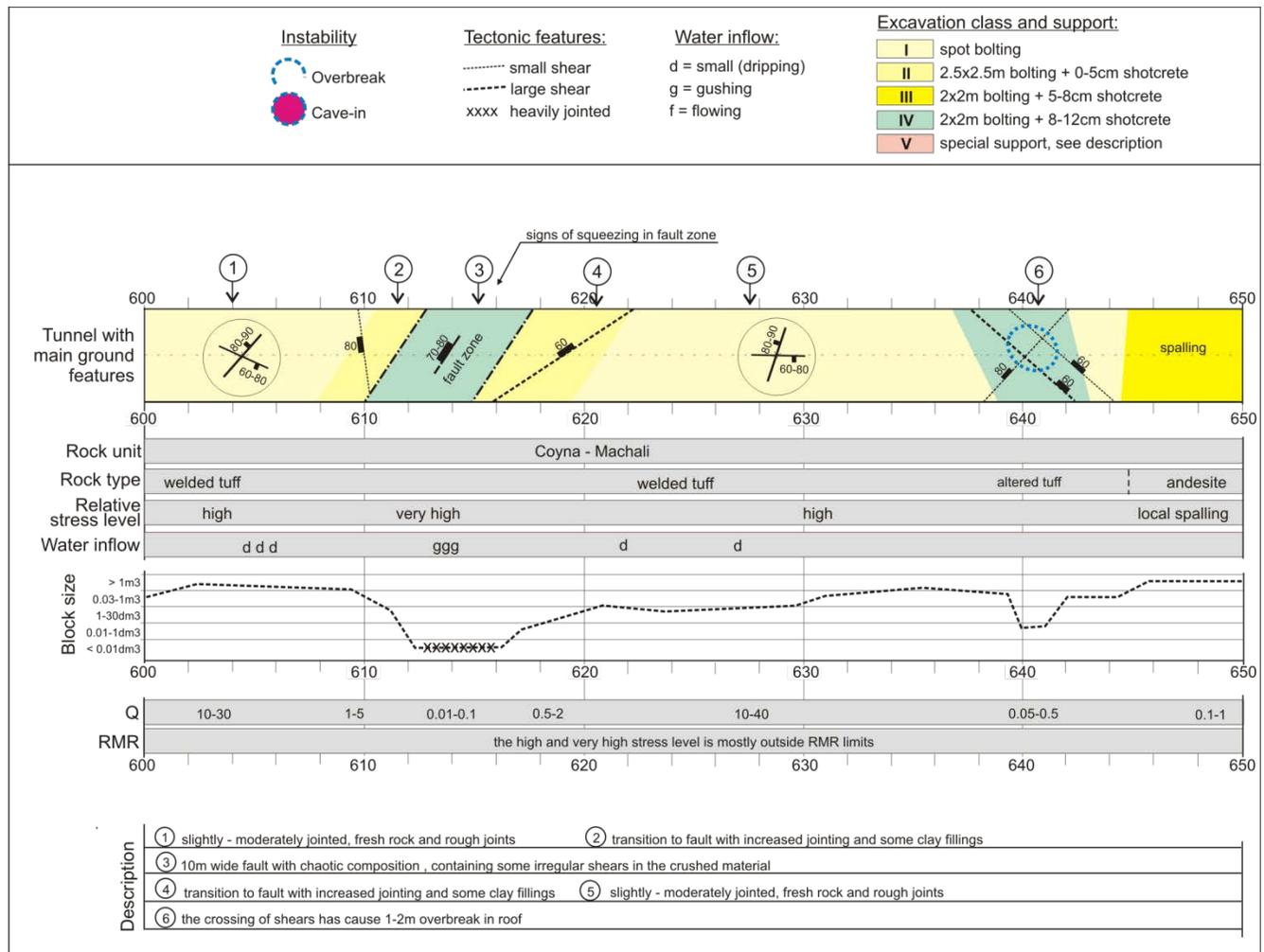


Figure 6.7 An example of presentation of tunnel conditions. It is important that the presentation along the tunnel is easily understood, omitting unessential details. Thus only main features influencing on stability and excavation difficulties should be shown

7. Technology development of tunnel grouting

7.1 Introduction

The objective of grouting in a tunnel is to reduce water flow into the tunnel. This will be achieved by filling up the water-bearing joints and fractures to a certain distance outside the tunnel, creating a water tight zone. The conductivity of the grouted zone is related to type of cement or other grout material used and to the thickness of the zone depending on the grout spread. Normally the target value of the grout spread is in the order of 5 to 25m. Thicker zones will only give minor reduction of water ingress. By performing pre-grouting (grouting ahead of the tunnel working face), it has been possible to reduce the water inflow by 90 to 99%, corresponding to an ingress of 1 to 5 l/min along 100m tunnel length. This is often a requirement to eliminate the risk of damage on the environment. Pre-grouted, unlined tunnels have therefore been standard in the Scandinavian countries. Cement-based grouts have proven to be adequate in nearly all cases.

