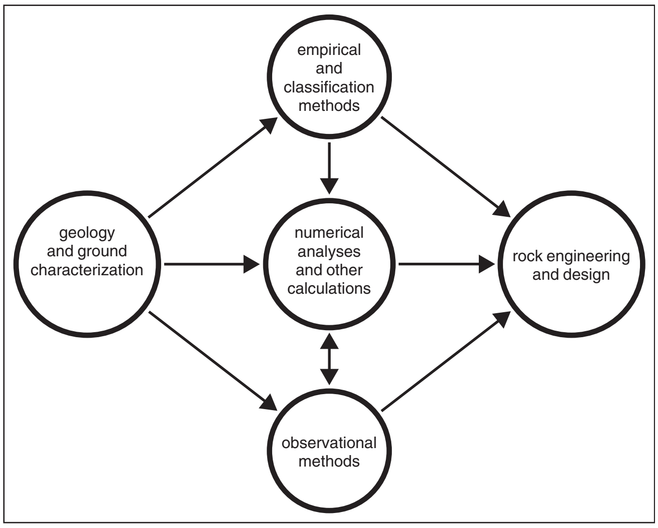
STIFTELSEN SVENSK BERGTEKNISK FORSKNING
SWEDISH ROCK ENGINEERING RESEARCH



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SveBeFo Rapport 61

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Informationsbaserad design av konstruktioner i berg

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Preface

Swedish regulations state that probability based methods like the partial coefficient method should be used in design of buildings where traditional building materials are used, like steel and concrete, but also for geotechnical design. In this case however, a design methodology is not very well developed, as soil and rock cannot be treated in the same way as prescribed construction materials like steel and concrete. Especially for rock and tunnelling, design and construction is therefore still to a large extent based on empirical methods with the use of classification systems and numerical modelling. This may still be accepted according to the regulations as long as one can demonstrate that requirements regarding safety, serviceability and durability are fulfilled.

Stricter demands will follow as the regulations are being developed and Eurocode implemented. Eurocode will also open up for the use of higher levels of probability based methods. Thus it is important to find and use a methodology based on a probabilistic approach throughout the whole design and construction process. To this end this pilot study has been performed to demonstrate a proposed methodology as a basis for further development and implementation in practical design technology for rock construction.

Parts of this methodology has already been applied in a few projects, which is shortly mentioned in the report, and the intention is to try and develop and implement these ideas for practical application via seminars and continued R&D.

The work has been co-sponsored by SveBeFo, SKB (the Swedish Nuclear Fuel and Waste Management Co.) and Banverket (the National Swedish Rail Administration).

Stockholm April 2003

Tomas Franzén

Förord

Samhället kräver enligt Plan- och bygglagen (PBL) att byggnader ska ha ”betryggande stadga, bärförmåga och beständighet”. Utifrån dessa krav har Boverket utarbetat föreskrifter och råd för byggnader. Olika konstruktionstyper behandlas, exempelvis betong- och stålkonstruktioner samt geokonstruktioner, som avser byggnadsdelar i jord. Konstruktionsreglerna utgår från användning av sannolikhetsbaserade dimensioneringsmetoder. För undermarksanläggningar finns ännu ingen sådan tolkning till konstruktionsregler utan byggherren har att svara för att PBL följs. Vägverket ställer i egenskap av byggherre kravet att Boverkets regler i princip ska tillämpas även för bergtunnlar. EU har också tagit fram ett förslag till norm via Eurocode, som kommer att gälla även för bergkonstruktioner.

Det råder i konstruktionshänseende väsentliga skillnader mellan konstruktioner där materialet kan föreskrivas och sådana där materialet är givet men delvis okänt. För den sistnämnda typen är tillämpningen av sannolikhetsbaserade metoder betydligt svårare. Forskning om hur metoderna skall kunna användas för konstruktioner i jord har pågått sedan slutet av 70-talet. För tillämpning i berg har bara enstaka arbeten utförts. Dimensionering baseras därför i hög grad på erfarenhetsbaserade, deterministiska metoder, bland annat med hjälp av klassificeringssystem i kombination med numeriska modellberäkningar.

För att skapa en grund för vidareutveckling av sannolikhetsbaserad dimensioneringsteknik har en metodikstudie genomförts inom ramen för SveBeFos forskningsprogram FP 2000. Rapporten redovisar hur dimensioneringsprocessen i sin helhet kan bedrivas och hur man i olika stadier av processen måste fatta beslut under osäkerhet under det att man successivt vinner allt bättre information, därav uttrycket ”informationsbaserad design”. Metodiken har i delar tillämpats vid några större bergprojekt under senare år, vilket kort kommenteras i rapportens slutkapitel. Avsikten är att denna förstudie ska följas av fortsatt arbete för att utveckla och göra metodiken mera känd, där ett viktig moment är att demonstrera tillämpningar i genomförda och planerade byggprojekt.

Riskbedömningar och sannolikhetsbaserade betraktelsesätt i samband med berg- och tunnelbyggande är ett område som uppmärksammas internationellt, vilket är ett av motiven för att publicera denna rapport på engelska. Det är samtidigt viktigt att föra ut informationen till dem som arbetar här i landet med kvalificerade projekterings- och bygguppdrag, vilket föreslås ske i seminarieform.

Medfinansiärer har varit Banverket och SKB. Projektet har stötts av en referensgrupp, där särskilt Per Andersson, Vägverket, Peter Lundman, Banverket, Magnus Nelson, SwedPower, och Lars Hammar, Elforsk, givit värdefulla synpunkter

Stockholm i april 2003

Tomas Franzén

Summary

The overall design process of an underground project is characterised by a chain of decisions taken during different phases ranging from the feasibility studies into the operational and maintenance phase. These decisions are all related to each other and a free flow of information from one decision to another is essential. The basis for the decisions is the objectives of the different phases. Other important issues are the outer constraints in terms of geology and topography, the owner's functional and economical requirements and the requirements of society.

In principle, designing underground rock openings is similar to other construction design work. The designer has to establish that the bearing capacity is higher than the load effect to a certain degree. However, the rock mechanical system is normally much more complicated than in ordinary buildings. In principle, it can be described as an interaction within the rock mass and the installed support and is essentially an unloading situation. Stress changes will result in a typical deformation pattern with movements directed towards the opening. Thus, the basic problem of designing the rock support measures cannot be analysed from the concept of constant load on the support since the load is deformation dependent. A deeper analysis of the mechanical system is required.

Underground construction projects are generally unique as the conditions and demands vary from one project to another. Furthermore, the rock has partly unknown and spatially varying properties. This also means that the final design cannot be completed before the rock has been inspected and actual conditions been determined after the opening has been excavated. A preliminary design must be based on an estimation of the actual conditions and the designer must be able to distinguish between the uncertainties associated with limited information of the actual rock condition, the uncertainties related to the rock mechanics models for the structural design and how uncertainties may later decrease when the underground excavation has progressed into the rock. Also, hazards are not only related to technical matters. Hazards can be found in all types of activities related to the design process. The organisation of the work or the contract for the design process may be built up in such way that they contain potential threats to a successful completion of the design work.

Consequently, the pronounced uncertainties involved with underground construction imply that risk analysis ought to be a very interesting tool to obtain a better understanding of the related problems. Risk analysis has been used as a part in different proposed methods in order to better estimate the time and cost consequences of a tunnel project or to make a decision of construction method and suitable working procedure to be able to in a adequate way handle a difficult and dangerous situation. A workable information based design methodology is needed.

To account for the challenges phasing the design work a *methodology for information bases design* is needed, where the design processes is described as a system with

decisions made at the different phases of the project. For each phase the work should be divided into the following seven steps:

- Problem analysis and system identification.
- System analysis.
- Analysis of the uncertainties and probabilities connected to the parameters of the system.
- Reliability analysis of the system.
- Decision analysis based on estimated probabilities and consequences
- Assessment of the information needs.
- Design management and quality assurance.

Approaches to problem analysis and system identification

The key to a successful problem solution starts out with a careful consideration on what really is the problem for the system we want to analyse. This contains both problem analysis and system identification.

It turns out that many problems in design and construction of underground openings should be regarded as very complex and that they concern the interaction between technology and people. This means that the wealth of problem solution techniques developed within 'operational analysis' is of high interest. It must be emphasised that the key to an adequate problem solution is to consider every problem as a decision problem. Behind every solution of a problem there has been a decision where different alternatives have been evaluated and weighed against each other based on the uncertainties related to the different alternatives.

When entering into an underground design problem the engineer may first consider the task given being quite straightforward. However, what may appear to be a simple engineering issue of, say selecting proper dimensions of reinforcement may turn out to be a wider issue on selecting construction methods, installing a proper control system or the overall design of the excavation. In a wider perspective a simple task is usually a part of a much wider context and is usually also connected to organisational matters and management. For proper problem identification the technical project and the people involved in the project should be assessed as an integrated system developing in time. There are well developed means of defining and analysing systems, which we recommend using. Specifically, experiences gained are useful as regards:

- Actors – who is affected (directly or indirectly) by the project?

- System and system identification – what is the problem about and what lies outside the project?
- Methods and models – how to analyse a problem?
- Uncertainty, risk and the decision to find an optimal solution.
- Communication.

System analysis and identification

System analysis is key to the problem identification. A system is an entity, which consists of different parts interacting though processes and event. The relations – the interactions – are at least as important as the individual parts. Selection of appropriate system boundaries allowing for a manageable system but including essential interactions is essential.

System identification can be made by different means. In simple cases reasoning and assessment of the key factors of the mechanical system to be analysed may be sufficient. However, in other cases the system may contain many different parts, whose interactions are not evident. In such cases more formal approaches for system identification could be used. An important example of formal methods for system identification is the interaction matrix approach. Fault trees and event trees are other important tools for system analysis.

Uncertainties and probabilities

Many design situations can be handled by risk based analyses. It implies that the uncertainties have to be expressed in terms of probability. This involves several considerations that have to be addressed.

Quantifying uncertainties related to underground construction work is highly subjective, since data usually are few. However, understanding the physics of a problem often makes it possible to select “model distributions” and there is a wide range of experience, which can be expressed as á-priori information. With additional data the á-priori estimates may be improved by Bayesian updating. Furthermore, even if the risk analysis requires quantitative uncertainty estimates, there are many decision situations where rough uncertainty estimates suffice for highlighting optimal decisions.

To a large extent uncertainty in rock properties relate to the fact that rock properties vary, strongly, in space. However, many stability problems depend on the spatially averaged properties. Averaging implies potential for substantial variance reduction – which again in cases reduces the need for extensive data.

System reliability

The reliability of a system can be expressed as the likelihood that it will fulfil its given task or achieve its specific objective. There are various tools for exploring reliability.

In order to have a good basis for decisions, it is often necessary to calculate the reliability of different possible designs, construction methods etc. Exact solutions generally imply solving multiple integrals analytically and this is thus seldom done. Usual calculation methods for the direct calculation of the probability of failure are numerical integration often by using simulation methods. In the construction industry, a proxy safety measure, the safety index β, has come into use. When the safety index is calculated according to certain principles, the probability of failure can be calculated from the safety index. In order to have a safety measure, which is more nuanced than the conventional safety factor and at the same time simple to use, the concept of partial coefficients has been introduced. The basic difference from the ordinary safety factor is that different partial coefficients are applied to the different uncertain variables in the limit state expression, at least to the load effect and the resistance.

An uncritical use of index methods and codes could, however, lead to erroneous conclusions. System understanding and identification of critical failure mechanisms should go before the numerical analysis. Of particular importance is whether the system is a parallel system, a series system or a combination thereof.

Decisions and decision aiding tools

Decision trees can be used to aid decisions made under uncertainty. Furthermore, just by structuring the problem to be analysed as a decision tree helps in defining the problem. Thus, it is not only the numerical outcome of the decision analysis, but also the very decision analysis itself, which eventually guide the decision-making.

In some decision problems it is very difficult to evaluate the consequences and thus to use an expected value as a decision criterion. In these cases one might instead use some sort of a ranking scheme, where the different alternatives are compared to each other and ranked according to their judged desirability (without calculating the possible outcomes.) This judgement and the ranking should be made in a systematic and stringent manner in order to avoid psychological biases etc. One method to do such rankings is the Analytic Hierarchy Process (AHP).

After the formal decision analysis it is necessary to assess its reasonableness, its sensitivity to various assumptions and data and to report the findings. The sensitivity analysis should tell whether the decision is robust or very sensitive to uncertainties in data. The findings of this need to be reported along with results of the actual decision analysis. In the end it needs to be remembered that decision analysis does not replace the decision-making – it provides support for the decisions to be made.

Acquiring information

From a decision perspective additional information is needed when the best decision is not clear e.g. when a sensitivity analysis shows that small changes in input data can shift the best decision. The additional information can be both related to the result from further pre investigation or information obtained from observation carried out during the excavation.

The cost from getting the additional information shall always be compared to the benefit from the additional information. Decision theory can be used to evaluate this issue before any investigation has been carried out based on the cost and the reliability of the method to be used.

Often in underground construction the so-called “active design” or “observational method” approach is applied. This method is based on a previous analysis of the problem and the determination (in advance) of modifications of the construction procedure to be taken, based on the observation made.

A special type is the use of an observation system with predefined alarm threshold. The alarm threshold is a predetermined value of a single or a combination of several observation results, which if exceeded will trigger pre-determined measures in order to avoid damage. In order to avoid unnecessary alarms or get failure without any warning it is essential to define the threshold in an appropriate way.

Project management and quality control

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

Quality work should always be focused upon important factors. Since many underground projects can be described as unique it will equal important to “Do the things right” as “Do the right things”. In others words: everything cannot be described in advance, many important decision has to be taken during the excavation work and thus be controlled during the excavation. Depending on the problem different tools may be used like pre defined quality system as ISO 9001 or the use of technical audits. The later type, which is recommended to be used for more complex underground construction projects, is more directed to check that the right things are done than the things are carried out correctly.

Sammanfattning

Utformning och design av bergrum sker genom en serie beslut som fattas i olika faser från förstudiefasen ända till drifts- och underhållsfasen. Besluten är alla relaterade och det är nödvändigt att den information som låg till grund för tidiga beslut också överförs till senare faser. Det är projektets mål i de olika faserna som ska vara utgångspunkten för besluten. Dessutom finns det alltid yttre begränsningar i form av geologi och topografi, beställarens funktionskrav och ekonomiska ramar, liksom samhällets krav.

I princip liknar design av bergrum annat konstruktionsarbete. Designern ska ta fram en lösning där bärförmågan med marginal är större än lasterna, men det bergmekaniska systemet är mer komplext än en vanlig byggnad. Det karaktäriseras av interaktioner inom bergmassan och bergförstärkningen och är väsentligen en avlastningssituation. För att välja bergförstärkning är det därför inte möjligt att göra förenklingen med att anta konstant last eftersom lasten beror på bergets deformation. En mer djupgående analys av det mekaniska systemet är nödvändig.

Projekt som omfattar design och bygge i berg är nästan alltid unika. Förhållanden och krav på anläggningarna varierar från fall till fall. Den avgörande komplicerande faktorn är att berget som byggmaterial aldrig helt går att karakterisera. Design av bergrum och andra undermarkskonstruktioner karakteriseras därför av att den slutgiltiga utformningen av anläggningen inte kan fastställas förrän de färdiga bergrummen har inspekterats och bedömning gjorts att till exempel förstärkning och tätning är tillfyllest. Vidare gäller att de olika faror och risker som behöver hanteras inte bara begränsas till tekniska frågor. Det finns faror inom alla delar kopplade till designprocessen. Inte minst gäller det att arbetet kan organiseras och att kontrakt kan utformas på ett sådant sätt att de inte utgör potentiella hot mot genomförandet av projektet.

För att hantera osäkerheter och olika faror behövs en *metodik för informationsbaserad design* där designprocessen beskrivs som ett system. Designarbete bör därför vara en process som karakteriseras av en kedja av beslut som tas i olika faser. I varje fas bör arbetet delas upp i följande steg:

- Problembeskrivning och systemidentifiering
- Systemanalys
- Analys av osäkerheter och sannolikhetsfördelning hos de parametrar som har stor betydelse för hur systemet fungerar
- Tillförlitlighetsanalys
- Beslutsanalys
- Värdering av informationsbehov

- Ledning och kvalitetssäkring.

Problembeskrivning och systemidentifikation

Nyckeln till en lyckad problemlösning är en noggrann analys av vad det egentligen är för problem som behöver beskrivas och lösas. Det kan tyckas vara elementärt, men är det inte. Det visar sig att många frågeställningar relaterade till design av bergrum är komplexa, både beträffande det bergmekaniska systemet och samverkan mellan teknologi och människor. En till en början enkel fråga om val av förstärkning kan efter vidare analys visa sig koppla till frågor om byggmetoder, kontraktsfrågor eller miljökonsekvenser.

En framgångsrik väg för problemformuleringen är därför att se hela designprocessen som ett system. Sådana frågor har sedan länge hanterats inom ämnesområdet ”operationsanalys”. Viktiga frågeställningar att beakta är framförallt:

- Aktörer – vilka är inblandade (direkt eller indirekt)?
- System och systemidentifikation – Vilka är problemets komponenter och interaktioner och vad ligger utanför det som behöver beskrivas?
- Metoder och modeller– hur ska problemet analyseras?
- Osäkerheter, risk och beslut.
- Kommunikation.

Systemanalys

Problembeskrivningen underlättas väsentligt av en systemanalys. Ett system kännetecknas av att det består av delar som samverkar via olika processer. Relationerna – interaktionerna – mellan systemets delar är minst lika viktiga för systemets funktion, som delarna själva. Vidare är väsentligt att välja en systemavgränsning som ger ett hanterligt system, samtidigt som viktiga relationer inte utesluts.

Det finns olika sätt att åstadkomma en systembeskrivning. Systembeskrivningen bygger på expertbedömningar och erfarenhet. I enkla fall räcker resonemang och erfarenhet, men det finns också mer strukturerade metoder som bör användas vid komplexa eller okända situationer. Exempel på sådana metoder är interaktionsmatriser, felträd och händelseträd.

Osäkerheter och sannolikheter

Osäkerheter behöver beskrivas och kvantifieras. För att bestämma systemets tillförlitlighet och för att kunna göra en beslutsanalys med felträd behöver sannolikheter bestämmas.

Kvantifiering av osäkerheter kopplade till undermarksprojekt har stora inslag av subjektiva bedömningar eftersom det nästan alltid finns få mätta data. Denna svårighet kan dock hanteras. Genom att förstå underliggande fysik och mekanik kan man ofta välja en lämplig ”modellfördelning” för ingående storhet. Dessutom finns en stor erfarenhetsdatabank som ger underlag till rimliga a-priori antaganden om många av bergets egenskaper. A-priorikunskapen kan dessutom förbättras, via bayesiansk uppdatering, om det finns tillgång till ytterligare mätdata. Dessutom är det ofta inte nödvändigt med alltför exakta osäkerhetsuppskattningar. Många beslut blir uppenbara även om osäkerheterna i ingående data är stora.

En viktig orsak till osäkerheter hos berget är att dess egenskaper varierar kraftigt i rummet. Många stabilitetsproblem beror dock på medelvärdet över en större volym. Medelvärdesbildning innebär möjligheter för en betydande variansreduktion, vilket kraftigt kan reducera behovet av omfattande data. Alla problem är dock inte medelvärdesbildande. Dessutom måste risken för bias (snedfördelning) i indata alltid beaktas.

Tillförlitlighetsanalys

Tillförlitligheten hos ett system kan uttryckas som hur troligt (sannolikt) det är att det ska kunna utföra sin uppgift och kunna uppnå sitt mål. Det finns olika sätt att utvärdera tillförlitlighet.

Tillförlitlighet, i form av en brottsannolikhet, kan beräknas för olika tänkbara designalternativ. När systemet och ingående sannolikheter är kända kan exakta lösningar göras genom att lösa ett antal komplexa integraler – men det görs sällan. Numerisk lösning kan användas med framgång, men det är vanligare med olika indexmetoder som betametoden och partialkoefficienter.

Ett okritisk användande av indexmetoder och normer kan dock leda tanken fel. Nyckeln ligger i systemförståelse, t ex om det är ett seriesystem, ett parallellsystem eller en kombination av dessa.

Beslut och beslutsstödsanalys

När beslutsunderlaget innehåller osäkerheter kan formell beslutsanalys i form av beslutsträd användas som stöd. Att ta fram beslutsträd hjälper dessutom ofta till med att tydliggöra vad som är det faktiska problemet. Det är med andra ord inte bara beslutsanalysens resultat utan erfarenheterna från själva analysen som är värdefullt.

För vissa beslutsproblem kan det vara svårt att beskriva eller uppskatta konsekvenserna av ett beslut. Då är beslutsträd mindre användbara, men det finns olika rankingmetoder som fortfarande kan användas, t ex AHP (Analytic Hierarchy Process).

Efter genomförd beslutsanalys är det nödvändigt att värdera om beslut verkar rimligt och att pröva hur känsligt det är gentemot ingående data och antagandet. Vidare måste resultat och slutsatser rapporteras. Beslutsanalys ersätter inte beslutsfattande. Varje beslut måste vara rimligt och logiskt, men beslutsanalysen ger underlag och nya insikter.

Inhämtande och värdering av information

När det inte är klart vad som är det bästa beslutet behövs ny information. Kostnaden för att erhålla ny information måste dock vägas mot dess tänkbara nytta och osäkerheten i informationskällorna måste värderas. Åtminstone under förundersökningsstadiet kan övervakningssystem och s.k. ”aktiv design” vara ett alternativ till att försöka skaffa mer data. Aktiv design förutsätter dock att lämpliga larmgränser kan formuleras och att det går att vidta åtgärder om larmgränserna överskrids.

Projektstyrning och kvalitetskontroll

Behovet av kvalitetssystem är stort. Kvalitetssystemet ska kunna reducera felsannolikheter eller minska konsekvenserna av olika missöden.

Kvalitetsarbetet måste fokusera på väsentligheter! Med tanke på att undermarksprojekt ofta är unika är det minst lika viktigt att se till att ”rätt saker görs” som att ”sakerna görs rätt”. Det är med andra ord inte möjligt att på förhand ange exakta instruktioner för alla tänkbara situationer som kan uppstå. Viktiga beslut måste fattas under pågående arbete. Beroende på problemet kan olika kvalitetsinstrument som kvalitetssystem under ISO 9001 och oberoende teknisk granskning (”technical aduit”) användas. Det senare är ett mer lämpligt verktyg för att kontrollera om rätt saker har utförts, medan kvalitetssystemen mer fokuserar på att saker utförs rätt. För mer komplexa undermarksprojekt rekommenderas att en oberoende expert får följa projektet för att säkerställa att rätt saker utföres.