Stop criteria have been empirically set so that grouting is completed when the grout flow is less than a certain value at maximum pressure, or the grout take is above a certain volume. Since empirically based stop criteria are determined without a theoretical basis and are not related to grout penetration, the grouting result may be inadequate or uneconomical, see Figure 7.1. In order to permit the choice of adequate and cost-effective grouting methods, stop criteria should be designed based on a theoretical analysis of grout penetration combined with experience.

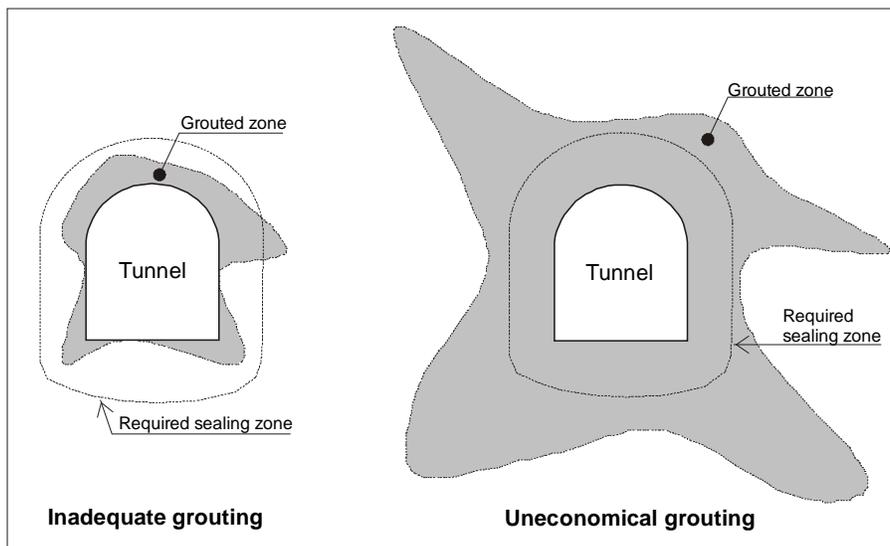


Figure 7.1 Illustration of inadequate grouting and uneconomical grouting. In the illustration on the left, the grout does not penetrate the required sealing zone. In the illustration on the right, the grout has spread too far from [29]

7.2 Cement grouting

Grouting properties will depend on handling of the cement, mixing conditions, time before grouting and temperature. It is essential that all persons involved are aware of this. There are many different properties of a grout, which constitutes its workability and effectiveness. In some cases, they are also contradictory. Good workability with small variance in properties is preferable. Low yield value and

viscosity will in most cases give shorter pumping time for the same grout spread. Good penetration is more important than low bleeding.

Bleeding

Bleeding is normally measured in cylinder with a height of 300mm. The requirement is often that the maximum acceptable bleeding should be less than 5% after one or two hours. However, this measure is not representative for the behaviour in fine (thin) joints. Bleeding is a result of two processes: sedimentation and consolidation. It is also influenced by flocculation and hardening of the cement. This means that the grain sizes have great influence on the results. In fine fractures, only the sedimentation process will be prevailing and this will happen very quickly and during the grouting process itself. Based on these results, bleeding is expected to be negligible in fine cracks [30].

Penetration

Penetrability is an important parameter in grouting and depends on many factors. It has been noticed that two levels exist. One is the minimum aperture of the joint, into which the grout can penetrate; it is denoted b_{min} . There is also an aperture for which the grout can freely penetrate and this is called b_{crit} .

Regarding the critical aperture (b_{crit}), tests carried out by [31] have shown as the rule of thumb, that joint aperture of at least 3 times the maximum grain size is valid for coarser cement. For micro cement the joint aperture must be as big as 10 times the maximum grain size to be penetrated of this type of cement. The results are shown in Figure 7.2. The minimum aperture (b_{min}) is, however, much smaller and is in the order of two times the maximum grain size.