Contents

1 Introduction

Underground space offers a stable and safe place for many types of human activity. Modern construction techniques are also bringing down the cost for underground work. In many cases the underground alternative offers an advantage by giving an optimal solution with a low and acceptable environmental impact, Winquist and Mellgren (1988). Underground projects have, however, a higher degree of complexity compared with most other types of construction. They can normally be characterised by long lead-time before the construction work can be started. The inevitable environmental impact can in many cases create political blocking and problem to get public acceptance even if they can be regarded as an environmental optimal solution to a difficult problem. Contracts and organisations are complex. Limitation in knowledge and competence may create dangerous obstacles to a successful completion of the project in time and at budget. Furthermore, underground projects concerns excavations etc. in a geologic medium, which conditions may be uncertain when the project commences. However, typically the knowledge increases as the project progresses.

An underground project will therefore normally be divided in a stepwise procedure to enable for the owner and the other parties involved taking necessary decision with acceptable uncertainties. The different phases are normally a feasibility phase, a preliminary design phase, drawing up of tender documents, construction-phase with final design and operation of the facility. In these phases there are many decisions that have to be taken and under uncertainty. Many aspects influence the different decisions and some of them are highly correlated. Many authors for example Anderson (1997), Reilly (1996), Stille et al (1998) and Tengborg (1998) have therefore emphasised the benefit to use a management with a risk perspective for underground projects.

Typical for many underground openings like tunnels for transportation and energy production is also that they have a rather long life time. Inspection and maintenance work are a normal part of the use. There is also an increasing demand for reuse of old abandoned mines and storage caverns. All these imply the need for redesign based on an investigation of the condition and state of an existing underground opening. Even if this report has its focus on design of new underground openings the general approach with an information based design is applicable on the above-mentioned issues as well.

1.1 Objectives

The objective of this report is to present a methodology for risk based – or rather “information based” – design of underground excavations. Decisions related to the design issues should be based on the available information at the time for taking the decision.

Design work for an underground project involves much more than structural engineering. The layouts, establishment of alignment, measures to get acceptable environmental impact are all part of the design work. Under some circumstances also construction method has to be addressed by the designer. The methodology for an information based design presented in this report is applicable to every design issue. However, to facilitate for the reader the application presented in the report is mainly relate to the structural design.

Risk management of underground projects in general is outside the scope of this report. Still, the interconnection between design and risk management will be discussed.

1.2 Decisions during the course of a project

An underground project can be divided into different phases such as a *feasibility* phase, a *preliminary design* phase, *drawing up of tender documents*, *construction*-phase with final design and *operation* of the facility. However, in principle, and especially for an underground project, the final design cannot be established until the actual conditions have been encountered at the excavation during the construction-phase. The objectives of the design decisions during the different phases are different and related to overall objectives of the different phases. The different design decisions will eventually converge towards the final design. The flow of information has to pass from one phase to another and to give the basis for decision of the final design.

The objective of the *feasibility phase* is to establish that the project can be constructed to an acceptable cost and time. It is also important to establish that the environmental impact is reasonable. Design decisions are to establish the preliminary layout or alternative layouts and the relevant measures needed to handle costs, mitigate hazards and control the environmental impact. Important input is the owner's requirements and other decisive requirements from the society affected by the underground openings. Establishing representative geological conditions is normally sufficient in this phase.

During the *preliminary design phase* more detailed design decisions have to be taken. They are all related to general objectives of this phase to give the basis to start up the construction work with specified time and cost limits. During this phase a more detailed site investigation is carried out. The aim is to establish the geological conditions regarding the expected variations and the major hazards that can influence the project in a decisive way. It is also important that during this phase to establish the final layout and several detailed design issues connected to the type of project. General decisions on the rock support and other measures, which have to be installed during the construction-phase, have to be taken. Both advanced rock mechanical analyses and more subjectively based design tools can be used.

During the *construction-phase* the actual geological conditions will be encountered. However, in principle they can never be evaluated with certainty. A final design has to be established, fulfilling all the requirements and preferences related to the project, which have been defined during the earlier phases. In many cases different types of active design work has to be carried out. Geological follow up, rock mechanical observations and complementary analysis are frequently used in this phase.

During the *operation* of the facility inspections and maintenance have to be carried out. These activities have to be regarded to be an integrated part of the design work. They are all related to the different design decisions that have been taken during the development of the project. All the maintenance work aims at upholding the requirements of well function and safety of the facility.

The overall design process of an underground project is, thus, characterised by a chain of design decisions taken during different phases. They are all related to each other and the free flow of information from one decision to another is essential. The basis for the decisions is the objectives of the different phases. Other important issues are the outer requirements in terms of geology and topography, the owner's functional and economical requirements and the requirements from society. All these issues are important parts in the process of identifying and analysing the problem, see Figure 1-1.

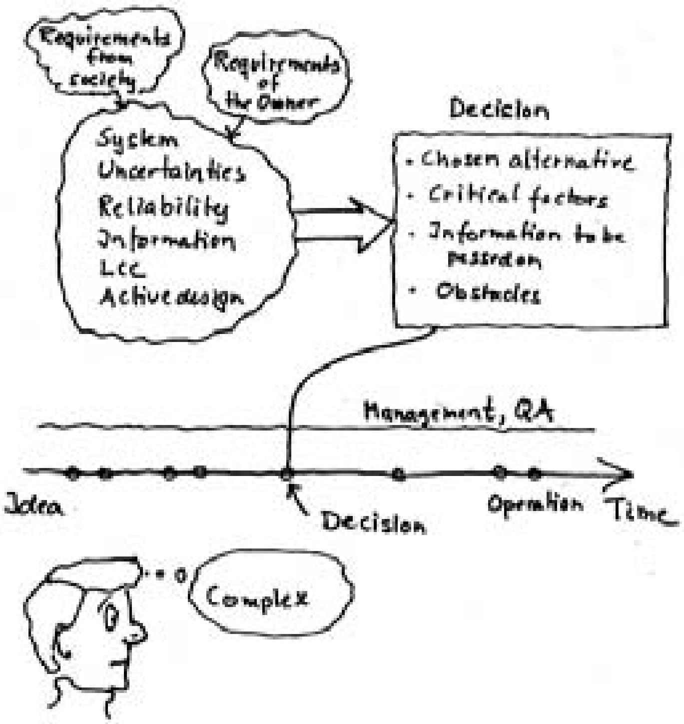


Figure 1-1 *The overall design process of an underground project is characterised by a chain of design decisions taken during different phases.*

A solution to a design problem is normally built up by different components in a more or less complex interaction and different solutions may exist. An essential tool for handling these components and interactions is to describe them as a system, which will enable a reliability analysis. The hazards, the uncertainties related to the outer requirements and the limits in the detailed understanding of the rock mechanics are all very specific for underground project and have to be taken into account in the design work. The complexity and involved uncertainties characterise the design process. Consequently, in many designs situations in rock engineering decisions have to be made under uncertainty. This also implies that a good design management and quality assurance are essential.

To account for these difficulties, major design decisions should be handled by an information based methodology with the following seven steps:

- Problem analysis and system identification.
- System analysis.
- Analysis of the uncertainties and probabilities connected to the parameters of the system.
- Reliability analysis of the system.
- Decision analysis based on estimated probabilities and consequences
- Assessment of the information needs.
- Design management and quality assurance.

1.3 This report

The report has therefore been divided into different chapters, each describing one of the steps presented in the previous section. For overview, some general aspects of designing of constructions in rock, different design approaches, risks in rock engineering and the mechanical system are presented first in the next chapter.

2 Designing underground openings in rock

This chapter provides an overview of the issues at stake when designing underground openings in rock. It briefly discusses the concept of risk related to rock engineering problems and the need to understand the essentials of the mechanical system comprising the rock, the excavations and various support measures. Also life cycle costs aspects are discussed briefly.

2.1 Overview of design approaches

Underground construction projects are almost always unique as the conditions and demands vary from one project to another. A high degree of complexity is also common as the project are often characterised by difficult geological conditions, high technical level, uncertainties related to the knowledge of the rock mass, complex contracts and environmental focus. The complexity is associated to every stages and phases in an underground project and thus also has a decisive influence on the design of constructions in rock.

The most crucial factor is that the rock as the building material cannot be prescribed. All other types of building material as concrete and steel can be manufactured and delivered to the work site according to a prescribed and specified quality. This implies that the design process must follow quite other rules compared to the normal design process in building industry.

The process of designing constructions in rock can thus be characterised by the condition that the final design cannot be completed before the rock has been inspected and actual condition been determined after the opening has been excavated. Therefore, the design is normally divided into a preliminary design phase before the actual rock excavation has been started and a final design phase during and after the excavation. It is obvious that the contract between the client and the contractor must deal with this situation.

From a designer’s perspective the preliminary design must be based on a relevant estimation of the actual conditions. The design must be able to distinguish between the uncertainties associated with limited information of the actual rock condition and the uncertainties related to the rock mechanics models for the structural design and the corresponding rock mass properties given an inspection of the actual conditions at a certain tunnel reach.

Some design issues like tunnel alignment are irrevocable and the decision must be based on the limited information that can be obtained from the preliminary investigation. For other design issues the final decision can wait until further information have been obtained during the tunnel excavation.

One common way to deal with this is to work with different designs often expressed in different support classes related to given rock conditions. For the preliminary design the designer has to both make an estimation of the possible actual conditions along the tunnel alignment and then select the support measures given the estimated ground conditions. One important reason to make a preliminary design is to get as good a basis as possible for cost and times estimation of the project.

During the final design phase the designer has to check the actual rock condition and match it with the estimated ground conditions in order to finalise the design. At this stage the uncertainties related to limited information from the pre-investigation can be disregarded. However, it must be mentioned that the match between estimated and actual ground conditions is never perfect.

In principle the designer has to establish that the bearing capacity is higher than the load effect to a certain degree. In this respect the design situation is similar to other design situation. However, the mechanical system is normally much more complicated. This will be discussed in a later section.

Rock is in general a very complex building material. The rock mass is intersected by joints and other weakness planes given in principle a discrete, in-homogenous, anisotropic and non-elastic (DIANE) material. The uncertainties related to the mechanical properties, which influence the load effect and the bearing capacity, are normally higher than for other building material due to this complexity. A lack of knowledge of the true behaviour or properties is one part of the uncertainties.

The design of today can be described as to great extent a subjectively based design. In principle three different design-approaches can be recognised. Every approach has its limitations and advantages. The approaches to be used depend on the problem and actual conditions. For very complex structures and where the failure is related to great consequences it is very common to use different approaches in parallel in order to take the final decision of the adequate design measures.

One approach, and maybe the most common one, is to use different empirical based design methods (see e.g. Andersson et al., 2002). The empirical design methods, like the mostly used systems, the Q-method and RMR (Barton et al 1974, Bieniawski 1989) are often called classification systems. The empirical methods are fundamentally subjective. They will prescribe a solution to the design problem that in principle is based on the experiences from some similar cases. It is not possible from the methods to estimate the safety factor or reliability measures like the probability of failure (Stille and Palmström 2003).

Another approach is to solve the basic rock mechanics differential equations by computer based numerical methods. Both continuous and discontinuous models exist. This approach is normally used for larger underground openings. However, in case the rock is described as a know property, the solution may not account for uncertainty and does not directly provide the factor of safety or the reliability. In fact, the discrepancy between the models and the reality is in many cases too high to solely rely upon the model results. The rock mass properties used, as input to the analysis, can in principle not be directly be determined by testing instead they have to indirectly be estimated by some empirical relation (see e.g. Andersson et al., 2002). In practical application this and other model uncertainties are often overlooked.

The different circumstances discussed above imply that other design approaches have to be developed and used in order to get a reliable design. They can be described under the headline “Observational method “ or “Active design”, which means that active observations by different types of measurement or visual observation are carried out during the construction work in order to establish or confirm the true design situation. In order to get a more active design process it is favourable to base the observation and measurement system on a prediction of probable behaviour and let the outcome be related to predefined counter measures.

Depending on the nature of the problem and the type of underground opening to be designed one or a combination of these different approaches is used. Normally all three of them are used to design large public underground openings, see Figure 2-1. Large underground openings have been built and will be built based on these design approaches and to full satisfaction. However, in many cases it may be questioned whether the design is overly conservative and, on the other hand, several accidents or mishaps have occurred after the openings have been taken in service. Both these observations indicate that there are limitations with current design approaches – or at least how and when they are applied.

According to our knowledge there is currently no general methodology where these different design approaches can be united and the reliability of the design can be expressed in adequate terms like probability of failure or safety index (see e.g. Nelson et al., 2000).

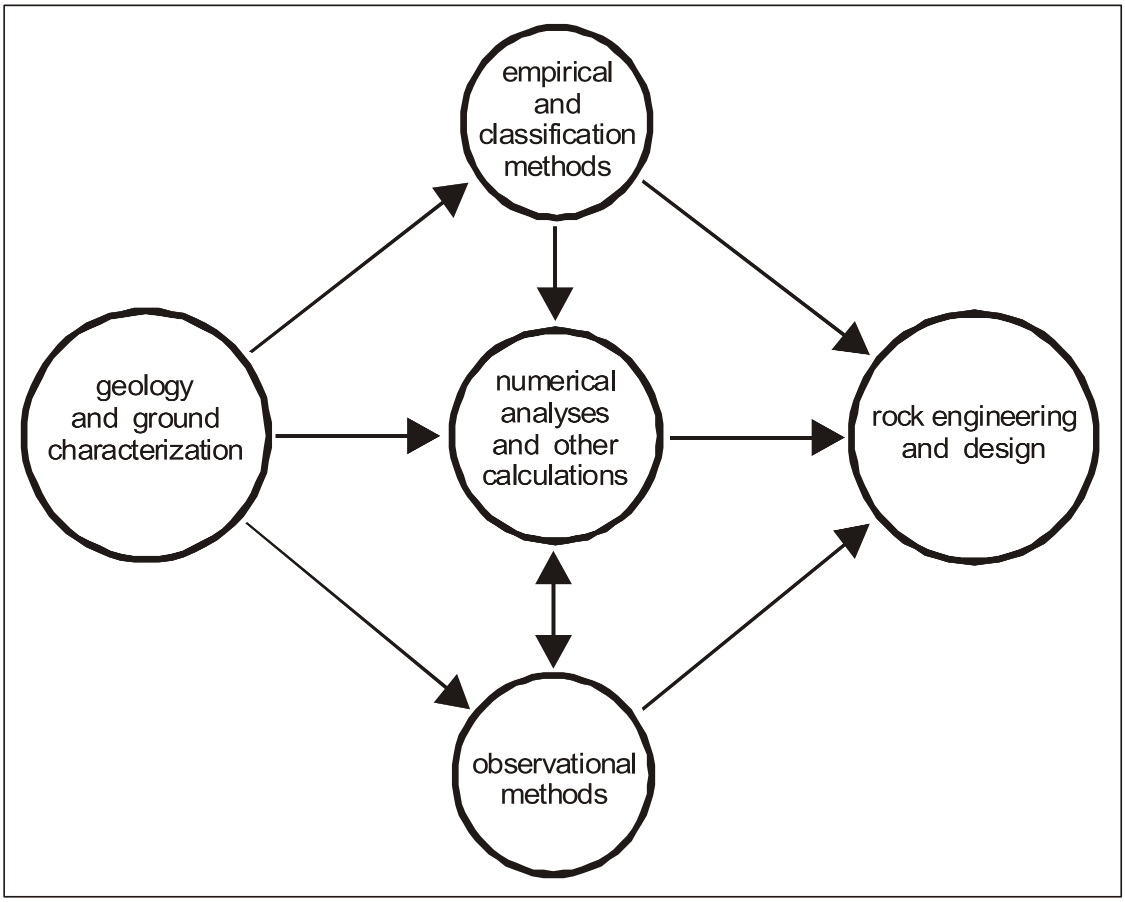


Figure 2-1 *Depending on the nature of the problem and the type of underground opening to be designed these different approaches are used solitarily or in combination.*

2.2 Risk in rock engineering

The pronounced uncertainties involved in underground construction have implied that risk analysis is a very promising tool to obtain a better understanding of the related problems. Risk analysis has been used as part of different proposed methods for better estimation of time and cost consequences of a tunnel project or for selection of construction methods and suitable working procedures to be able to adequately handle difficult and dangerous situations, see for example Einstein and Vick (1974) and Isaksson (2002).

There are different definitions of the word risk. In common language the word risk is used both for describing the probability of occurrence, the consequences of damage events as well as for the event itself. However, in risk analyses risk is defined as the combined effect of the probability of a damage event and the consequences caused by the damage event. Depending on different situation the description of risk needs to be more or less detailed.

A hazard is a threat of a potential damage event and is a built-in property of a risk object. A damage event is an unintended and (sometimes) an unpredictable event that may cause damage to humans, properties or the environment or implies disruption in an ongoing process. The damage event causes damage i.e. an unwanted consequence. The damage object is affected by the damage. The initiating event triggers a damage event. Warning bells indicate that a hazard is about to being realised, see Figure 2-2.

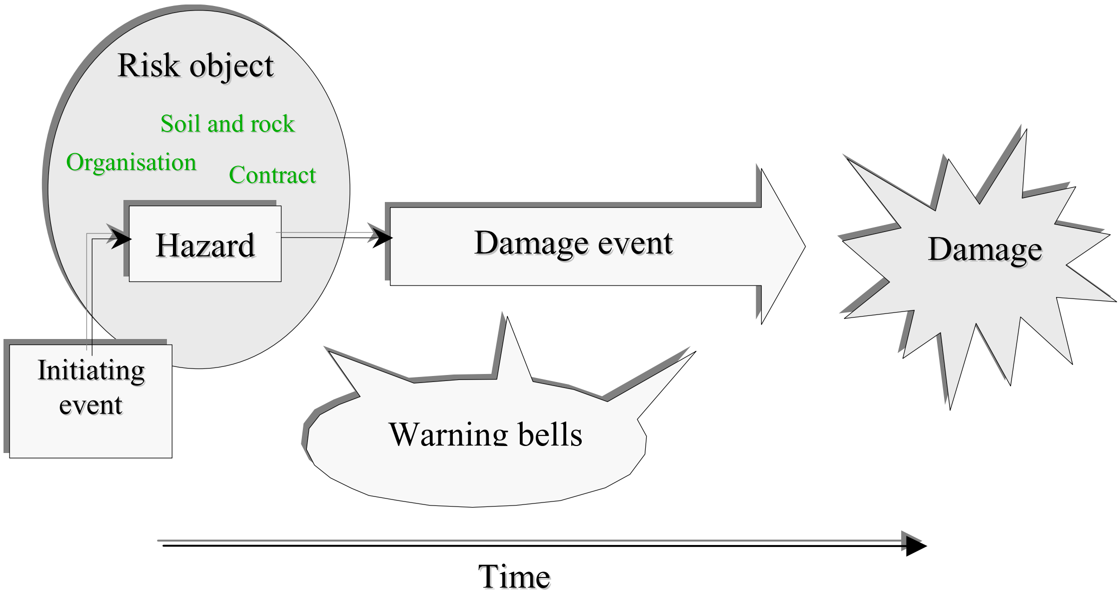


Figure 2-2 *Hazards and initiating events creates the risk (Sturk 1998)*

It is important to point out that hazards are not only related to technical matters like geology. Hazards can be found in all types of activities related to the design process. The organisation of the work or the contract for the design process may be built up in such a way that they involve potential threats to a successful completion of the design work. Such matters or obstacles have also to be analysed when identifying the problem.

Obstacles may be divided into the following groups (Stille et al., 1998):

- *General obstacles*: lack of knowledge, contractual blocking, wrongly defined demands or prerequisites.
- *Organisational obstacles*: indistinct organisation, indistinct responsibilities and indistinct working procedures.
- *Person obstacles*: lack of competence, lack of insight, prestige, human errors

It is very important that different risks are described and are communicated between the different actors or parties involved in the process. Risk management has therefore been an integrated part of underground construction. The risks related to the design must therefore be a natural part in an information based design.

2.3 The mechanical system

Design of underground opening involves different issues that have to be addressed and solved. Many of them are related to the function of the opening like the shape, cross section area and alignment of the tunnel. A very central issue is to design the opening so that the stability and safety can be guaranteed. The mechanical system of the supported opening is therefore an essential part or may be the most important one in designing an underground opening.

The mechanical system can in principle be described as an interaction between the rock mass and the installed support (see e.g. Hoek and Brown, 1980 or Brady and Brown, 1985). It can also be described as in principle an unloading situation. From an initial stress situation the excavation of the opening will create a redistribution of the stresses with unloading in the direction towards the free surface and normally an increase of stresses tangential to the surface of the opening. The stress changes will give a typical deformation pattern with movements directed towards the opening. Thus, the basic problem in designing the rock support measures cannot be analysed from the concept of constant load on the support since the load is deformation dependent.

Different types of stability problems may occur due to the complexity of the geology (building material). Four different types of instability can be described, see Figure 2-3.

1. Fallout of blocks that is generated by existing joints and weakness planes the rock. Propagating forces are the gravity and the restricted deformation in certain direction due to the local stress field.

2. General shear failure in the rock mass caused by overloading from the existing stress field. Shear failure of the type bearing capacity failure in weak side wall or roof failure due to incomplete arch formation in mixed ground come under this category.

3. Problems of instability due to high stresses. The intensity may vary from splitting, spalling, bending and buckling of slabs to explosive failure and rock burst, which may extend far into the rock mass.

4. Problems of instability due to different physical or chemical processes with the origin of stress changes or changes in water content like slaking, swelling and squeezing. This type of instability is often related to time dependent behaviour.

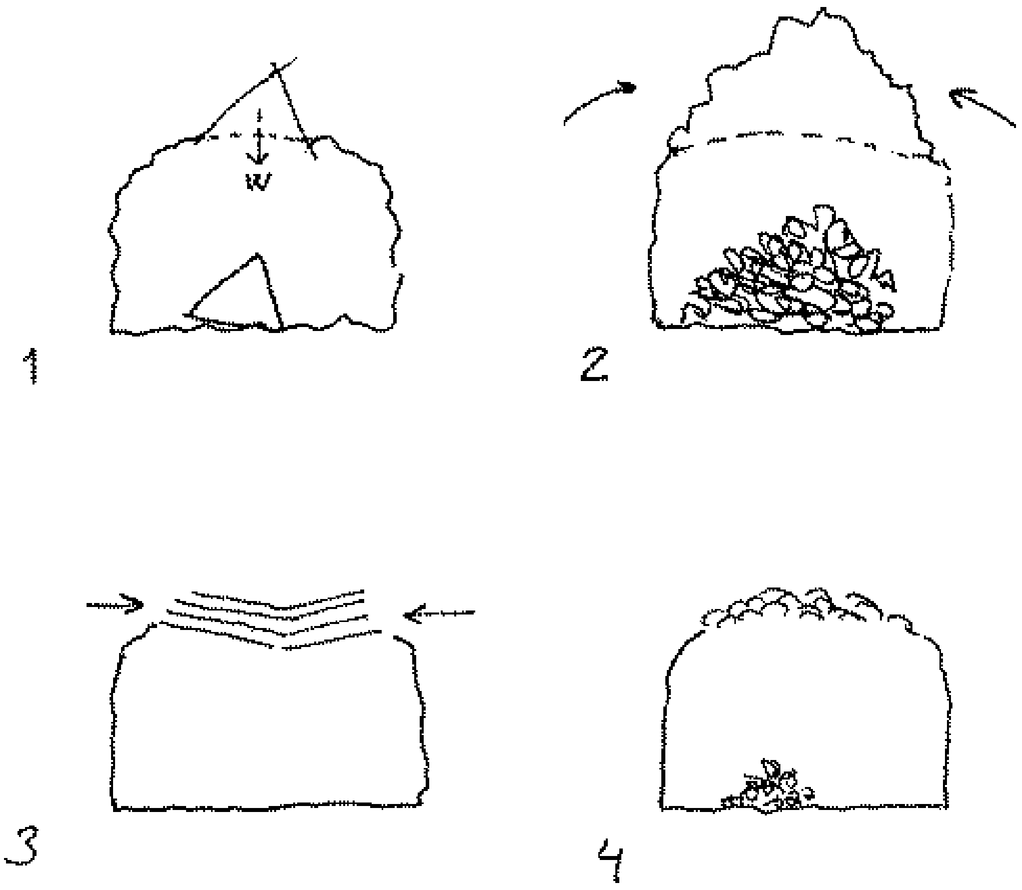


Figure 2-3 *Different types of stability problem may occur due to the very complexity of the geology (building material).*

The local instability can be regarded to be of the type “weakest link” e.g. it is the local properties of the rock mass that are governing the behaviour. The failure may be slow and related to plastic failure but normally and more often it is brittle, which may result in sudden failure without any early warning. The general instability is normally an interaction between the rock mass and the installed support. In many cases larger rock volumes are involved that give a more plastic behaviour and related to the mean value of the strength rather than the lowest value. The instability due to high stresses is normally related to brittle and sudden failure and involves releasing high levels of energy. Time dependencies of different types complicate the situation. Slaking, squeezing, swelling and deterioration with time will all in one way or another influence the design situation. Detailed knowledge of these different mechanisms is limited.

The rock support is a part of the mechanical system. The most common system used to stabilise underground opening in hard rock is rock bolting and shotcrete lining. Rock bolts are normally designed to carry tensile load but also sometimes designed for shear load. They are used to act singly or as a group, depending on the volume of the unstable area. Shotcrete lining can act as an arch carrying compressive forces or as a beam carrying bending moments. Un-reinforced shotcrete is brittle but reinforcement makes it more ductile. The combination of rock bolts and shotcrete is normally regarded as a ductile support with high bearing capacity. The combined system of rock and support measures can in many cases be regarded as a system of parallel elements, which gives a less sensitive system especially compared to a serial system like block bolt support.

The mechanical system governing the design of underground openings can be characterised by the following:

- It is in principle an unloading situation.
- The load on the support is in principle an interaction between the rock mass and the support.
- Several different modes of failure exist.
- The support can be both brittle and ductile with high bearing capacity depending of the type.
- The knowledge of the mechanical properties of the rock mass, especially its time dependence, is limited.
- The knowledge of the rock mass mechanical properties, especially its time dependent, is limited.
- The mechanical system can both be a parallel or serial system.

Given this complicated situation it may not be surprising that the design tools normally used today are subjective. However, also situations with uncertainty can be handled by more objective methods, as those presented in subsequent chapters.

2.4 Life cycle cost aspects

An underground opening is normally a part of a more general system like a hydro power plant or a railway link. The design of the underground opening is therefore one part in the system design process. It is very important to keep in mind that the design affects the use and the use affects the design. Two types of activities can be distinguished in the system operation phase: normal operation or maintenance and repair (Hazelrigg 1996).

The system reliability is an issue of increasing importance. Some systems involve inherent risks that have to be accepted by the owner or the user. For systems used by the public due concern for the user's safety is expected. This issue has to be addressed by the designer and is related to the reliability of the system or expressed in another way by the probability of failure expressed as the annual probability of failure. Important for evaluating the reliability is to consider that the structure may be built up by several building elements and that the probability of failure normally is evaluated for a single element. The correlation between the single elements is essential for the evaluation of the reliability of the whole structure.

Failure and failure recovery may be a major issue in the design and maintenance of a system. Two different strategies can be identified: a program of preventive maintenance or “fix things when they break”. Under the preventative maintenance strategy the failure has to be anticipated and remedied before failure. This strategy works well if the quality control is good and the understanding of the failure mechanism is high. In many cases warning bells are efficient in foretelling the failure. It is anticipated that in the future non-destructive evaluation methods will play an important part in foretelling the failure. When failures are not crucial to safety or the function of the system, the “fix when it breaks” strategy can lead to an economic solution.

A good technical knowledge is a prerequisite to be able to describe how the use affects the design and the design affects the use. Tools like life cycle cost analysis can be used to be able to compare different design solution that includes both the building costs and the costs during the operation phase. The decision problem of identifying the economically optimal solution may be solved within the framework of classical decision theory. The life cycle cost analysis will therefore play an important role in an information based design of underground opening in the future (see e.g. Lindquist et al, 1999 and Johansson et al, 1996).

The life cycle cost can in principle be described with the following equation:

$$LCC=LCCA+LSC+LCCC$$

Where LCC stands for the Life Cycle Cost, LCCA stands for Life Cycle Cost Acquisition and LSC for Support Cost and LCCC for Life Cycle Cost Consequence. The costs are capitalised during the lifetime of the project. However, estimating these different costs involves difficult judgements of the future behaviour and the need for reparation and maintenance.

3 Approaches to problem analysis and system identification

This chapter concerns general approaches to problem solution, applicable to design of underground openings. The key to a successful problem solution starts out with a careful consideration on what really is the problem for the system we want to analyse. This contains both problem analysis and system identification.

It turns out that many problems in design and construction of underground openings are to be regarded as very complex and concern the interaction between technology and people as briefly was discussed in chapter 2. This means that the wealth of problem solution techniques developed within 'operational analysis' is of high interest. This chapter focuses on the general approaches, whereas subsequent chapters describe some specific techniques in more detail. It must be emphasised that the key to an adequate problem solution is to consider every problem as a decision problem. Behind every solution of a problem there has been a decision where different alternatives have been evaluated and weighed against each other based on the uncertainties related to the different alternatives.

Still, there are no shortcuts. It is the author's experiences that the base for an adequate analysis of the problem is a deep understanding and knowledge of the underlying rock mechanical issues. Even if we argue for a top down approach a phenomenological description of the often complex rock mechanical issue may be a cornerstone to an adequate analysis of the problem.

3.1 What is the problem?

Problem solution starts out with a careful consideration on what really is the problem. This may seem trivial – but is not.

3.1.1 Different aspects of a rock design problem

When entering into an underground design problem the engineer may first consider the task given being quite straightforward. However, what may appear to be a simple engineering issue of, say selecting proper dimensions of reinforcement may turn out to be a wider issue on selecting construction methods, installing a proper control system or the overall design of the excavation.

In a wider perspective a simple task is usually a part of a much wider context. For example:

- The task may be perceived as just applying a building code, but underground construction is often a complex undertaking. Rock is a heterogeneous material and its spatial variability is hard to characterise from few measurements (see section 5.3). Building codes and empirical design rules may be overly restrictive in order to handle this uncertainty or, worse may in fact be misleading (see chapter 6).

- Underground design needs to consider potential technical hazards and damage events like mechanical stability, workers protection, lowering of groundwater and environmental impacts. There are also non-technical hazards related to the design. They could be of different kinds like contractual, economical (‘profits’, costs) or even political (what are the implications of a ‘failure’, c.f. Hallandsåsen). Implicit in most design tasks are (or should be) to develop means of handling hazards.
- Even if the specific task given to an engineer may be to design something quite specific, this is usually just a part of a larger project, i.e. to build a road tunnel, a water tunnel for a hydro power plant or a storage cavern. The problem and its solution may not be evident unless other parts of the system than the specific task being given are considered.
- The nature of a problem may change with time. As more information is being gathered, or events occur in other parts of the overall project the specific problem may need to be redefined.

Even if a task may seem trivial, the best solution to a ‘problem’ will depend on the attitude to the above (and similar) issues. Clearly, this is difficult if the task being given is restricted. Still a responsible engineer (and consultant) should take an overview perspective – even if someone else would be ‘responsible’.

3.1.2 Problem analysis

A problem can only be solved if we know the nature of the problem. Proper problem identification is the key to problem solution. The nature of the design problem of underground openings has been discussed in chapter 2. The rock is a very complex building material and the different design approaches are to great extent subjective.

A design task usually implies a need for identifying both technical hazards and the other types of hazards. When a specific task is given to an engineer in project, the hazard identification may not be complete. This is understandable; finding all things that can go wrong is not a simple task.

Identifying hazards requires an understanding of the mechanical stability and hydrology difficulties at stake as well as the interaction between technology and people. Close attention to coupled events is also needed.

Risk analysis and risk management are, therefore, essential tools to handle the different hazards involved in underground construction. It has been pointed out that hazards are not only related to technical matters and that an understanding of the different obstacles is essential.

It is essential to have a top-down approach. The problem is the different design issues. The problem is not that we do not have full information of the geology, something which we never will have. Pre-investigation and system to handle the uncertainties are measures to solve the problem and is not in this sense a problem in itself. To blame an unsuccessful construction of an underground opening on the fact that the pre-investigation was not adequate may direct the focus from the real shortcomings in handling the always existing uncertainties.

This fact has been very clearly been pointed out by Danielsson et al. (2002) in their analysis of the problem encountered with the tunnel project through the Hallandsås ridge. The problem was connected to the fact that the project was treated as project of implementation and not as a project of innovation that due to the uncertainties had to be the correct way. The problem was not connected to lack in the pre investigation, all the information were there in principle, the problem was connected to the handling of the inherent uncertainties coupled to the type of geology and the project.

For proper problem identification the technical project and the people involved in the project *should be assessed as an integrated system developing in time*. There are well-developed means of defining and analysing systems, which we recommend using. System analysis is part of *operational analysis*, discussed in subsequent sections.

3.2 Operational analysis

Many problems in underground construction concern the interaction between technology and people. Such problems can generally be handled by techniques developed within 'operational analysis'. Operational analysis is 'an applied, multidisciplinary, scientific approach for assessing problems of organised systems concerning technology and man, aiming for solution most beneficial to the organisation' (see e.g. Ackoff and Sasieni, 1968).

Operational Analysis developed substantially during the World wars. Mathematicians, physicists and other scientists were given the task to solve various practical military problems like convoy tactics or how to organise military units. After the wars the credit (and experience) gained made operational analysis popular in civil applications like production planning, marketing strategies or urban development planning.

For any civil engineering project operational analysis provides insights in the overall issues and strategy for handling a project. Specifically, experiences gained are useful as regards:

- Actors – who is affected (directly or indirectly) by the project?

- System and system identification – what is the problem about and what lies outside the project?
- Methods and models – how to analyse a problem?
- Uncertainty, risk and the decision to find an optimal solution.
- Communication.

This will be further outlined in the text below. Operational analysis is described in many text books.

3.2.1 Actors

Any construction project concerns interaction between several different groups of people. Some are directly involved like client, contractors, consultants etc. Other are indirectly involved as they may be affected by the project, or have influence in decisions. Examples of the latter category include resident potentially affected by hazards, other local residents, the general public, 'the taxpayers', different associations, NGO:s (literally 'non-governmental organisation' or usually 'green groups' etc.), etc. The different groups of people of some relevance to a project/problem are generally called '*actors*'. The actors constitute a wider group than directly affected stakeholders.

The problems to be solved may not appear the same for different actors – and the different actors also have various ways of influencing the problem or its solution, both directly and indirectly. The client wants to conclude the project within time and budget. The contractor needs to make a profit. Workers (and of course also the contractor) need to be assured that hazards are properly handled. The general population wants the tunnel to be ready for use, whereas people living close to the construction work are interested in low impacts.

It should be asked whether:

- all important actors are identified,
- to what extent the problem definition and solution consider the concerns of the different actors
- to what extent the problem assessment is (and should be) communicated to different actors.

Identification of actors and actors needs is an essential part of the problem identification.

3.2.2 System and system identification

Underground construction projects should be seen as a system (Figure 3-1). Once the components of the system, its interactions and its boundaries are understood, the solution to the problem is often straightforward. For example, a problem may first just be seen as designing the dimension of rock bolts, but a wider assessment of the construction problem as such may reveal that the reason for potential instability is a concern over the thickness of the rock overburden. Alternative approaches may thus be to obtain better information on the position of the rock surface – or to redesign the depth of tunnel.

There are many engineering applications where experience is substantial and where good practices are developed. There is no need to conduct a system analysis in these cases. However, when conditions are new or changed or when potential consequences are grave, one cannot take old experience for granted.

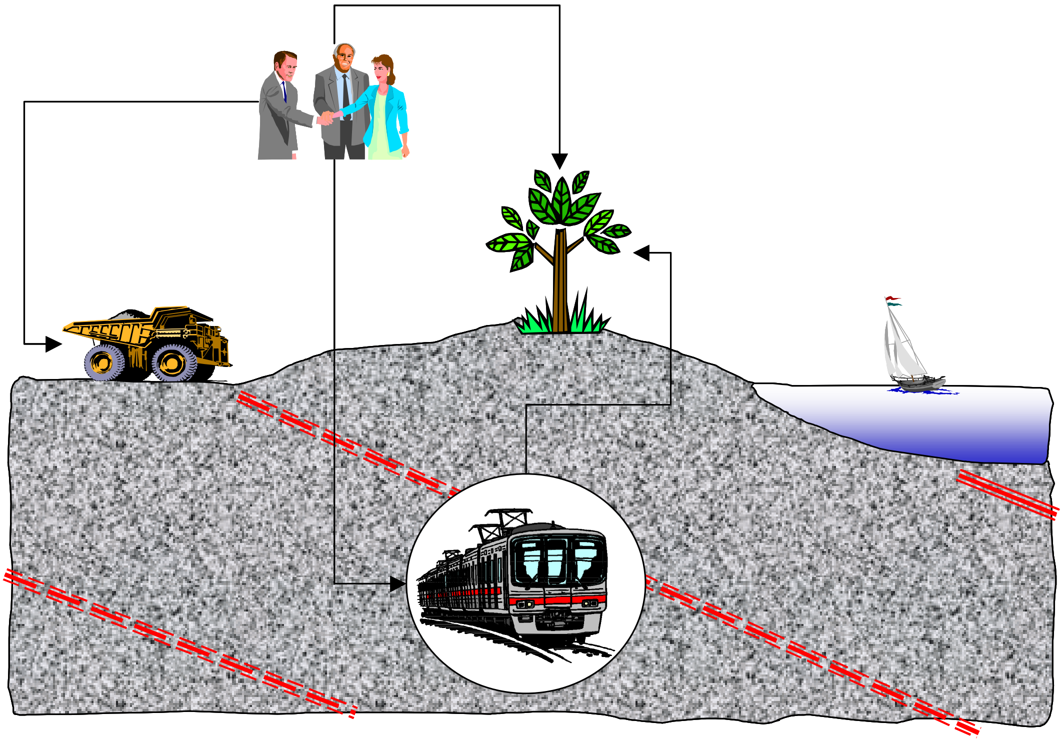


Figure 3-1 *Underground excavation problems should be viewed as a system involving the interaction between various natural processes (mechanical, hydrological, etc..), with the technical process (the construction work), the environment as well as interaction with people.*

System identification

Generally, a system is an entity, which consists of different parts interacting though processes and event. The relations – the interactions – are at least as important as the individual parts. IEC 300-3-9 provides the following definition

"***System:** Composite entity, at any level of complexity, of personnel, procedures, materials, tools, equipment, facilities and software. The elements of this composite entity are used in the intended operational or support environment to perform a given task or achieve a specific objective. (IEC 300-3-9)"*

Examples of systems in underground construction include:

- A tunnel with the interacting parts: surrounding rock, history of construction, reinforcement, groundwater pressure, grouting, rock stress, tunnel stability, ingress of water etc.
- The tunnel construction project with the interacting parts: design, construction work, environmental impacts, costs, consultants, local inhabitants, contractors, etc.

It needs to be understood that the system is a conceptual construction, the same physical objects may be framed in different system descriptions depending on who is describing the system and for what purpose. All interacting parts cannot be identified, this would eventually lead to a need to describe the total universe.

The following questions should be addressed when identifying the system:

- Function: What is the purpose of the system?
- Components: Which are the main components of the system – and how do they interact?
- Environment: How can the system affect its surroundings and how do surroundings affect the system?
- Resource: What is available for the system to fulfil its function?
- Management: Who are in control?

System identification can usually be divided into defining *state* variables and *interactions*. The state variables concern the conditions to be described, for example rock stress, rock mass deformation properties, tunnel geometry, water pressure or tunnel stability. These states interact with each other through different processes such as deformation, cracking, water flow etc. Evidently, it is not possible to find all possible interactions, but all relevant should be identified. If an important interaction is overlooked – the resulting 'solution' to the problem may be misleading.

Identifying system components and interactions is a judgmental process. However, there are several tools, which help structuring the logic in this process. An important example of such tools is the interaction matrix, which will be further discussed in the next chapter (chapter 4).

System boundaries- the system environment

All interacting parts cannot be identified; this would eventually lead to a need to describe the total universe. An essential part of system identification is to define a proper system boundary.

Selecting a proper system boundary is crucial for a good problem definition, but also for the subsequent assessment of the problem. Inside the system all (relevant) interactions need to be described – whereas the outside is just seen as an environment. A good system boundary is one where the system environment is simple and well defined. The situation may well be compared with software engineering who is responsible for the internal operation of a routine, but want to achieve a clear an unambiguous input and output definition.

For example, if in a design phase the system is restricted to the rock reinforcement, whereas tunnel size and orientation is left outside the system (e.g. to be handled by another consultant) may lead to poor overall solutions. At least, subdividing a system into many subsystems may lead to complex negotiations with the team in control of other parts of the overall system. Too wide system boundaries, on the other hand may lead to very complex systems – hard to evaluate.

For reasons given, assessing and controlling the system boundary is essential, even if there may be administrative restrictions on what a single consultant may do. It should also be recognised that the proper selection of system boundaries may change during the course of the project. In early phases overview is essential, whereas later on many decisions are made and it is necessary to focus on the details of specific parts. On the other hand new insights or new developments may necessitate a widening of the system boundaries once more understanding of the overall problem is reached. This is an important interface to risk management in general.

What may happen?

The system evolves with time both due to gradual processes occurring in the system and due to initiating events. For example, the future tunnel stability would be effected by the gradual degradation (corrosion) of the re-enforcement, but may – at least in more tectonically active regions – change as a consequence of an earthquake.

Understanding the future evolution is necessary for the design as it may set requirements on the construction. A typical example could be the need for evacuation shafts in road tunnels. These needs are based on assessing risk for accidents and subsequent evacuation needs. The future conditions, which need to be considered, are usually specified by the client or is given by codes. But in other cases the situation may be less evident.

Generally, an exact prediction of the future is an impossible task, but exact predictions are seldom needed. For complicated system, the scenario approach may useful. In order to get a handle on the future evolution a set of plausible future events and conditions are selected and the resulting evolution is then explored. Each such selected possible future chain of evolution is called a scenario.

It is important to understand that the design process also involves the operation of the opening and the maintenance of the facility. Life cycle cost analysis (LCC) may be a tool to be used to describe the future costs.

A crucial element in scenario analysis is also to select initiating events and conditions. This can in fact only be made from expert judgement and experience. Still, there are formal techniques for making such selections, for example within the areas of Safety Assessments of nuclear waste repositories (see SKB, 1999).

3.2.3 Methods and models

Once the system is described in overall terms, further analysis usually requires a model of the system. Generally a model is an analogue to the object on which knowledge is sought for. Models are necessary, since they can be explored and assessed instead of the objects themselves.

Especially in underground construction every project has unique components since information on the rock is limited. The information is mostly indirect (evaluation seismic signals, well tests etc), is based on a very small volume of the rock of interest (a few boreholes) and rock properties vary in space (see further section 5.3). This makes it necessary to formulate a model of the rock. All persons involved in rock construction projects have their model of the rock, but it is essential to understand that they are just models – not reality.

Assessing consequences of decisions in the system also require model analyses. Such analyses could be simple and qualitative or involve complex quantitative numerical analysis. Chapter 6, will discuss some methods for assessing system reliability like the ‘beta-method’, ‘partial coefficients’, and related codes. Rock mechanically stability may be assessed though empirical methods or complex FEM-analyses.

In selecting methods of analysis it is essential to remember that ‘the problem should select the tool’ and not ‘select a problem for a tool’. In some cases a simple analyses is what is needed. Sometimes the focus should be on overview and high degree of creativity. In other cases careful and accurate numerical analysis is required for answering a specific issue.

Complex problem could require assessment using different methods and models. Different methods are made from different perspectives, which can yield different important aspects to the ultimate problem solution.