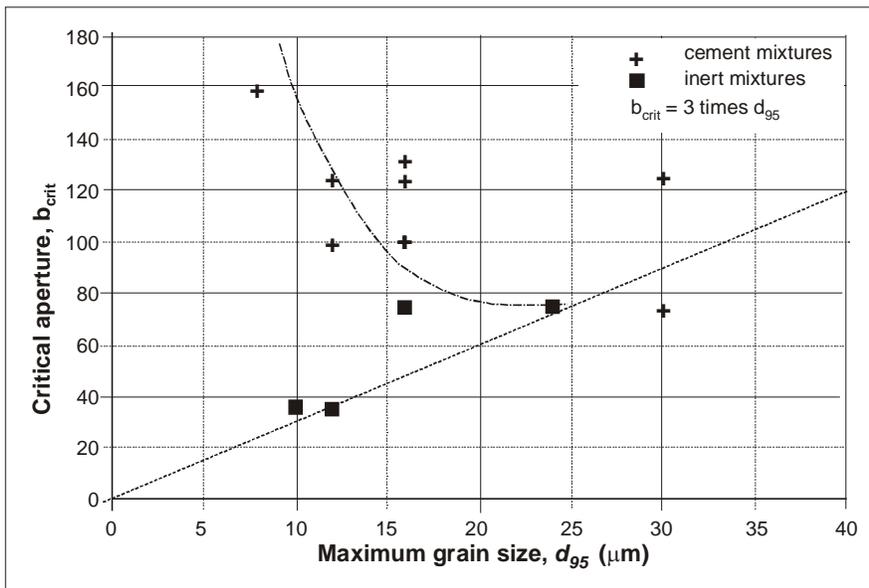


Figure 7.2 Critical fracture aperture to be penetrated as a function of maximum grain size from [31] The conclusion is that, if micro cement is used, special attention should be put on the handling and mixing of the grout in order to get a better penetration than ordinary grouting cement.

7.3 Real time grouting control

By using the theories for grout spreading in joints, it will be possible to control the grouting process. This is a very powerful tool to optimize the process [32]. It will also give opportunity to check that unwanted jacking or backflow to surface or surrounding tunnels will not happen. Important factors are

the dimensionality of the flow and the flow properties, e.g. viscosity and yield value. By analysing the first 5 to 10 minutes of the grout flow, it will be possible to estimate the flow and penetration versus time and give adequate information when the grouting should be stopped.

The research during recent years has also given a better understanding of the water-bearing structures of the rock mass as well as analytical solutions of the grout spread as function of pressure and time. Together with a computerized logging tool, an active control method has been developed in order to be able to govern the grout spread in real time during the grouting operation. The concept is called the "Real Time Grouting Control Method" see [29] and [33].

Pressure

By grouting process, the effective stresses in the ground will be changed. As long as the grouting pressure is less than the initial stresses in the rock mass no deformation will take place. It has been confirmed by [34].

When the pressure exceeds the initial stresses, the grouted fracture will open up. If the grouting pressure exceeds this critical pressure, it is only the exceeding pressure, P_e , that loads the rock mass. If the excess is small compared to the total pressure and the grout penetration relatively short, only a small region close to the bore hole will be loaded, this due to the sharp drop in pressure with distance from the injection point. When the penetration length, r_c , increases the excess pressure acts over a larger area, causing larger dilation. If the dilation of the fracture is large, the dilation may spread a considerable distance away from the borehole, even past the penetrated distance of the grout.

The deformation during jacking will be completely governed by how the rock mass reacts to the additional load. The exact expression will vary greatly from case to case. The jacking will be connected to the largest fracture and it can be anticipated that the minor fracture will be closed to some degree. The majority of these deformations are expected to be elastic. With increasing pressure and grout spread, the deformations increase and at the end ultimate hydraulic jacking can take place.

The risk for ultimate hydraulic jacking has been discussed by [35]. They proposed the GIN-Value to evaluate the risk for jacking. They used the product of grouted volume and pressure to describe the risk. The reason to use volume instead of the theoretically correct penetration was due to practical reason. The limitation and problem with the method was the problem to estimate the so called GIN-value of the rock mass. With the new development, which gives a possibility to estimate the grout spread and the penetrated apertures, a more direct approach can be used.

[36] proposed the following relation based on the grout spread

$$p_n \leq 1 + \frac{1}{I_n} + \frac{1}{3I_n^2} \quad (1)$$

where I_n is the relative grout spread expressed by the ratio between the grout spread and the depth to the free surface, h . p_n is the relative grout pressure expressed by following equation:

$$p_n = \frac{p \cdot k_2}{3\rho gh} \quad (2)$$

where p is the grout pressure and k_2 is a constant describing the relative contact area of the fractures, normally set to 1, ρ is the density of the rock mass.

The equations are illustrated in figure 7.3. The equations indicate that the pressure for ultimate hydraulic jacking will be the weight of the overburden at infinite grout spread, which is reasonable. At limited grout spread, a pressure with a magnitude much larger than the overburden can be accepted.

However, the fractures will be jacked for much smaller pressure. Based on the assumption with an infinite solitary fracture inside an infinite homogenous rock mass, the deformation can be estimated by classical mechanics. With the same notation as above a critical level when the opening of the fracture exceed a given acceptable value, δ_{accept} , can be calculated by equation:

$$p_n \leq \frac{k}{3I_n} + \frac{1}{3} \quad (3)$$

where k_n is the following:

$$k = \frac{3}{4} \cdot \frac{E}{(1-\nu^2)} \cdot \frac{\delta_{accept}}{\rho g h^2} \cdot \frac{p_g}{p_e} \quad (4)$$

No general consensus exists about the level of acceptable jacking. There is difference in practice between the Scandinavian countries. In general, Norway is using higher grout pressure than in Sweden and Finland. The positive effect with a higher pressure will be that the penetrations of the grout will be improved and the spread of the grout will go faster, but this will only be valid in the largest fracture. In the smallest fracture the aperture will instead decrease and the penetration will be reduced. The deformations are mainly elastic and will go back when the pressure is relieved. The smallest fractures will then be unsealed, which may have a negative effect on the achieved hydraulic conductivity of the grouted zone. The conclusion may be that, if the target is only to seal the largest fracture, an elastic jacking can be positive; but if the target is also to seal smaller apertures, the jacking may have a negative effect.

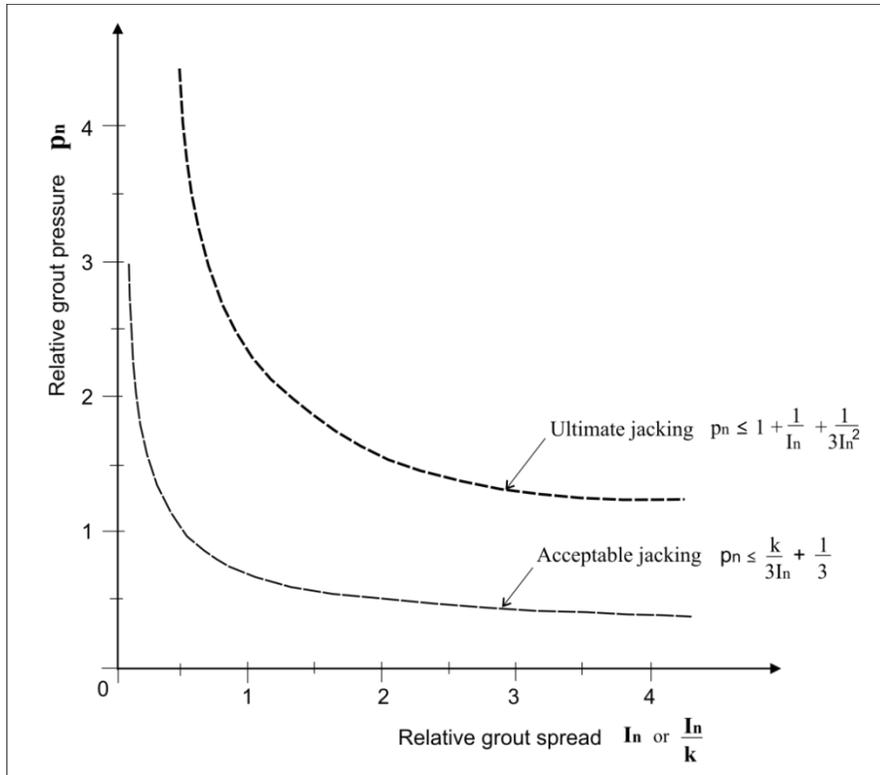


Figure 7.3 Maximum relative pressure as a function of relative grout spread (penetration), both for the ultimate limit state and the serviceability limit state.

8. Conclusion

The art of tunnelling is not only related to excavation technology. Important factors are also organisation and quality assurance of the work. Maybe the most important issue is to handle the geological uncertainties which always are connected to underground work. It implies that the observational approach has to be applied in tunnelling. The design is never completely before the excavation has been finished. This ties together the pre investigation with the tunnel excavation work. The success of the tunnel work will therefore be dependent on how well the results of the pre investigation can be connected to the observation procedure used during the excavation.

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