3.2.4 Uncertainty, risk and the decisions needed to find an optimal solution

Problem identification and solution is complicated by the fact that parts of the system and its evolution will always be unknown. In a complicated system, like an underground construction problem, there is usually more than one way to solve a problem. The question then arises on how to select the 'best' or at least avoid the really unfavourable ones. Uncertainty about the system and uncertainty about its future evolution make the choices even more unclear. In operational analyses such problems lie under the headings of 'optimisation' and 'decision under uncertainty'. Some basic features of this will be discussed here, but the specific recommendations as regards underground design and construction will be dealt with in detail in the remaining chapters.

Decisions

In operational analysis decisions may fall into three broad categories:

- Decisions made under *certainty*: The consequence of a decision is (indisputably) known,
- *Risk based* decisions: A decision may lead to several outcomes, but the probability and the consequence of these outcomes can be estimated.
- Decisions made under (genuine) *uncertainty*: All outcomes of a decision cannot be foreseen.

True-life decisions are a mixture of all these three categories. In system analysis engineering decision analysis are usually risk based. This is the underlying philosophy behind decision trees (see chapter 6) and reliability analyses (see chapter 7). Such approaches may seem to forget the other types of decisions, but in reality many situations can in fact be handled with risk based analyses.

Decisions made under certainty are evidently just a special case of risk based decisions, were the consequence has the probability of one. Decisions under uncertainty are more complex, but there are several cases where consequences or probabilities can be bounded (i.e. 'it cannot be worse than'). Other controls may be the installation of surveillance and control system as will be discussed in chapter 8.

Estimating and handling uncertainties and probabilities is essential for the decision making. This will be further discussed in chapter 5. If uncertainty estimates are poor their impact on the decision could also be explored by sensitivity analysis. How much need a probability of an outcome be changed for a decision to be altered?

Finding an optimal solution

Optimisation and decision analysis regards finding a course of action, which will optimise an object function. Usually the object function is coined in monetary terms. For example, a decision tree (see chapter 7) may help to explore various decision paths and to assess various outcomes depending on the probability of different events supposed to have an impact on the object function. While such decision analysis is strongly advocated, there is also a need to be careful about the object function.

In reality, there are usually more than one objective and some may in fact not be well known – or understood. Streamlining a system with regard to a very narrow object function may lead sub-optimisation. (A ‘classical’ example is the planning of appointments to a doctor. If the object function only considers making the most use of the doctor it is optimal to plan bookings such that the waiting room always is full. If also the lost work of waiting patients are considered this may no longer be true).

Underground construction problems have multiple objectives, which also change in relevance for the different actors involved. For example:

- maximising profit,
- minimising construction costs,
- minimising construction time,
- avoiding ‘bad-will’ events,
- minimising life cycle costs
- etc.

Operational analysis provide different approaches for handling multiple objective decisions (see e.g. Ackoff and Sasieni, 1968). These methods will not be further discussed here. However, even if the object function ultimately is coined in monetary terms there is nevertheless all reason to be careful on its formulation – in considering which factors (e.g. see the points above) it should include. This is particularly true if the assessment includes aspects of genuine uncertainty or if consequences are extremely high in relation to their probability. As a rule of thumb one should never simply let the outcome of decision analysis determine the decision. The decision must make sense.

3.2.5 Communication

Problem formulation and assessment are useless unless they are properly communicated to the ones concerned. Part of the problem assessment thus needs to be spent on the communication between the different actors involved. Essential elements in this are the understanding of the objectives of the study, assessment of actors' concern and understanding the different actors' frames of references ('paradigms'). Objectives of the study as regards communication could for example be to:

- give advice,
- convince,
- initiate a discussion,
- create a language,
- provide frames,
- warn,
- provide arguments,
- distribute responsibility.

Clearly, more that one of these could be valid in a given study.

It is also essential to understand the concerns and frames of reference of the different actors (see section 3.2.1). Among other things, successful communication rests on the answers to the following questions:

- Are the important actors identified?
- Are the needs and concerns of the actors assessed in a dialogue between the actors or is the study based on you 'own needs'?
- Are there true differences in the frames of references ('paradigm') of the different actors and how are they handled?

It needs to be understood that, for example, a theoretical scientist, a rock mechanics trained civil engineer, a company director, politicians or regulators do not see the world exactly the same way. They have different vocabularies, different knowledge and different experiences. Models of thought like rock mechanics, budgets, 'ill-being', or contracts all have their merits and pitfalls. Yet, in complex projects, decisions are made by such a diverse group of people. Handling communication, dialogue between actors and a clear understanding of responsibilities are essential components in any large project.

It may be concluded that communication or the flow of information play an important role in decision making throughout an underground project. In order to utilise the information properly the following requirements have been proposed (Sturk 1998).

- The information must be adapted to current decisions and current project stage.
- Uncertainty related to the information should be quantified.
- Information must be understandable and should flow properly through the project organisation.
- The information should be quality assured.

A prerequisite for a good communication is an understanding of the obstacles that can prevent the intention of the communication. The obstacles may be divided into general obstacles, organisational obstacles and person obstacles as discussed in section 2.2.

3.3 Conclusions

What we want to emphasise in this chapter is the importance to use a top-down approach in order to define the problem and also enhance a free flow of essential information through the project. Good engineering is based on a phenomenological understanding and description of underlying rock mechanical issues and the ability to communicate it with the different parts involved in the project.

An essential part is also to clearly define proper system boundaries and the system environment. Many of the problems we have faced with construction of underground openings lately are to great extent related to poorly or wrongly defined boundaries. These boundaries can both be of technical nature and of other types like organisational boundaries.

An example of this is the caverns and tunnels where the ingress of water to the opening has created an unacceptable environment for the installations without getting an unacceptable lowering of the ground water table. The problem to avoid an unacceptable lowering of the ground water table and related ingress of water to the opening is normally carried out by a hydrogeologist without any knowledge of the demands the installation has on the humidity. On the other hand the design of the installation is carried out by a mechanical or electrical engineer maybe without any experiences of the humidity encountered in an underground opening. There are cases where the ambition to reduce the construction costs especially the activities on the critical line like pre-grouting has created high costs for maintenance due to more a high humidity than to large ingress of water.

4 System analysis

As discussed in previous chapters it is efficient to view a problem as a system. The system description provides the structure for the decision analysis and analysing the system is necessary for reliability analysis and design, which will be discussed in chapter 6. This chapter discusses methods for system identification by interaction matrices and how the system behaviour may be explored through fault and event trees.

4.1 System Identification

As discussed in chapter 3 a system analysis approach is key to the problem identification. A system is an entity, which consists of different parts interacting though processes and event. The relations – the interactions – are at least as important as the individual parts. Examples of systems in underground construction include a tunnel with its interacting parts, a tunnel construction project where also interactions with organisations are involved etc. (see section 3.2.2). It needs to be understood that the system is a theoretical concept, the same physical objects may be framed in different system descriptions depending on who is describing the system and for what purpose.

The system identification can be made by different means. In simple cases reasoning and assessment of the key factors of the mechanical system to be analysed (see chapter 2) may be sufficient. However, in other cases the system may contain many different parts, whose interactions are not evident.

Examples of more complex systems include underground excavations in complex environments e.g. high rock stress situations or volcanic regions, facilities with complex functions like nuclear waste repositories, gas storage facilities, etc. and projects with substantial interactions between different actors, contracts and technical constraints. In such cases more formal approaches for system identification could be used.

4.1.1 The interaction matrix

An important example of formal methods for system identification is the *interaction matrix approach* introduced by Hudson (1992). (Harrison and Hudson, 2000, provide a more pedagogic description of the method). In Sweden this and the similar approach “influence diagrams”, has mainly been used within the nuclear waste area (see e.g. Eng et al., 1994, Chapman et al., 1995, Andersson and King, 1996, and SKB, 2001) but interaction matrices are certainly useful outside this area. In fact, interaction matrices were used in planning the Österleden tunnel (Stephansson et al., 1994). Still, there should be reason for a wider use of the method.

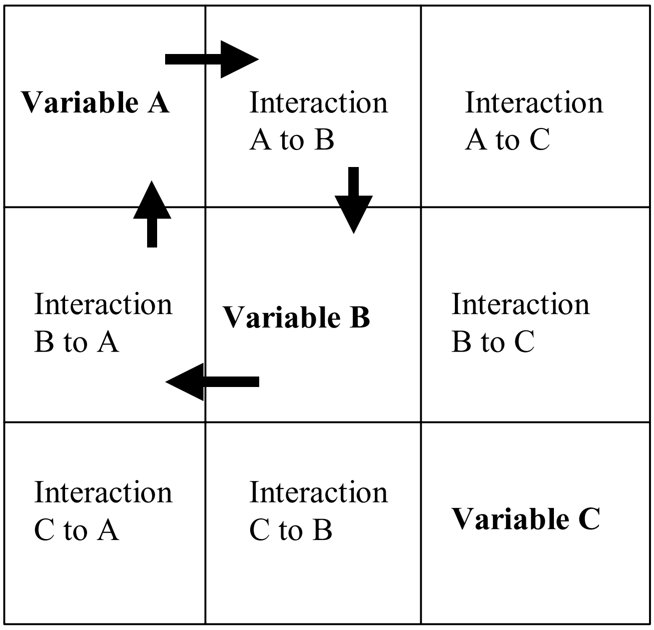
System identification can usually be divided into defining the state variables with system boundaries and identifying the interactions between the state variables. The state variables concern the conditions to be described, for example rock stress, rock mass deformation properties, tunnel geometry, water pressure or tunnel stability. These states interact with each other through different processes such as deformation, cracking, water flow etc. Evidently, it is not possible to find all possible interactions, but all relevant should be identified. If an important interaction is overlooked – the resulting ‘solution’ to the problem may be misleading.

The basic principle of an interaction matrix is to list the parameters defining the properties and conditions in the physical components of the system studied along the leading diagonal elements of a square matrix, see Figure 4-1. Events and processes that are influenced by and affects the properties and conditions defined in the leading diagonal elements of the matrix occur in the off-diagonal elements of the matrix.

The development consists of the following steps:

- Selecting State Variables
- Identifying Interactions
- Ranking of importance

All steps and decisions should be documented.



Variable A	Interaction A to B	Interaction A to C
Interaction B to A	**Variable B**	Interaction B to C
Interaction C to A	Interaction C to B	**Variable C**

Figure 4-1 *The principles of an interaction matrix. The diagonal elements represent system state variables such as rock stress, rock mass deformation properties or tunnel geometry. Interactions (i.e. “processes”) between the variables are listed in the off-diagonal elements.*

4.1.2 Selecting State Variables and System Boundaries

The first step is to select parameters required to describe the properties and conditions in the physical components of the system and to list them in the leading diagonal elements of the matrix (see Figure 4-1). This is done by exploring how the system state can be described in terms of physical components, spatial and temporal extension of the system and initial and boundary conditions of the system.

Selection of the diagonal elements should be done with care. It has been found practical to let the diagonal elements to represent system state variables such as rock stress, rock mass deformation properties, tunnel geometry, water pressure or tunnel stability and not by processes. Processes should be listed in the off-diagonal elements of the matrix, i.e. a state variable affect another state variable though a process!

Also the selection of diagonal elements clearly defines the extent of the system and its boundaries. (The off-diagonal elements describe the interaction inside the system). Usually it is also necessary to let the last diagonal element to represent the system boundary, in order to take care of interactions outside the system.

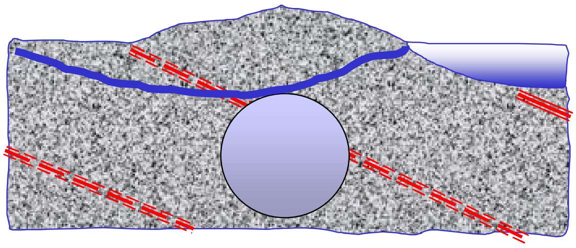
Example of state variables may be “ground water level” and “Water ingress to the tunnel”. The humidity in the tunnel may be the last diagonal element and as such define the system boundary to the condition for the installations.

An important example of the setting of the system boundary can be taken from designing bridge support. It is not uncommon that the contract situation in bridge design introduces a contractual system boundary between the rock surface and the bridge pillars. Still, in describing the rock there is a need to represent this boundary with its position and loadings. Furthermore, assessing the interactions in this system would probably reveal that many highly important interactions would be to and from these boundary variables. By expanding the system boundary to also include the bridge itself may place these interactions inside the system – resulting in a better understanding of the mechanical system, although at the price of a larger interaction matrix.

4.1.3 Identifying Interactions

The second step is to identify the binary interactions between the diagonal elements, by going through all off-diagonal elements in the matrices, using a clock-wise convention for the direction of the interaction (see Figure 4-1). All interactions should be binary, i.e. they should be direct interactions between variables in two diagonal elements and not a path via a variable in a third diagonal element. Examples of interactions are deformation, cracking and water flow.

The identification process works systematically with all off-diagonal elements. For each such element the question is asked whether there are any potential events or processes that are affecting any of the variables assigned to the target diagonal element and at the same time are affected by any of the variables in the source diagonal element. If the answer is yes, a short description of the interaction should be documented together with the variables in the two leading diagonal elements that are involved in the interaction. If the answer is no, this is also documented and if possible also the reason for not finding any interacting event or process. For example, if the physical components defined by the variables in two diagonal elements are physically isolated, there is no direct dependence between the variables in these diagonal elements. This does not preclude that the variables may be indirectly dependent via a path involving additional diagonal elements. For example if the state variables are "ground water level", "rock permeability" and "ingress of water" the interaction is the relationship describing flow in rock (see Figure 4-2). The drainage system to be used in the tunnel is the corresponding interaction between ingress of water and the humidity in the tunnel.



Ground water level		Ground water flow	
Ground water flow	**Rock permea-bility**	Ground water flow	
Ground water flow		**Ingress of water**	Drainage
			Humidity

Figure 4-2 *For the state variables are "ground water level", "rock permeability" and "ingress of water" one interaction is the relationship describing flow in rock.*

4.1.4 Ranking of importance

The last step is to judge the importance of the interactions using a pre-defined priority scale for the problem at stake. The question should be asked whether the interaction is crucial, relevant or only marginally import for assessing the relevant performance of the system. A simple colour coding (red, yellow, green) could be used for displaying this.

The prioritisation could thus be an effective means of bringing down the complexity of the system description such that it focuses and the important aspects of the problem. However, one should note that the *prioritisation is problem dependent*, i.e. the question on importance is made in relation to the problem being analysed and usually also *subjective*. Experience is needed to make proper priorities. For example the ingress of water to a hydro power tunnel may be less important than the ingress to a road tunnel in urban areas.

4.1.5 Potential uses

The first, and perhaps most important, advantage with setting up the interaction matrix is that it focuses the mind on the problem to be solved. When different experts are involved it is an effective means of communicating expertise among the participants. Furthermore, it is a good way of testing appropriate system boundaries. A proper selection of state variables clearly affects how easy and logical it is to set up the matrix. Also if the system boundaries are too narrow, too many interactions will occur across the boundaries of the matrix. This means that the process of setting up the matrix provides general system understanding.

Secondly, the interaction matrix offers the basic structure for modelling the system. In case the system is to be described by mathematical models or computer codes it can be checked that the model actually contains the state variables and the interactions needed. For example, in setting up a fault tree (see section 4.2 below) the interaction matrix can be used to check possible routes of evolution - is there at all a mechanism that could lead to that a change in a state variable would affect another variable. Usually it is easier to first try to answer such a question (e.g. during an interaction matrix set up) than to directly provide a valid mathematical formulation of the interaction.

An important example of the setting of the system boundary can be taken from designing bridge support. It is not uncommon that the contract situation in bridge design introduces a contractual system boundary between the rock surface and the bridge pillars. Still, in describing the rock there is a need to represent this boundary with its position and loadings. Furthermore, assessing the interactions in this system would probably reveal that many highly important interactions would be to and from these boundary variables. By expanding the system boundary to also include the bridge itself may place these interactions inside the system – potentially resulting in a better understanding of the mechanical system, although at the price of a larger interaction matrix.

It is also possible to conduct more formal analyses. Hudson (1992) and Harrison and Hudson (2000) suggest different ranking methods etc. However, the highest value of the methodology is probably the insight it provides, as discussed above. Even projects without resources of elaborate documentation and procedural efforts (like those applied in the radioactive waste projects) would benefit from short, more informal, use of the method.

4.2 Fault trees

4.2.1 Basics

Fault trees are tools to help the analyst answer two related questions:

- What chains of events can lead to a specified (usually undesired) event?

- How probable is the specified event?

For further reading see e.g. Ang and Tang (1984), Rausand (1991).

The fault tree illustrates the (binary) logic of chains of events staring from some initiating event (basic event) and working up to the specified top event. For example, the top event (i.e. the “fault”) may be fallout of a rock block. This may occur if the following basic events all occur: i.e.

i) fractures form kinematically possible key blocks,

ii) the weight exceeds the friction forces,

iii) failure of reinforcement (if existent).

A very basic fault tree is shown in Figure 4-3 with four events that each (singly or in connection with another) can be the staring point of a chain leading to the top event.

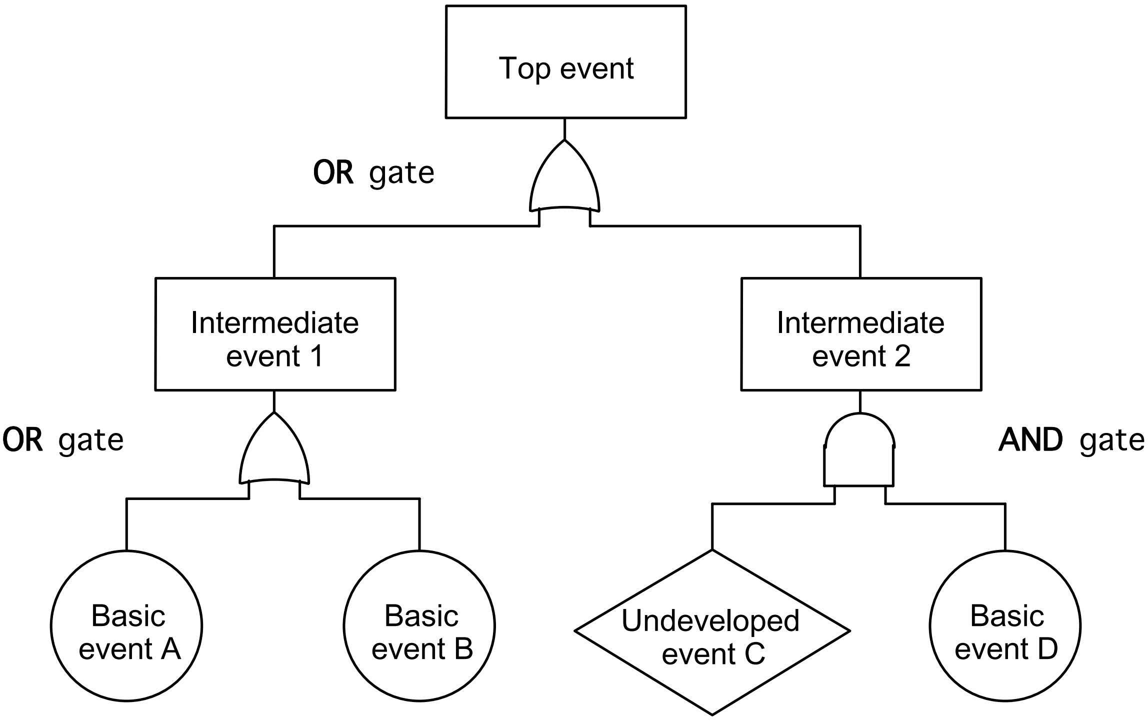


Figure 4-3 *Basic fault tree*

To describe the logic in the tree, gates are used. Figure 4-3 only illustrates two basic types: AND-gates and OR-gates. For the AND-gate, both “incoming” events must occur if the chain of events shall not be broken, for the OR-gate it is sufficient if one event occurs. The basic events are such that their probability can be estimated, whereas "undeveloped events" are such which in turn depend on a series of additional sub-events.

The different chains of events, which all lead to the occurrence of the top event, are called cut sets. In the example above three cut sets can be identified, see Figure 4-4:

Cut set 1: Basic event A occurs

Cut set 2: Basic event B occurs

Cut set 3: Undeveloped event C and Basic event D both occur

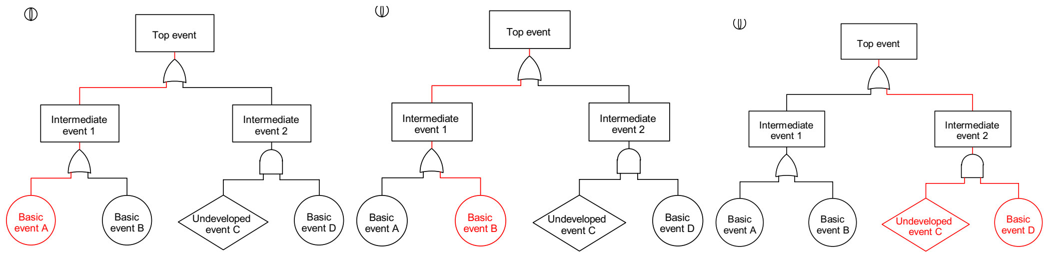


Figure 4-4. *Cut sets are chain of events leading to the top event. In the example there are three cut sets.*

4.2.2 Quantifying fault trees. Calculating probabilities

In the previous section the fault tree illustrated was a *qualitative fault tree*, i.e. it had no probabilities assigned. Such trees are very valuable on their own for illustrating and analysing systems and often the analysis is not carried further. However, fault trees can be used to calculate the probability of the top event. Such trees are called *quantified fault trees*.

If probabilities can be assigned to the bottom events (basic events or undeveloped events) all other probabilities can be calculated. The calculation for the example fault tree is shown in Figure 4-5.

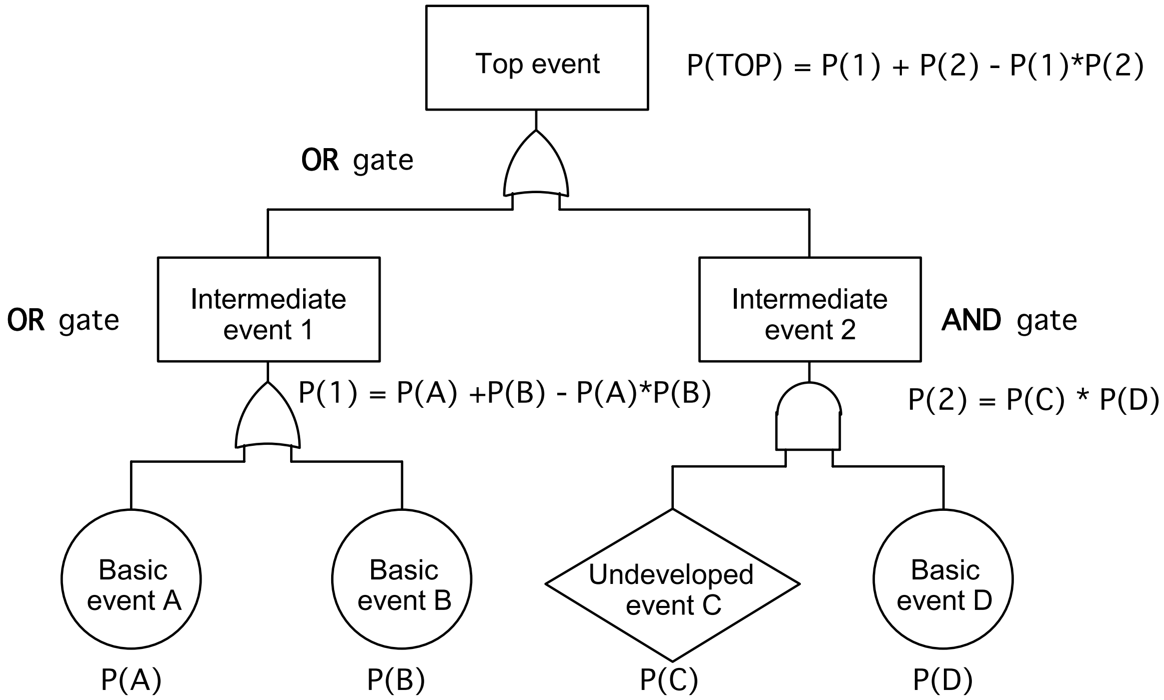


Figure 4-5 *Quantified fault tree*

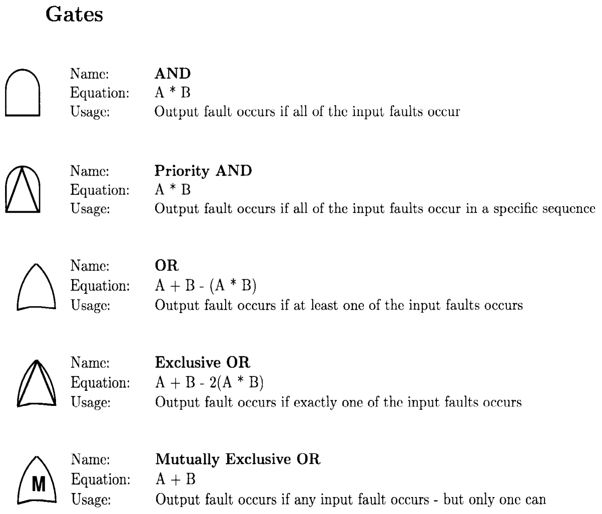
When a fault tree is quantified one can calculate measures that describe the relative importance of basic events and cut trees, i.e. perform a kind of sensitivity analysis of the system.

4.2.3 Construction of fault trees

Constructing fault trees it is ‘top-down’, starting with the top event, although the evaluation of a fault tree proceeds bottom up. The following steps are used:

- Start with the top event.
- List all events that can directly lead to the top event.
- Go down one level and repeat the above step for the intermediate events and so on.

One shall aim to finish one gate before going on to the next. Furthermore, all events must be clearly defined. Any ambiguity might lead to misunderstandings and errors. For most of practical modelling the basic gates are sufficient, but there are other that can be useful, see Figure 4-6.



Name: **AND**
Equation: A * B
Usage: Output fault occurs if all of the input faults occur

Name: **Priority AND**
Equation: A * B
Usage: Output fault occurs if all of the input faults occur in a specific sequence

Name: **OR**
Equation: A + B - (A * B)
Usage: Output fault occurs if at least one of the input faults occurs

Name: **Exclusive OR**
Equation: A + B - 2(A * B)
Usage: Output fault occurs if exactly one of the input faults occurs

Name: **Mutually Exclusive OR**
Equation: A + B
Usage: Output fault occurs if any input fault occurs - but only one can

Figure 4-6. *Examples of fault tree gates*

Fault trees tend to be rather large. It is often to advantage to split the fault tree in parts so that it is more well-arranged. These parts can be connected together using transfer in and transfer out functions that are features of most software for fault tree construction and analysis.

The question of how and when to stop further developing of the tree is not easy to answer. If the tree is to be quantified, it must necessarily be developed so far that events of which one knows the probability (basic events) are included. If it is to be a qualitative tree, it is more a question of engineering judgement and experience.

If a system is well understood, construction of a fault tree should be relatively straightforward, but usually fault trees are used when then system is poorly understood. Fault tree analysis may then be seen as an alternative means of system identification. The structured approach in exploring origins of events often focuses the mind onto the critical system components and interactions. However, in case the system is very poorly understood, it may be worthwhile to first spend some effort on system identification only, e.g. using interaction matrices. This may result in more logical structure and fuller understanding of potential sub-events, which may lead to the top event etc.

4.3 Event trees

Event trees are used to analyse a system staring with an initial event, which is considered to have occurred. From that event possible subsequent events are modelled as branches leading up to the consequences if the chain of events follows that particular branch.

What path the chain of events will follow is governed by chance nodes in the tree, where the “state of nature” is described as the probability of each branch leaving the node will be the one followed. An example showing the basic elements is shown in Figure 4-7.

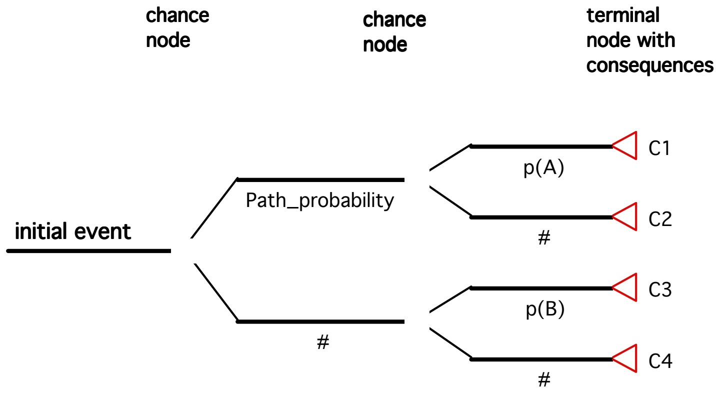


Figure 4-7. *Event tree*

One can see the similarity between event trees and decision trees, which will be discussed in chapter 7. Event trees will therefore not be discussed in any detail here.

As with fault trees, event trees can be *qualitative*, showing the structure of the system, but with no evaluation of probabilities and/ or consequences or they can be *quantitative*, with evaluated probabilities and consequences.

When evaluating the probabilities in an event tree, one can make the observation that we are searching for the probability of a specified event. Often it is advantageous to use a fault tree to find this!

It should be observed that when evaluating a quantitative event tree in the same manner as a decision tree, one would get a conditional (on the initiating event occurring) expected loss. This is just a mathematical construct, which cannot occur in the real world. The possible outcome is one of the branches and to get a true picture of the system one should show the possible outcomes together with the branch probabilities.

4.4 Conclusions

In this chapter different methods have been described in order to identify the system and how to establish the interaction between different components of the system. It is the authors' experiences that these methods will help an engineer to get a good overview of the often complex problems encountered in rock engineering due to the logical structure of the methods. They can also facilitate to define the boundary of the problem and thus give valuable input to define which essential information that has to flow through the project.

These methods reflect the way an experienced engineer is thinking but may facilitate the communication. It is important to emphasise that a requisite to be able to adequately define the system is a good knowledge in rock mechanics and engineering geology.

In order to get a first overview of a problem the methods are used in a qualitative manner. However, combined with a probabilistic description of the uncertainties and a reliability analysis they will be real powerful instruments to help the decision making during the progress of an underground project. These aspects will be discussed in the coming chapters.

5 Uncertainties and probabilities

This chapter discusses uncertainties and probabilities. It provides some tools for how to describe uncertainties. As discussed in previously many design situations can be handled by risk based analyses. It implies that the uncertainties have to be expressed in terms of probability. This involves several considerations that have to be addressed, as for example how uncertain and spatially varying properties may be averaged in different design situations. Handling and describing uncertainties is thus essential for proper decision analysis as will be further discussed in Chapter 7. However, even if the risk analysis requires quantitative uncertainty estimates, there are many decision situations where rough uncertainty estimates are sufficient.

There are different kinds of uncertainty; some can be quantified into probabilities, whereas others are less quantifiable. The chapter will start discussing different types of uncertainty and how they could be dealt with. The majority of the chapter then goes on and discusses practical approaches for handling quantifiable uncertainties, i.e. such that may be described by probabilities etc. Finally, the implications of spatial variability and various means of describing spatial variability are discussed.

5.1 Different kinds of uncertainty in rock engineering

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 system or its components sufficiently well for the issue at hand.

Depending on the origin or ‘nature’ of the uncertainty, it may be grouped into different categories. An often used division is *scenario uncertainty*, *conceptual or model uncertainty* and *data uncertainty*. Another way to categorise uncertainties is into *aleatoric* uncertainty (natural variability) and *epistemic* uncertainty (uncertainty due to ignorance). Of these, information gathering can only influence the epistemic uncertainty (but spatial variability also influences ignorance).

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 quantification by e.g. stochastic models, and into parts which may need other treatment.

5.1.1 Scenario uncertainty

Scenario uncertainty of a system, such as an underground excavation project, is generally the part of the uncertainty in the evolution depending on uncertain future external events or uncertain boundary conditions. The evolution of external events is a continuous development, which cannot be predicted in its 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 - are selected. These different scenarios could then be factored into the reliability (chapter 6) and decision (7) analyses.

For example, scenario initiators for a road tunnel may include (Figure 5-1):

- *human actions* (changes in traffic, potential new underground construction projects,…),
- *changes in engineered* components (like corrosion of rock reinforcement, degradation of grouting,..) – if this is not already considered being part of the system description itself,
- changes in *natural environment* such as climate change (may affect infiltration of water)
- political development.

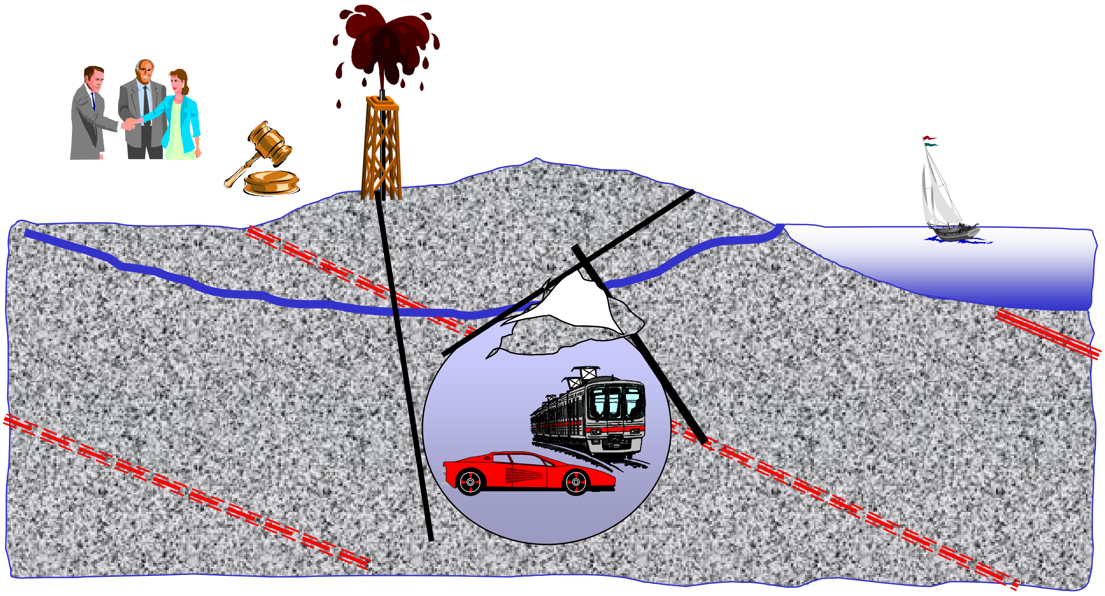


Figure 5-1 *Future scenarios for a road tunnel may concern changes in traffic patterns, unexpected corrosion of reinforcement, political changes affecting safety standards, etc. For the understanding the life-cycle costs and the design requirements it is important to get a handle on such scenarios. A decision analysis may show to what extent an optimal decision is affected by the probability of different scenarios.*

Other underground excavations may be affected by similar events. Section 5.1.5 discusses some modelling implications of scenario uncertainty.

5.1.2 Model (conceptual) uncertainty

Model (or conceptual) uncertainty concerns the uncertainty originating from an incomplete understanding of the structure of the analysed systems 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.

The basic principle for describing the rock is often called the *conceptual model* of the rock. Examples of different conceptual models of the rock may be 'typical Swedish low fractured crystalline rock', 'complex deformation zones' (like Hallandsås), 'sedimentary rock', volcanic regions', 'high stress rock' etc. Clearly, the conceptual model affects how data are interpreted and the overall confidence in the system description. This is further discussed in section 5.4. Among geologist it is also quite common to denote uncertainties in the geometrical model — such as the number and position of fracture zones — as conceptual uncertainties, but these uncertainties are actually related to data uncertainties (see below). The use of 'conceptual uncertainty' in this context should be avoided.

The model uncertainty as regards interactions essentially concerns overlooked or oversimplified description of processes. For example, in hydropower tunnels hydraulic fracturing may be an issue (if the water pressures are high in relation to the rock stress), but the consequence would (of course) be overlooked unless this process is included in the description of the mechanical system. Section 5.1.5 discusses how to handle the uncertainty in conceptual and calculation models.

5.1.3 Data uncertainty

Data uncertainty concerns uncertainty in the values of the parameters of a model. Data uncertainties may be caused by, for example, measurement errors, interpretation errors, or the uncertainty involved in extrapolation when the parameter varies in space or in time. Conceptual uncertainty, data uncertainty and spatial variability may all be related (Figure 5-2).

There exists an extensive arsenal of methods for describing and quantifying uncertainty (see section 5.2) 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.

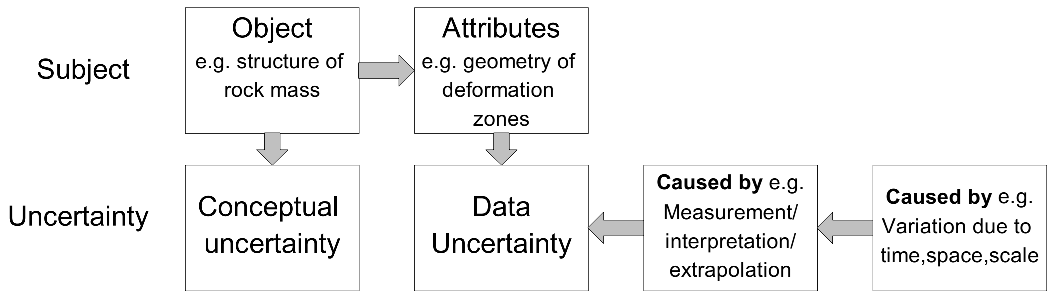


Figure 5-2 *Conceptual uncertainty, data uncertainty and spatial variability may all be related (from Andersson, 2003).*

Error, precision, bias and accuracy

In discussing data uncertainty it is important to separate between error, precision, bias and accuracy, Figure 5-3. Error is the deviation between an estimate and the true value. Error is the deviation between an estimate and the true value. Accuracy is the degree to which the mean of repeated measurements deviates from the true value, the difference being the bias. Precision is the spread of repeated values. Thus, measurements can be accurate, even though they are not precise.

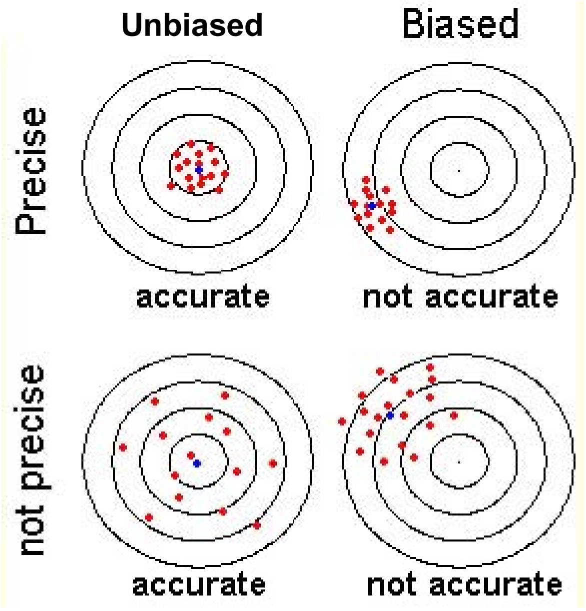


Figure 5-3 *Accuracy, precision and bias*

If data are biased additional measurements would not reduce errors, and worse if measurements are precise and biased this may lead to an erroneous conclusion that errors are small. On the other hand, even if measuring procedures are imprecise, averaging many measurements may lead to accurate predictions, provided the measurement procedures are unbiased. Consequently, it is critical to consider whether data are biased. If that is judged to be the case a high uncertainty need to be assigned to the data, even if they may appear to have little internal spread.

5.1.4 Spatial variability and scale

Spatial variability concerns the variation in space of a parameter value. Spatial variability is not uncertainty per se because it can be well 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. Section 5.3 discusses different ways of describing spatial variability.

Connected to spatial variation is the concept of 'scale'. Scale concerns the spatial resolution of the description. For a spatially varying property, the scale is the size of the domain over which properties are averaged. Spatially varying properties will manifest different values when described at different scales (see Figure 5-4). For example, using a high resolution description, i.e. at the 'small scale', intact rock and fractures would be described as individual entities but, at the larger scale, the descriptions would be combined into a 'rock mass' value. Scale should not be confused with accuracy or precision (see above).

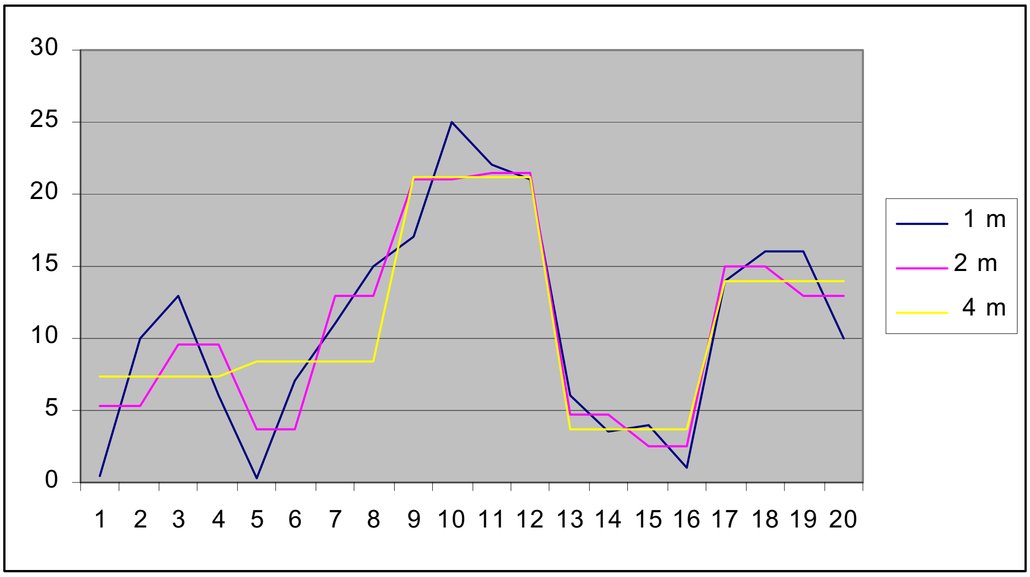


Figure 5-4 *Description of a parameter (e.g. rock surface in m) in different scales (as averaged over 1, 2 or 4 m). The decreasing resolution tends to smooth the variability (from Andersson, 2003).*

The selected scale also affects the values of properties defined as (volume) averages such as rock mass mechanics properties or hydraulic conductivity – which are scale dependent. In a high-resolution description, e.g. fracture zones and large fractures will be given their own mechanical and hydraulic properties and will thus not be included in the averages representing the rock mass in-between these features. In a description with less resolution these features (with significant impact on the properties) will be included in the averages.

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 (variance reduction, see section 5.3.2) if it is small the small scale variability will directly affect performance, without any 'variance reduction'.

5.1.5 Modelling implications

The various types of uncertainty all have implications on how to model the system. This is generally discussed here, whereas chapter 8 discusses how to assess information to reduce uncertainties in particular applications.

Handling scenario uncertainty

In predicting the future it is also necessary to understand (sufficiently) the system, i.e. to be able to predict what will be the consequence of the future conditions. Handling scenario uncertainty rests on identifying a sufficiently revealing set of scenario initiators. Imagination and experience are the essential tools, but also the selection of effective system boundaries (see also chapter 3).

From the potential scenario initiators a set of future scenarios may be selected. To explore whether the reliability of the system (chapter 6) or the optimal decisions (chapter 7) as regards the system are affected by these scenarios, a probability needs to be assigned to each scenario. Such a probability assignment can usually only be made subjectively (see section 5.2). In order not to "double count" probabilities attention is also needed to ensure that different scenarios are mutually exclusive.

Conceptual models

Practically, model uncertainty is handled by attention to the problem identification and system analysis, see chapters 3 and 4. Imagination and experience are the key factors leading to effective descriptions. The choice of scenarios and of the conceptual models is made on the basis of the individuals engineering judgement and knowledge, which in turn depends on both the personal knowledge and experience and the knowledge of the trade ("tribal knowledge").

Lack of personal knowledge can lead to a misunderstanding of the problem at hand, which will lead to large uncertainties in the predicted behaviour although these are not directly apparent. Uncertainties caused by lack of knowledge in the trade cannot be avoided, as everybody, including the best experts share the same knowledge. This can be changed of course by research and experience from new projects.

Baecher (1979) shows an interesting example of how the geological maps of an area in Canada change radically, not because of more data, but because of a change in the theory of granitization. (Such commonly shared theories is sometimes called “memes” or “cultural genes” in literature on creativity, see Vedin, 2000)

Calculation models

Calculation models include numerical models but also simple equations and other means of obtaining quantitative results. All calculation models are imperfect representations of nature and its response to various actions so one should always consider the inaccuracy of the model (the model error). This inaccuracy is composed of both bias and imprecision, c.f. section 5.1.3. One way to correct for the model error is to introduce a correction factor, which is a stochastic variable with a mean and a standard deviation. In soil mechanics it is not uncommon to find that the mean of this factor deviates from 1.0, i.e. there is a systematic error. The spread of the model error (its standard deviation) is often quite large, which means that it has a substantial influence on the total inaccuracy, Olsson, Rehnman & Stille (1985).

A simplified model is expected to have a larger inaccuracy. However, we are interested in the total prediction uncertainty, which is compounded of the model uncertainty and the uncertainty of the data used in the model. As data normally is scarce in underground construction work the data uncertainty is normally large, especially in the light of the spatial variation. This means that one must find a balance between the model simplification and the amount and type of data required by the model. The simplified models thus do have their legitimate place in the calculations.

Handling “competing” models

At instances it may also be necessary to formulate alternative models and the question then arises on how to handle this. This both concerns conceptual models and calculation models.

Discriminating between models can be done subjectively, using expert judgement to assign to each model the probability that it is the correct one. An extension of this is to use Bayesian methods, e.g. to compare posterior data with actual observed data, see e.g. Gelman et al. (1995), Baecher and Rackwitz (1982).

Another way to handle the problem with competing calculation models is to use a combined model, which is a linear combination of the different models, where the weight factor is the probability that the model is the correct one. These weights can be obtained using expert judgement.

Furthermore, the need for actually discriminating between the models may be considered in decision analysis (see chapter 7) similar to the handling of other quantified uncertainties. If the decision analysis shows that the probabilities of different alternative models have a large impact on the decision, this may be a strong argument for improving the understanding of the process, i.e. to gather more information. This is further discussed in chapter 8.

5.2 Methods for describing and quantifying uncertainty

In order to be able to make decisions in the face of uncertainties, methods are needed to describe and to quantify those uncertainties. As there are usually several sources of uncertainties in a typical decision problem, some methods are needed to combine the uncertainties to calculate the total uncertainty from the different parts. There is also a need to be able to use different information sources when estimating probabilities.

Quantification of uncertainty is usually handled by describing the uncertain property as a stochastic variable. It is then necessary to find the distribution function and its associated parameters. In underground engineering problems this can only be made subjectively, although assisted by a few measurements. There are two important means of handling this situation. One is that there are quite a few instances where logical reasoning or physical understanding provides a quite clear framework for what can be the distribution for a certain stochastic variable. If we know the type of distribution (“model distribution”) it is possible to estimate, although perhaps poorly, the distribution function parameters (and thus the probabilities we are after) based already on few measured data. The other is to improve the generic (á priori) understanding by Baysian updating.

5.2.1 Probability

There are different methods to describe uncertainty. The two most frequently used in engineering work are probability and fuzzy logic. Of these two, only probability is described here.

From a philosophical standpoint there are different ways of interpreting the word ′probability’: From a ‘*frequentist*’ perspective ‘true’ probability exists, but we cannot determine it. We describe the power of our method, but do not really talk about the data at hand. From a ‘*subjective*’ perspective probability is an expression for a person’s subjective estimate of how likely an event is. Probability can be described using stochastic variables.

Which interpretation is correct? Among statisticians the debate has been going on for literally centuries and there is still no definite answer. For an engineering purpose the authors advocate that a pragmatic point of view be chosen:

- Let the problem at hand rule the choice and use whichever interpretation is most useful.
- Lack of data will almost always be the case, so a Bayesian point of view will usually be the one most suitable.

The Bayesian point of view, which is more general than Bayesian statistics discussed in section 5.2.8, stresses the following:

- Probability is subjective and one can talk of the probability of a "one of a kind" event.
- Information from different sources can be compounded, so that experience from similar projects can be utilised.
- One can talk about statistical parameters (for instance the mean) as being themselves random variables. (In frequentist statistics one considers them as fixed but unknown, and the focus comes on the statistical method used to calculate the parameter).

Remember also that we want to make engineering decisions and therefore use probabilities in modelling our uncertainty, not to describe reality, but to be the basis for good decisions.

5.2.2 Some axioms and rules

In order to estimate probabilities it is necessary to understand the fundamental axioms and rules for probabilities. The most important ones are given below (for a more complete exposition see e.g. Benjamin and Cornell, 1970). Let P(E) denote the probability that the event E will occur:

1. The probability of an event is a number between 0 and 1. $0 \leq P(E) \leq 1$
2. The probability of a certain event is 1. $P(S) = 1$
3. The probability of an event which is the union of two mutually exclusive events is the sum of the probabilities of these two events: $P(A \cup B) = P(A) + P(B)$
4. The conditional probability of the event A, given that event B has occurred, P(A|B), is $P(A|B) = P(A \cap B) / P(B)$
5. Two events are said to be independent if and only if $P(A|B) = P(A)$

These axioms not only form a fundamental theoretical basis, they can often be directly applied when estimating probabilities.

5.2.3 Stochastic variables (random variables) and their description

A very common way of modelling the uncertainty of a certain parameter is to represent it as a stochastic variable. A stochastic variable (also called random variable) is a numerical variable whose specific value cannot be predicted with certainty before an experiment.

The behaviour of a random variable is described through its probability law. The usual way of describing this probability law is by its cumulative distribution function, $F_X(x)$. (The random variable is usually denoted with a capital letter and values it may take on with a lower-case letter)

The cumulative distribution function (CDF) for the random variable X is:

$$F_X(x) \equiv P(X \leq x) \text{ for all } x$$

Discrete random variables

If the random variable X is discrete, i.e. it can only take a countable number of values, its probability law can be described as a probability mass function (PMF):

$$p_X(x) = P\ (X=x)$$

An example of a discrete stochastic variable is the expected number of joints per meter in a section of a proposed tunnel. This is illustrated in Figure 5-5.

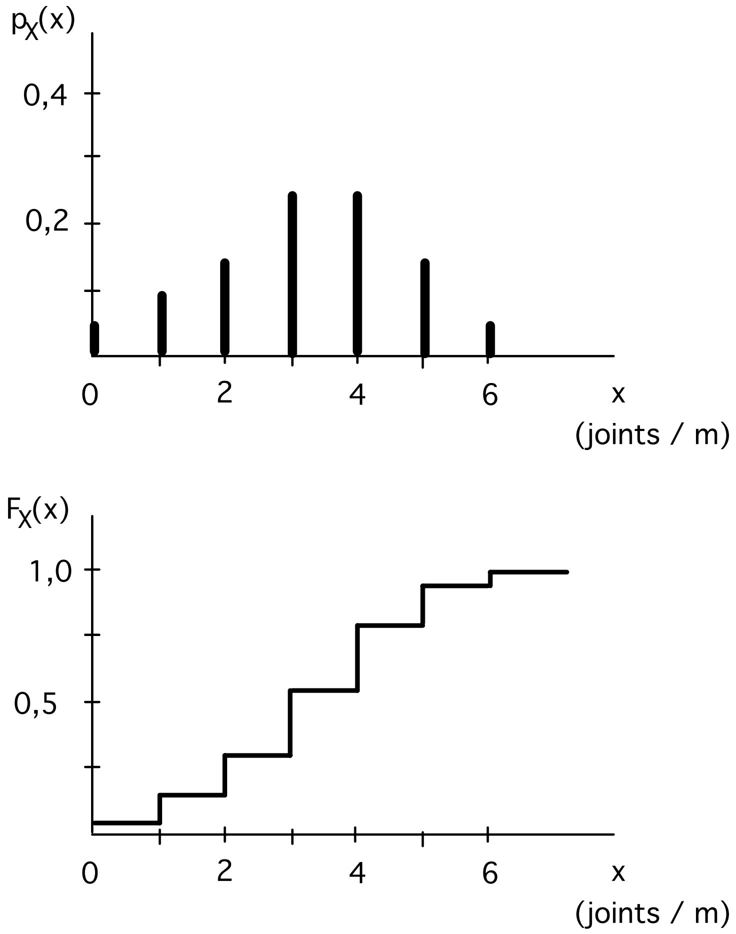


Figure 5-5 *Probability Mass function and its Cumulative Distribution Function for a discrete random variable. The number of joints encountered along a certain distance is an example of such discrete random variable.*

Continuous random variables

If the random variable is continuous, like the distance between fractures, the definition of the CDF still holds. However, the function corresponding to the PMF, which is called the Probability Density Function, $f_X(x)$ is defined such that for each infinitesimal interval dx of the x-axis the probability that X belongs to the interval x + dx is $f_X(x)$ dx. This means that the probability of X taking on a value in the interval $x_1 \leq X \leq x_2$ is

$$P\,(x_1 \leq X \leq x_2\,) = \int_{x_1}^{x_2} f_X(x)dx$$

The relationship between the PDF and the CDF of a continuous random variable is thus given by:

$$f_X(x) = dF_X(x)/dx$$

and analogous:

$$F_X(x) = \int_{-\infty}^{x} f_X(s)ds$$

An example of a continuous PDF is shown in Figure 5-6 and the corresponding CDF is shown in Figure 5-7.

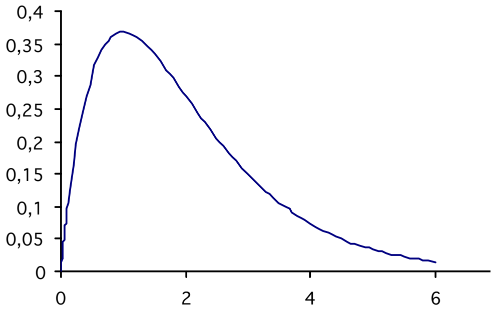


Figure 5-6. *Probability Density Function for a continuous stochastic variable e.g. representing the distance between joints along a line in rock.*

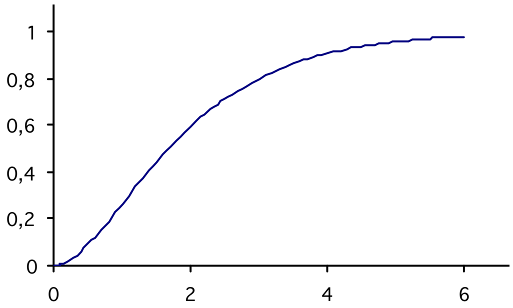


Figure 5-7. *Cumulative Distribution Function. The curve shows the probability (on the y-axis) of the stochastic variable being lower or equal to the value of the x-axis.*

It should be pointed out, that probabilities can only be read from the CDF. The PDF shows the probability density, and integration is needed to find a probability.

Mixed type random variables

It is possible to have not only discrete and continuous CDF:s but also mixed CDF:s. An example is shown in Figure 5-8, where the possible economic outcome of a project has been modelled as a mixed CDF. In the CDF there is a discrete part, which corresponds to a catastrophic event causing a very large loss. It should be noted that it is the total probability mass (i.e. the probability of the discrete event plus the integral of the continuous distribution) which is unity (in accordance with the probability axioms discussed above).

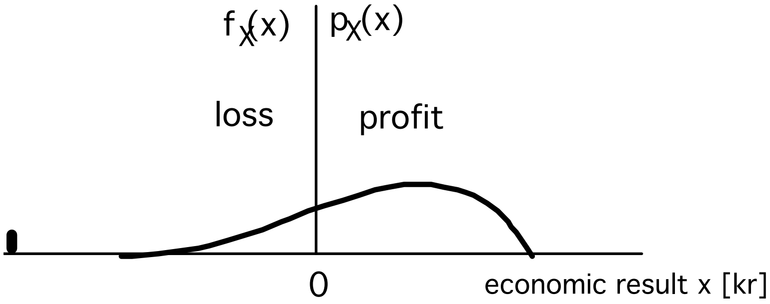


Figure 5-8. *Mixed distribution. A discrete part related e.g. to a catastrophic event may represent a very large loss, whereas the normal loss/profit probability is a more even distribution. (Note that it is the total mass under the CDF plus the mass of the discrete event, which should add up to unity).*

Many random variables - dependence

In many situations, rock design included, there is more than one uncertain parameter. For example, the stability of rock blocks depends, among other things, upon the size of the blocks, the friction angle, the stress situation and the strength of the reinforcement. All these conditions are, to a certain extent uncertain, and could thus be described as stochastic variables. However, in addressing the stability issue it is not only important to handle the distribution of each parameter individually, but also to consider if the parameters may be statistically dependent. Statistical dependence may have a profound impact on the probability of combined events. For example if the probability of the events A, B and C is 0.1 for each event, the joint probability of all events occurring is 10^{-3} if the events are independent and 0.1 if the events are fully dependent (a factor of 100 difference!).

Dependence between stochastic variables in rock mechanics is not uncommon and must thus be considered. This will be further discussed in section 5.2.6.

5.2.4 Describing random variables

The main features random variables can be described using the so-called moments, single value descriptors of essential properties of the random variable. Usually the first two central moments, the mean (expected value) and the variance are used, although the higher moments are sometimes used. These two moments describe the “position” and the “spread” of the random variable.

The *mean* corresponds to the center of gravity of the PDF and is calculated as a weighted average:

$$E(X) = \sum_{all x_i} x_i p_X(x_i) \qquad \text{for discrete random variables, and}$$

$$E(X) = \int_{-\infty}^{\infty} x f_X(x) dx \qquad \text{for continuous random variables}$$

The *variance* corresponds to the moment of inertia and is calculated as the weighted average of squared deviations from the mean:

$$\sigma^2 = Var[X] = \sum_{all\, x_i} (x_i - \mu_X)^2 \, p_X(x_i) \qquad \text{for discrete random variables, and}$$

$$\sigma^2 = Var(X) = \int_{-\infty}^{\infty} (x - \mu_X)^2 f_X(x) dx \qquad \text{for continuous random variables}$$

The square root of the variance, σ, is called the *standard deviation*. It contains the same information as the variance and has the advantage of being expressed in the same units as the random variable itself, and the mean.

The ratio between the standard deviation and the mean is called the *coefficient of variation*. It is often used in soil and rock mechanics as it is considered as known and constant (within limits) for certain materials and properties. It should be recognised that a constant coefficient of variation means that the standard deviation increases with increasing mean. If the main cause of uncertainty is constant measurement errors, one should rather assume a constant standard deviation.

Other useful measures when describing a random variable are:

- The *percentiles* (fractiles): the values of x corresponding to a stated probability, e.g the 95 percentile. They are easily read off from the CDF. A special name, the median, is given to the 50% percentile, which is the value of x where there are equal probabilities to be above and to be below.
- The *mode:* the most likely value, the highest point on a PMF.

Another way of describing the random variable is of course to give the mathematical expression of the PDF or the CDF. This can be simplified if one uses named mathematical functions. Then the random variable can be completely defined by the distribution name and the values of the parameters of the distribution. It should be observed that the distribution parameters usually are different from the moments, although the Normal distribution is an exception.

5.2.5 Model distributions

In rock engineering it is unusual or even impossible to have access to lots of measured repeated outcomes of a specific condition (such as intact rock strength or fracture frequency) to be described stochastically. This means that pure statistical estimates of the mean, variance and other moments of these variables cannot be made with confidence. However, there are ways to handle this situation, where two of the more important ones are:

- using *model distributions* and
- Baysian statistics (will be discussed in section 5.2.8).

The idea behind model distributions for the stochastic variables is that there are quite a few instances where logical reasoning or physical understanding provides a quite clear framework for what can be the distribution for a certain stochastic variable. If we know the type of distribution it is possible to estimate, although perhaps poorly, the distribution function parameters (and thus the probabilities we are after) based already on few measured data.

Below are listed some distributions that are useful for rock engineering work. For a listing and description of more distributions, see e.g. Evans, Hastings & Peacock (1993)

Binomial

A usual problem in rock engineering is to assess the probability of a damage, like a blasting damage, as a function of the tunnel length. It may be possible to assess the probability of failure, p, for a single blast and the issue then is to assess the probability of any failure after a number, n, blastings. This situation is well described by the binomial distribution, which is a discrete distribution. It concerns the results of a sequence of (so called) Bernoulli trials, in which there can be either the occurrence or the non-occurrence of an event, like for instance the exceeding of a allowable vibration limit when blasting. The probability of the occurrence is constant for each trial. The binomial distribution gives the probability of having (an exact) number of occurrences in a certain number of trials. Figure 5-9 shows the binomial distribution for 100 trials with a probability of “success” (exceeding a limit) = 0,02.

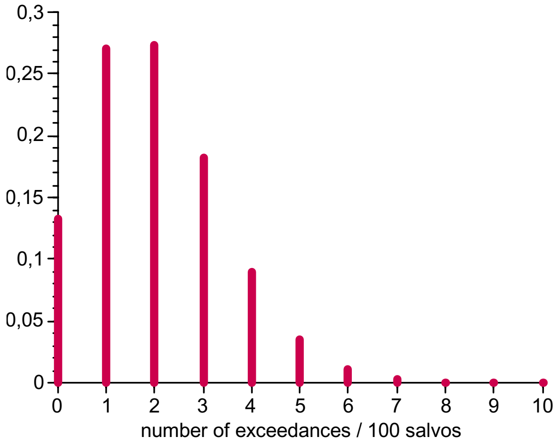


Figure 5-9. *Binomial distribution. It gives the probability of having (an exact) number of occurrences in a certain number of trials.*

Poisson distribution

Another rather common problem in rock engineering concerns the number of events, which may occur during a certain time or along a certain distance. An example of the latter may be to assess, how many highly transmissive fracture zones will be encountered along a certain tunnel distance. This situation may, under certain circumstances, be modelled by a Poisson distribution.

The Poisson distribution is a discrete distribution that can be used to model occurrence of events (in space or time) that follow the following:

- An event can occur at random and at any point (in space) or at any time.
- The occurrence of an event in a given interval is independent of that in any other (non-overlapping) intervals.
- The probability of occurrence of an event in the small interval Δt is proportional to Δt. The probability of two or more occurrences in Δt is negligible.

For example, the number of fractures encountered a certain distance along a line (or in a borehole) often follows a Poisson distribution, since fracturing is an (almost) random event. An example is shown in Figure 5-10.

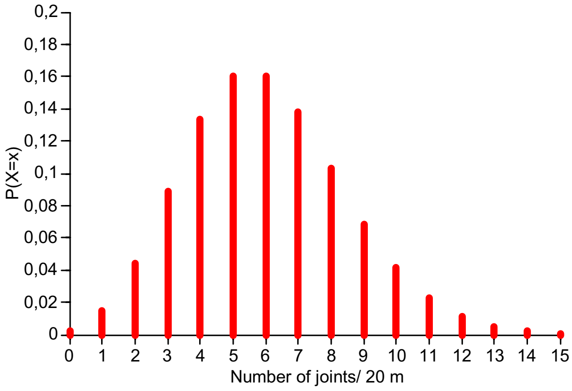


Figure 5-10. *Poisson distribution; corresponds to the number of independent events, which may occur during a certain time or along a certain distance (could e.g. be a good model for the number of fracture zones to encounter during certain tunnel length).*

Normal distribution

The normal (Gaussian) distribution, see Figure 5-11, is probably the best known continuous distribution. For rock engineering purposes normal distribution is of interest as the central limit theorem states that the sum of a large number of random variables tends towards the normal distribution. Physically this means that e.g. the total resistance of a slope, which can be seen as the sum of many small elements, can be modelled as Normal. However, it must always be remembered that the Normal distribution has a span from $-\infty$ to ∞.

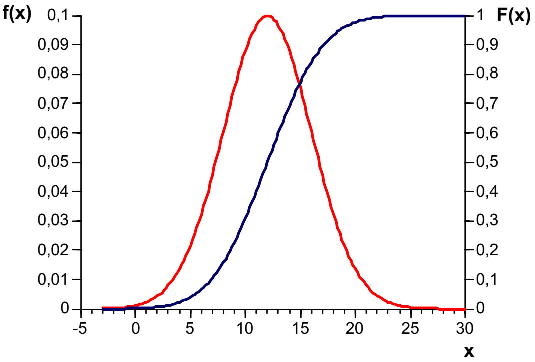


Figure 5-11 *Normal (Gaussian) distribution, which usually is a good model of phenomena implying a sum of many events (like slope resistance).*

Lognormal distribution

The lognormal distribution is the distribution of x when ln x is normal distributed, see Figure 5-12. This means that the lognormal distribution is not defined for negative values of X. Parameters like hydraulic conductivity or rock strength tend to follow log-normal distributions since they are the net effect of geometrical averaging.

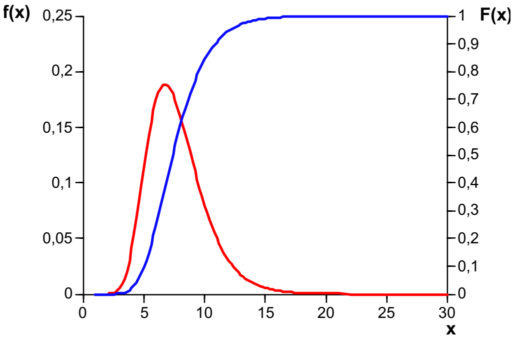


Figure 5-12 *LogNormal distribution, which usually is a good representation of products of many events (like the hydraulic conductivity distribution in rock).*

Exponential distribution

If events occur according to a Poisson process the interval (length or time) between two consecutive events follow an exponential distribution, Figure 5-13. For instance, if the number of joints in rock per meter is Poisson distributed, the distance between them follows an Exponential distribution)

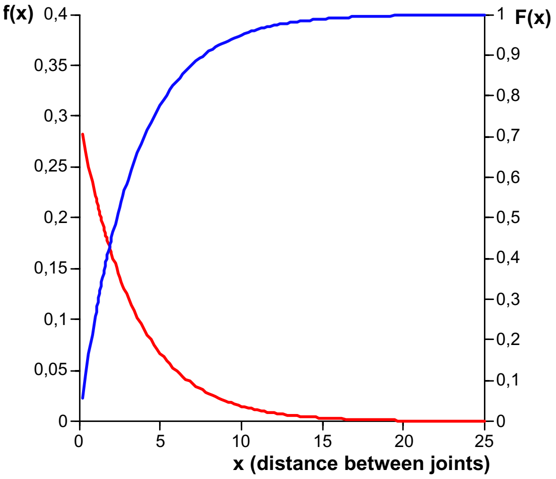


Figure 5-13 *Exponential distribution, which describes the distance between two consecutive independent evens (like distance between fractures, or time to failure).*

Gamma distribution

The gamma distribution, Figure 5-14, with an integer shape parameter is also called the Erlang distribution and is used to model costs and time. Fracture sizes also tend to follow a gamma distribution.

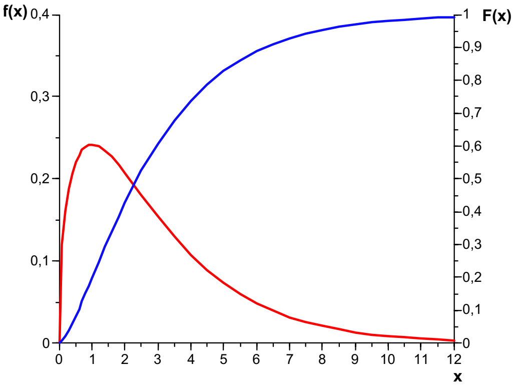


Figure 5-14 *Gamma distribution is used to model costs and time. Also fracture size tend to follow the gamma distribution.*

Uniform distribution

The uniform distribution is used to model a random variable when you are only willing to specify its range but not anything more.

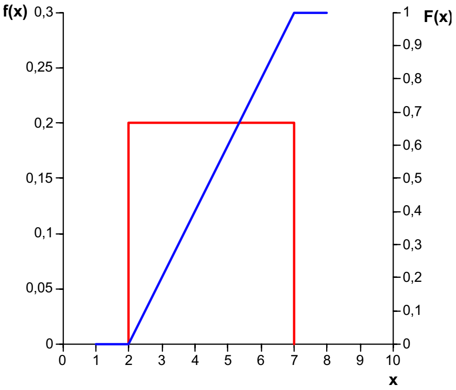


Figure 5-15. *Uniform distribution is used to model a random variable when you are only willing to specify its range.*

Triangular distribution

The triangular distribution is used to model the case where you are willing to state the range of the random variable and also the most likely value. It is useful for modelling experts' opinions as it is tail-heavy and thus somewhat counteracts over-confidence on the expert's part.

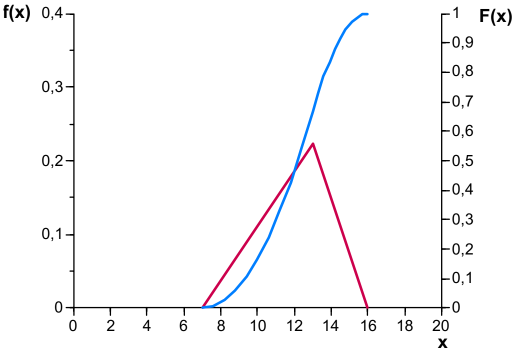


Figure 5-16. *Triangular distribution used to model the case where you are willing to state the range of the random variable and also the most likely value*

5.2.6 Relationships between stochastic variables – statistical dependence

Rock engineering decision problems usually concern more than one random variable. Of special importance is to assess if there is any relationship between the variables, or in statistical terms a correlation. Dependence may concern mechanical properties. For example, the shear strength of clay usually is depth dependent, in-situ rock stress may be dependent on the intact rock strength etc. But, dependence may also concern specific events, human actions or the outcome of engineering decisions. A trivial example of the latter is that the probability of unsuccessful grouting probably is higher in a complex rock mass than in a regularly fractured one.

Capturing statistical dependence may have a profound impact on the probability of combined events as already discussed. If a substantial database were at hand, dependence may be explored by statistical analyses of the data, but for practical engineering applications this is rarely an option. Dependence has to be assessed – or assumed – based on the understanding of the problem being analysed. This means that the best source for capturing statistical dependence is through the problem system description (cf. chapters 3 and 4).

Two random variables X and Y can have a measure of statistical relationship, which can be expressed by their correlation coefficient ρ and the covariance function (Cov):

$$\rho = \frac{Cov(X,Y)}{\sigma_X \sigma_Y}$$

$$Cov(X,Y) = E[(X - \mu_X)(Y - \mu_Y)]$$

It must be observed, that a calculated statistical correlation does not necessarily mean that there is a causal relationship, and also that a lack of correlation does not necessarily mean that there is no relationship between the two random variables.

Another problem is that quite often one wants to use random variables as input in some mathematical expression and to have the result expressed as a random variable, i.e. one needs to calculate functions of random variables. The reader is referred to stochastic/statistical textbooks for actual procedures.

5.2.7 Finding distributions and model distribution parameters from data

In order to find the CDF or PDF to be used in a real project one has to determine the distribution and its parameters. If data are abundant and several "trials" could be carried out – this can be estimated statistically from data. However, in rock engineering applications data are scarce and only one "trial" (i.e. the reality we measure) exist. This means that one has to use other information to supplement the data, both in selecting distribution types and to find its parameters. Statistical analyses of the existing data are still useful, but the data are much more effectively used in case we have some pre-understanding of the nature of the distribution. In particular, a mean and standard deviation are not always the most important statistical measures to consider.

Finding distribution type

A suitable distribution for the modelling can be found by considering the physical background of the problem or by examination of the data to find a matching distribution.

- The *physical background* for some distributions has been touched on in section 5.2.5.
- *Examining data to find the distribution* can be done either by graphical examination e.g. using probability papers or numerically using specific rules to define what constitutes a "good" match between data and distribution.

For a description of probability papers, see e.g Ang & Tang (1975) or Alén (1998). It should be observed, that a spreadsheet program with statistical functions for $F^{-1}(X)$ can simplify the work to a large extent.

For a description of numerical methods, see e.g Ang & Tang (1975). There are also computer programs that can assist. It must be observed, however, that a uncritical use of these methods, without considering the rules used for choosing a distribution, can be very misleading.

Finding distribution parameters

In order to fully describe a statistical distribution, one must know its parameters. Which these are varies with the distribution type, for a Normal distribution the parameters are the mean and the standard deviation, for a triangular distribution they are the minimum, most likely and maximum values.

Two methods are used to estimate the parameters of a distribution, the method of moments and the ML (maximum likelihood) estimator, see e.g. Ang & Tang, 1975, Benjamin & Cornell (1970), Mishra (2002).

- When parameters are to be assessed from data one often tries to find the moments and then calculates the parameters from them. In the method of moments, the sample moments are used as estimators for the population moments, though in some cases a correction factor is used for the standard deviation.
- The basis of the method of maximum likelihood is that one finds the parameters that maximise the likelihood of obtaining the data sample that has been observed.

The maximum-likelihood estimate of the parameter θ , is the value that causes the likelihood function $L(\theta)$ to be maximum.

$$L(\theta \mid x_1, x_2, ..., x_n) = \prod_{i=1}^{n} f_X(x_i \mid \theta) \quad \text{where } x_i \text{ are observed samples}$$

For example, applying the ML-method shows that estimating parameters to a lognormal distribution should be made using the moments of the logarithms of the data (not the data directly).

Sometimes one wants to describe the relationship between two stochastic variables. This can be done by correlation analysis or regression analysis. It must be observed that in some of these methods, e.g. least squares regression, one presupposes that there is a linear relationship. This can lead to errors if the relationship is of another form

5.2.8 Bayesian statistics

In rock mechanics, it is almost always the case that one has some sort of engineering knowledge and experience and rather little “hard” data. One naturally wants to make use of all information available in a stringent way. This can be done using Bayes’ theorem, named after the Reverend Thomas Bayes (1763).

Bayes’ theorem can be derived from the multiplication rule:

$$P(E_1E_2) = P(E_1|E_2)\ P(E_2) \text{ or } P(E_1E_2) = P(E_2|E_1)\ P(E_1)$$

and the theorem of total probability:

$$P(A) = P(A|E_1)P(E_1) + P(A|E_2)P(E_2) + \ldots + P(A|E_n)P(E_n) \text{ as follows}$$

If we know that the event A has occurred, what is the probability that E_i also occured? That is we are interested in the joint probability $P(AE_i)$. Using the multiplication rule:

$$P(AE_i) = P(A|E_i)P(E_i) = P(E_i|A)P(A)$$

$$P(Ei|A) = P(A|E_i)P(E_i)/P(A)$$

If we expand P(A) using the theorem of total probability we get Bayes' theorem:

$$P(E_i|A) = \frac{P(A|E_i)P(E_i)}{\sum_{j=1}^{n} P(A|E_j)P(E_j)}$$

The main difference between bayesian and frequentist statistics is the subjective interpretation of probability in bayesian statistics. Also, in bayesian statistics the parameters of a stochastic variable are viewed as stochastic variables themselves.

Following Ang & Tang (1975):

- Suppose that the possible values of a statistical parameter Θ (e.g the mean) of a stochastic variable is assumed to be a set of discrete values, θ_i , i = 1,2,…,n
- Each of these have a relative likelihood to be correct, $p_i = P(\Theta=\theta_i)$
- Suppose that drillings are made and that we thus get the additional information ε. How can this be used to modify our assumptions about the PDF of the parameter Θ, i.e. how should the p_i:s change?

Applying Bayes' theorem:

$$P(\Theta = \theta_i|\varepsilon) = \frac{P(\varepsilon|\Theta = \theta_i)P(\Theta = \theta_i)}{\sum_{i=1}^{n} P(\varepsilon|\Theta = \theta_i)P(\Theta = \theta_i)} \qquad i = 1,2,\ldots,n$$

- $P(\Theta = \theta_i)$ the *likelihood* of the outcome ε if $\Theta = \theta_i$, i.e the conditional probability of obtaining a particular experimental outcome ε assuming that the parameter is θ_i.
- $P(\Theta =\theta_i)$ the *prior* probability of $\Theta = \theta_i$, that is prior to the availability of the experimental outcome ε
- $P(\Theta =\theta_i |\varepsilon)$ the *posterior* probability of $\Theta = \theta_i$; that is the probability that has been revised in the light of the experimental outcome ε.

Bayes theorem can also be formulated for the case of continuous stochastic variables:

$$f''(\theta) = k\, L(\theta)\, f'(\theta);\ 1/k= \int L(\theta)\, f'(\theta)d\theta$$

where

- $f''(\theta)$ is the *posterior* (to getting more data) distribution of the parameter θ. (θ might be a vector)

- L(θ) is the *likelihood* of observing the data that has actually been observed
- f'(θ) is the *prior* (to getting more data) distribution of the parameter q
- k is a normalising constant to make f''(θ) a true probability distribution

An example

Working on a foundation problem the designing engineer has to make a statement on the friction angle of a sand. Based on literature and some previous experience from similar sand he assesses the friction angle as Normally distributed $N(\mu_\phi;\sigma_\phi)$, where the mean μ_ϕ is unknown, but the standard deviation is considered to be fixed and known: $\sigma_\phi = 5$ °. This distribution is called the data generating distribution (of the observable physical variable) or sometimes the model distribution. In bayesian statistics, the parameters of the basic (data generating) distribution are themselves stochastic variables, which are described by a distribution function and the parameters of that function. Some possible realisations of the data generating distribution (for different means) are shown in Figure 5-17.

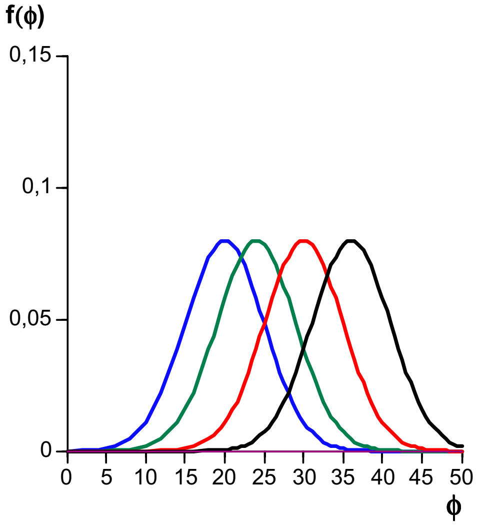


Figure 5-17 *Some possible data generating distributions of ϕ*

If the true value of μ_ϕ was known, one could pick the corresponding distribution of ϕ and use that in the decision making. However, as this is impossible, the engineer makes a judgement on possible values of the mean in the form of a probability density function. The parameter Θ of the data generating distribution, in this case the mean μ_ϕ is assessed by the engineer as distributed $N(\mu_\mu;\sigma_\mu)$.

The best estimate that the engineer can achieve is that $\mu_\mu = 30$ and $\sigma_\mu = 3$, see Figure 5-18. This distribution is called the *prior distribution* as it is the distribution prior to a possible gathering of more data.

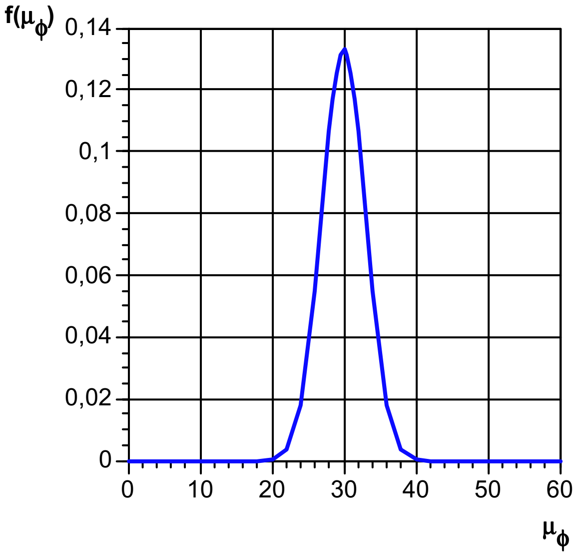


Figure 5-18 *Prior distribution of mean*

The total uncertainty in the value of the friction angle ϕ is thus composed of two parts:

- the variation in the data generating distribution as described by its standard deviation σ_ϕ (which in the example is supposed to be known $\sigma_\phi = 5$ °)
- the uncertainty about the mean of the data generating distribution as described by the prior distribution

These uncertainties can be combined by making a weighted summation (in this case which is continuous: an integration) of all the possible data generating distributions, where the weight is the probability that the respective distribution is the “true” one. These weights are given by the prior distribution of the mean μ_ϕ. Such a compounded distribution is often called a “bayesian distribution” or a “predictive distribution”. It can be calculated by:

$$\tilde{f}_{\Phi}(\phi) = \int f(\phi \,|\, \mu) f\ (\mu) d\mu$$

i.e. the unknown parameter μ of the model (data-generating distribution) is integrated out see e.g Benjamin & Cornell (1970) p 632 ff.

The bayesian distribution will with the specific assumptions made in this case be $N(\mu_\mu ; \sigma_\phi + \sigma_\mu)$, see e.g. Lee (1997) and is shown in Figure 5-19 .

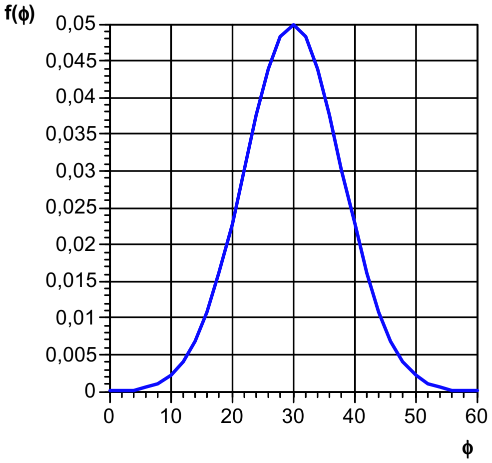


Figure 5-19 *Prior bayesian distribution of friction angle*

After performing a decision analysis of the problem (see Chapter 7) the engineer decides to gather more information by having samples taken and tested. Three samples are taken at points chosen randomly and some distance apart. They show a friction angle of 29, 31 and 32 degrees respectively. The engineer now wants to combine these data with his prior (to the data) estimate. The tool for this is Bayes' theorem.

Some observations:

- Bayes' theorem requires, not only allows, a prior distribution of the parameter θ
- The underlying data-generating process is not explicitly present in the theorem, but it governs the likelihood function. The latter thus contains the statistical modelling, including the sampling plan.
- The sample locations chosen influence the likelihood function. Often it is assumed in the updating calculations that the samples are random and independent of each other, which might not necessarily the real case.
- The result is an updated distribution of the parameter θ, not of the underlying data-generating function

In the example, the sampling points are considered to be so far apart that the samples are independent. For this case, with the specific assumptions made, there exists a closed form solution. (The prior distribution is a so called conjugate prior, see Ang & Tang (1975).

$$\mu''_\mu = \frac{\dfrac{\mu'_\mu}{(\sigma'_\mu)^2} + \dfrac{\bar{x}}{\sigma_\phi^2 / n}}{\dfrac{1}{(\sigma'_\mu)^2} + \dfrac{1}{\sigma_\phi^2 / n}}$$

$$(\sigma''_\mu)^2 = \frac{1}{\dfrac{1}{(\sigma'_\mu)^2} + \dfrac{1}{\sigma_\phi^2 / n}}$$

$\bar{x}$ is the arithmetic mean of the sample outcomes (29 + 31 +32)/3

n is the number of samples = 3

σ_ϕ is the known standard deviation of the data generating process (i.e. the friction angle ϕ) (=5 degrees)

μ'_μ is the prior mean of the mean μ_ϕ of the data generating process (=30)

σ'_μ is the prior standard deviation of the mean μ_ϕ of the data generating process (=3)

With the test data, μ''_μ is calculated to be 30,35 and σ''_μ to be 2,08. Then the posterior distribution of μ_ϕ is N(30,35; 2,08), see e.g. Ang & Tang (1975), this distribution is shown together with the prior distribution in Figure 5-20

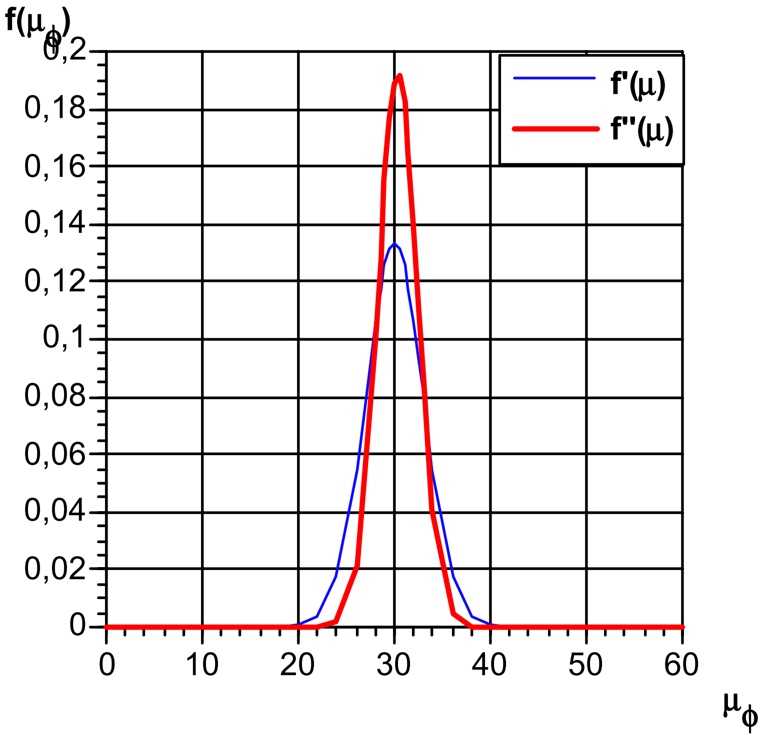


Figure 5-20 *Posterior distribution of mean*

It is possible to calculate the information content of the prior as an equivalent number of samples: $n' = (\sigma_\phi/\sigma'_\mu)^2$. In our case this gives an equivalent number of samples = 3. Olsson (1986) suggests that the number of actual physical samples to be taken exceed n' in order to safeguard against overestimation of the prior knowledge, especially if the test results are known before the bayesian analysis is made.

To find the distribution of the friction angle ϕ itself, the posterior bayesian distribution is calculated. This calculation is done in the same way as for the prior distribution, but of course the posterior distribution of the mean is used. The posterior bayesian distribution, which will be used in the subsequent design, is shown in Figure 5-21 with the corresponding prior bayesian distribution.

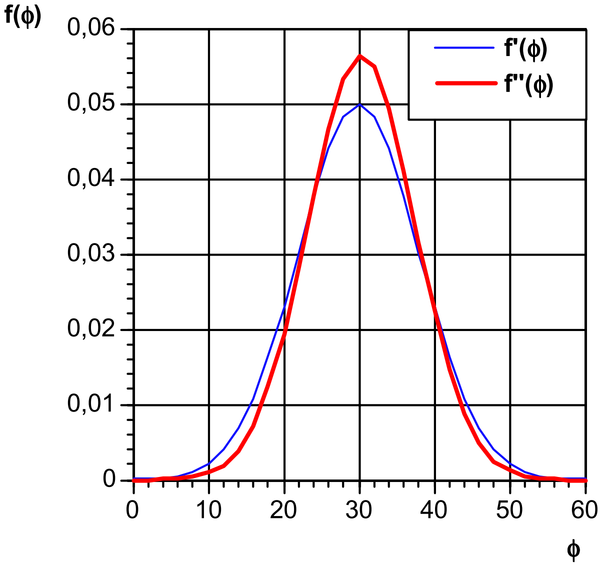


Figure 5-21 *Posterior bayesian distribution of friction angle*

Some comments

The above is a short account of Bayesian statistics, with the aim of showing its use for engineering tasks. For a fuller description of theory, mathematics etc, the reader is directed to the literature, see e.g. Ang & Tang (1975), Benjamin & Cornell (1970), Lee (1997), O'Hagan (1994), Press (1989).

In the example, Normal distributions were used for the friction angle (the data generating process) and also for the prior distribution of the mean. This means that one is willing to accept that there is a finite probability of a negative friction angle! On the other hand, computations were easy!

It should be pointed out, that although some computations are difficult, modern personal computers can handle them using numeric integration or other computer intensive methods, e.g. Markov Chain Monte Carlo simulation, see Gilks, Richardson & Spiegelhalter (1996) and Sturk (1998). This means that one is not restricted to certain assumptions about data-generating functions and priors for reasons of calculation ease, but that one can use a realistic modelling of the problem.

5.3 Describing spatial variability of rock and its associated uncertainty

It is necessary to describe the spatial variability and its correlation. There are different models available for this.

In simple cases a stochastic variable with a certain distribution function (or a constant value) is attributed to different regions (structural domains, see e.g. Hudson and

Harrison, 2002). Different rock domains may have different values. This representation is, for example, practical to use for e.g. the rock type distribution in a geological model.

In other cases more sophisticated descriptions may be needed. There are two main ways of representing this – though continuum descriptions and through discrete descriptions.

5.3.1 Continuous variation and auto-correlation

For some properties it is may not be sufficient to know its average value. An important example of such a parameter, with a continuous variation, is the location of the rock surface. In foundation work or when building a shallow tunnel the variation of the rock surface may be critical to know. It may also be important to get a handle on the variability of the rock quality along a tunnel – in order to get a handle on the potential construction problems.

The variability as such may be described by the variance (and a trend), but almost equally important is the autocorrelation properties, i.e. the value of a property at a certain point may be correlated to the value at a point close by. Knowledge of these correlation properties represents additional information that can be extracted from exploration data. For example, if we know that the rock surface level changes slowly, the result from one bore-hole can be used to estimate the level over a larger surface than if we disregard the information about correlation. In that case more bore-holes might be needed to get the same confidence in our estimate.

This is illustrated in Figure 5-22, which shows two hypothetical rock surfaces, one fluctuating more slowly than the other. In the figure the autocorrelation functions are shown. The autocorrelation function shows the correlation between two points as a function of their distance apart. The autocorrelation distance δ is also shown. This distance is defined as the distance where the autocorrelation equals 1/e.

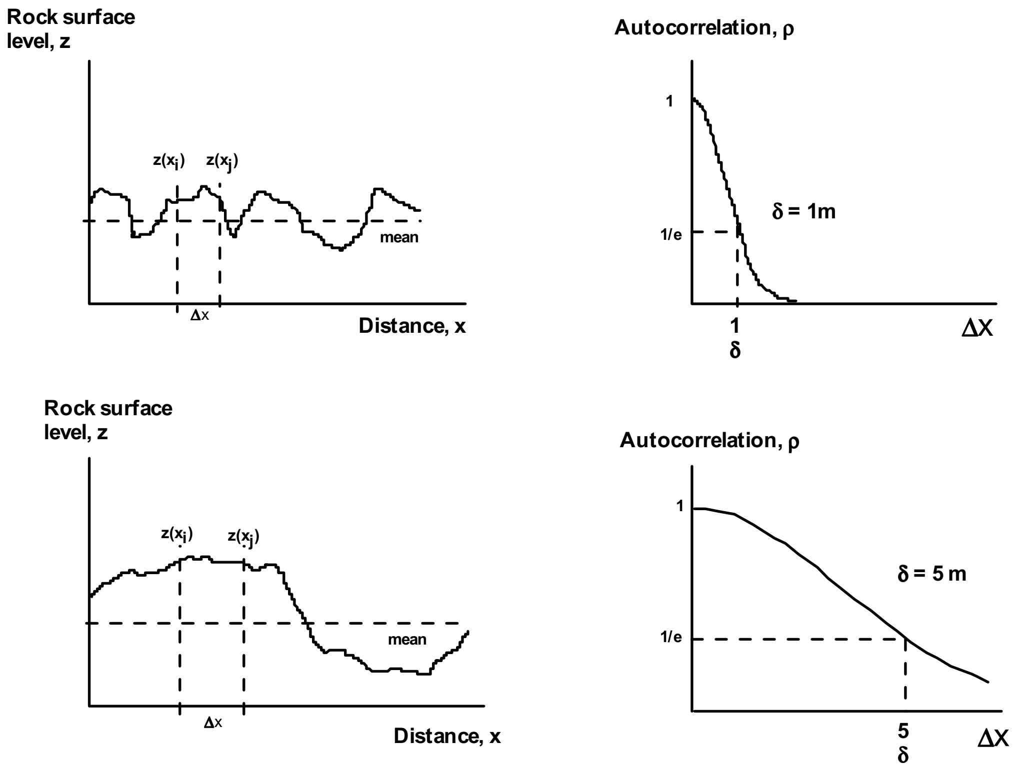


Figure 5-22 *Fluctuating rock surface and autocorrelation*

For continuous parameters correlation could be described using a correlation function or variograms. The variogram 2γ(h) of a property p(x), see e.g. Journel and Huijbregts (1978) is expressed as:

$$2\gamma(h) = E(p(x)-p(x+h))^2$$

where p(x) is the rock property value at location x, and p(x+h) is the value at location x+h.The estimation of the semivariogram is normally based on the experimental semivariogram.

$$\gamma(h)=\left(\frac{1}{2n}\right)\sum_{i=1}^{n}[p(x)-p(x+h)]^2$$

where n is the number of sample pairs, p(x) is the rock property value at location x, and p(x+h) is the value at location x+h. The variogram and the autocorrelation (or autocovariance) function can both be used to depict the spatial variation properties. The relationship between a semivariogram and the corresponding autocovariance function is shown in Figure 5-23.

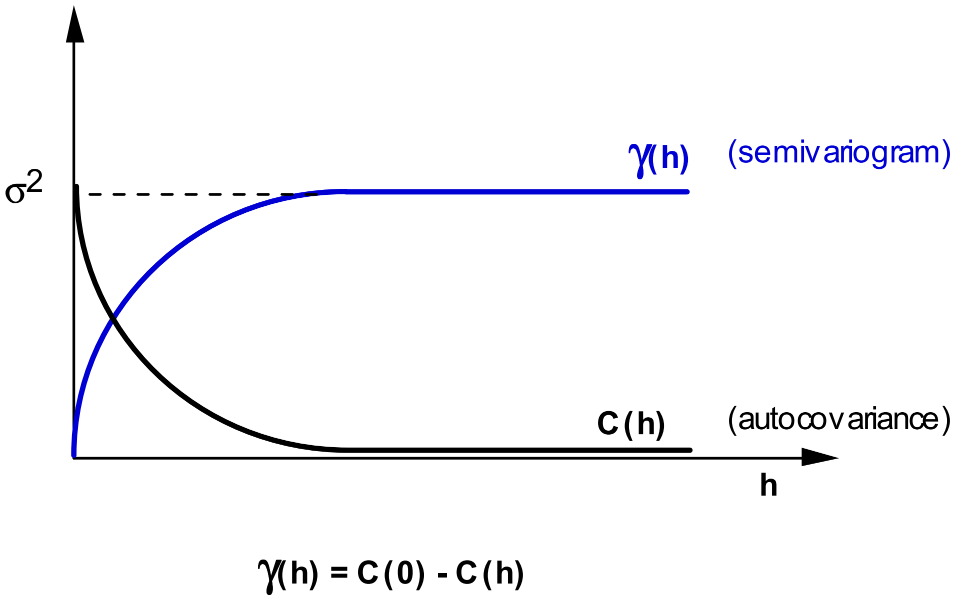


Figure 5-23 *Semivariogram and autocovariance*

Figure 5-24 shows a variogram of RMR along a borehole. It exhibits a ‘nugget effect’, i.e. that there is a short range variability in the data, and a short range (20-30 m) correlation scale (autocorrelation). This means that RMR values in two adjacent blocks are correlated, but that the ‘statistical memory’ does not extend to further distances.

Information about the nugget and the range have direct implications on how to average rock properties. When averaging RMR over larger distances than the range, e.g. for estimating large scale rock mass deformation modulus the variance of the average will decrease as a function of scale (variance reduction). However, this variance reduction will be less pronounced for averaging scale less than the range since then neighbouring values tend to be correlated.

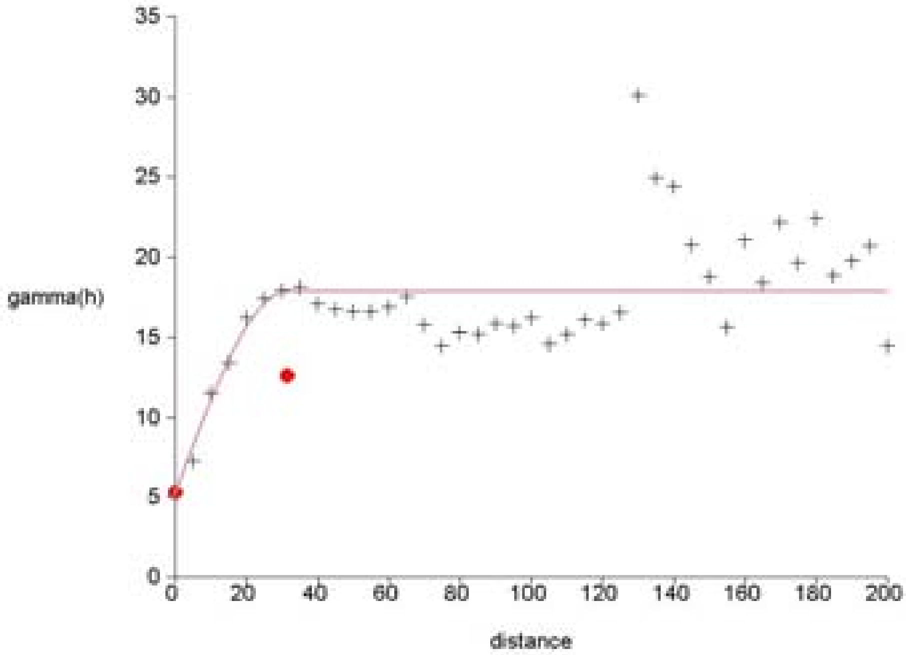


Figure 5-24 *Example of semi variogram of RMR along a borehole (from Andersson et al., 2002). It has nugget effect and a short range. The spread of points at large separation is likely to be statistical noise but could also be an indication of a changed statistical behaviour over longer distances. Substantial variance reduction results if a property is averaged over distances larger than the range, but not necessarily otherwise as neighbouring points then tend to have the same (unknown) value. (The red dots are used by the software for fitting the curve to the data – they have no other meaning).*

The variogram can also be used for kriging interpolation, see Journel and Huijbregts (1978) or Andersson, Stille & Olsson (1984). The kriging estimate can also be combined with estimates of the kriging variance as shown in Figure 5-25, which shows the kriging variance of the preconsolidation pressure of clay, estimated around two boreholes Outside the correlation range the specific borehole information does not affect the prediction. There the kriging variance is the same as the ensemble variance. This means, that in such design problems where one is interested in the point-to-point variation, the boreholes must be placed closer than the correlation range.

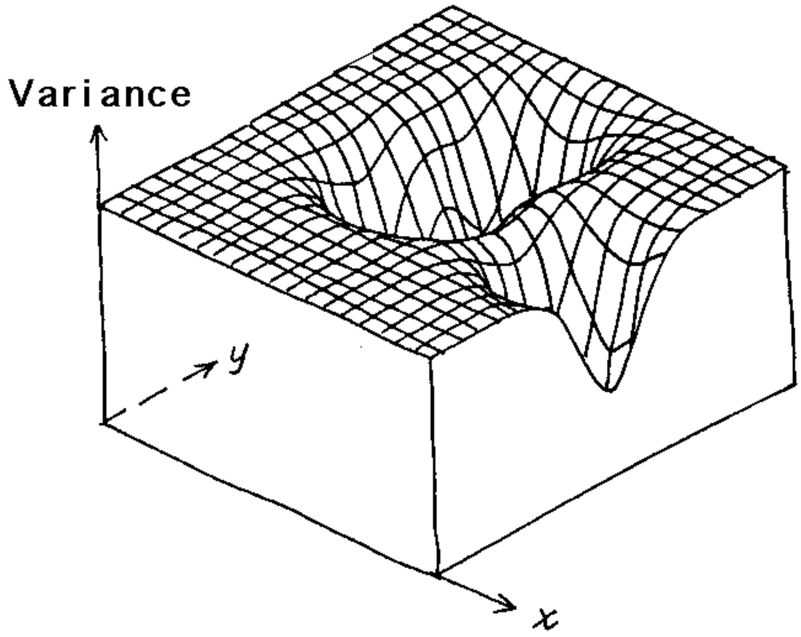


Figure 5-25 *Kriging variance around two boreholes (from Sällfors 1990).*

An interesting property of the kriging variance is that it can be calculated from the borehole positions only, without need for the actual results. The decrease in variance as a result of an extended investigation can thus be calculated in advance. Variograms and kriging are thus important tools in judging whether more information is needed and to what extent the uncertainty in a prediction of the rock properties may be reduced.

Furthermore, substantial variance reduction results if a property is averaged over distances larger than the range, but not necessarily otherwise as neighbouring points then tend to have the same (unknown) value.

5.3.2 Variance reduction

In several cases, the soil or rock design is not governed by the point value of some property, but by a sum (integral) or equivalently by the mean over some surface or volume. Examples are the mean vertical load of the overburden of a soil volume or the mean level of the rock surface (which can be of interest when calculating the necessary excavation for a foundation at the bidding stage).

Another example considers the resisting force in calculating slope stability. This force can be expressed as the integral of element forces over the slip surface or equivalently as the mean shear strength multiplied by the area of the surface. Here a *caveat* is in place: This holds only when the demand that the property can be considered as a sum is fulfilled! This is for instance the case for ductile parallel systems, but it is not generally the case!

From statistics it is known that the estimate of the mean of a sample (or population) has a smaller variance than the variance of the elements. This is caused by the averaging out of high and low samples, so that the more samples are averaged, the smaller the variance of the mean will be:

$$\sigma^2_{\text{mean}} = \sigma^2/n \qquad \text{(for independent elements)}$$

However, this (fast) variance reduction is only valid for independent samples, e.g. data sampled outside the autocorrelation scale. When there is dependence between the samples, as depicted by their autocorrelation function, there is a corresponding reduction of the variance of an average over a length, area or volume. This reduction is described by the variance reduction factor Γ^2:

$$\sigma^2_{\text{mean}} = \Gamma^2\,\sigma^{2,}$$

where σ^2 is the point variance. The relationship between Γ^2 for the average over a line of length T and the autocorrelation function is given by:

$$\Gamma^2(\mathrm{T}) = \frac{1}{\mathrm{T}^2}\int_0^T\int_0^T \rho(t_1 - t_2)\,dt_1\,dt_2$$

This expression can be seen as the average of the correlation between all points on the line segment. There are corresponding expressions for the average over a surface or over a volume. These can also be seen as the mean correlation between the points on the area or in the volume.

Numerical integration of autocorrelation function

The application of a proper variance reduction will often have a profound effect on the design of underground constructions, as the variance has a large influence on the probability of failure. For practical purposes the calculation of the variance reduction can be done by numerical integration of the autocorrelation function, by using block kriging or by using Vanmarckes "scale of fluctuation" approach.

The interpretation of the variance reduction factor Γ^2 as the average correlation between all points on the specific line segment (or area or volume) in question can be used to calculate the variance reduction factor, see e.g. Olsson (1986). One way of doing the calculations is by Monte Carlo simulation:

- Sample two random points belonging to specific the space over which averaging is done and calculate the distance between them along all axes

- Calculate the correlation ρ between them, using a suitable autocorrelation function, e.g. $\rho(\Delta x,\Delta y;\Delta z) = \exp(-[(\Delta x/bx)^2 + (\Delta y/by)^2 + (\Delta z/bz)^2])$ where Δx is the distance between the points in the x-direction and so on, bx, by and bz are constants (Vanmarcke, 1977, Rackwitz & Peintinger, 1981).

- Repeat and calculate the mean of all the values of ρ. This mean is the variance reduction factor Γ^2 for the specific space considered.

Block kriging

When using kriging for extrapolation, one has the option of doing block kriging, i.e. kriging over a surface or over a volume. The kriging variance for a block is the reduced point variance. (In usual kriging software, a variation of the method above is used, with a number of fixed points used for averaging the correlation.)

Vanmarcke's method

Vanmarcke (1977, 1980, 1983) has treated the problem of estimating the variance reduction. He has introduced the concept ot the "scale of fluctuation δ_u" which is the "distance within which the soil property u(z) shows relatively strong correlation or persistence from point to point". For the reduction of the standard deviation $\Gamma_U(\Delta z)$ over a line with length Δz, Vanmarcke has suggested a "standard reduction factor, see Figure 5-26.

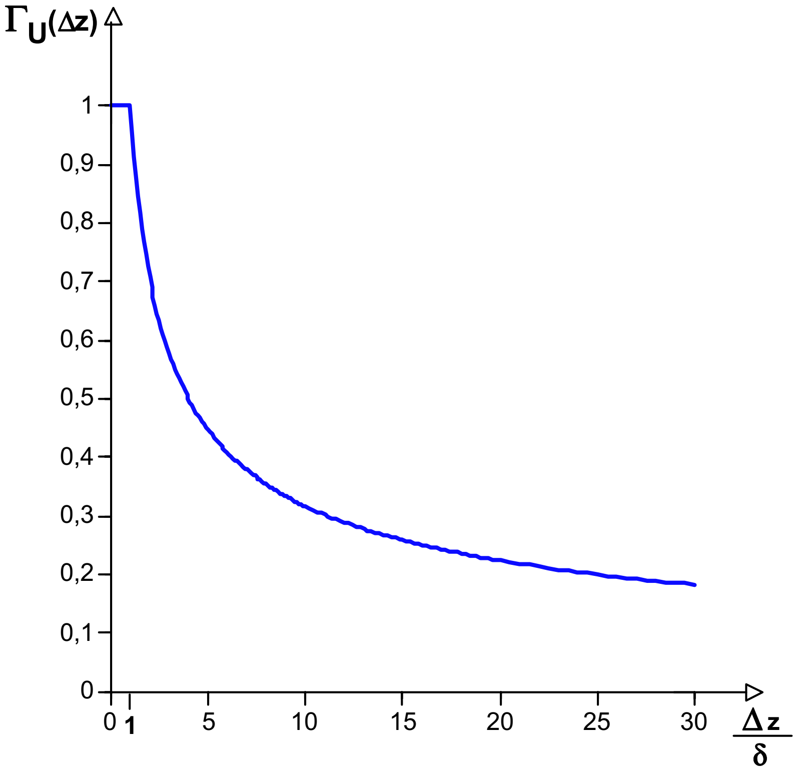


Figure 5-26 *Standard reduction factor (for standard deviation) as a function of the ratio between averaging length (Δz) and scale of fluctuation δ.*

The diagram is valid only for a line. As a line is fully is described by its lengths only, one can use this standard diagram to find the one-dimensional reduction factor for the actual length of the line. The scale of fluctuation must of course also be known, methods to estimate it are given in Vanmarcke (1983). (Another method that can be used in practice is to use the autocorrelation function and the relationship between this and the scale of fluctuation.)

It is also possible to use the scale of fluctuation for areas and volumes, but these applications are not as straightforward as for the one-dimensional case. It is therefore suggested, that the one-dimensional case be used to find a conservative value of the variance reduction, and to use the method in above for two- and three-dimensional cases.

5.3.3 Discrete representations

Fractures and fracture zones are important features in hard (crystalline rock). Fractures and fracture zones show a strong persistence of properties in their two-dimensional plane but have little extension transverse to this plane. This spatial structure is not easily captured by a continuous representation. Instead they are better viewed as stochastic objects in space, which is the basis for discrete stochastic representations. The most important example of discrete representations is the Discrete Fracture Network (DFN) concept, which primarily is used for representing fractures and deformation zones.

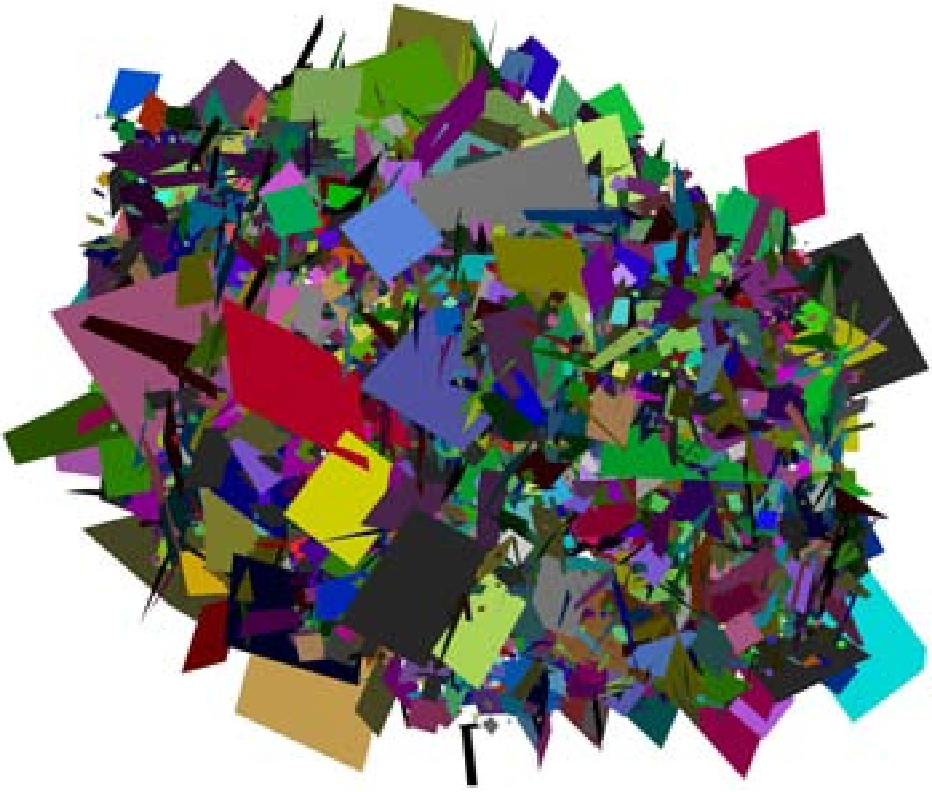


Figure 5-27 *An example of a Discrete Fracture Network (from Andersson, 2003).*

The crystalline rock mass contains deformation zones on a wide range of scales, from micro-cracks in the 'intact rock', individual visible joints, to regional fault zones. While the larger features may be described explicitly (deterministically), the smaller features require some kind of statistical representation. In some cases, like when assessing the overall stability of a rock cavern, the details of fracture geometry could be handled as averages and described as rock mass parameters (like rock mass deformation modulus). However, in other cases, like in key-block stability problems, the function of an underground construction will depend on the details of the fractures and a discrete, yet statistical, representation is needed.

The statistical description within the discrete fracture network terminology, see e.g. Dershowitz et al. (1998), typically comprises the following:

- Fracture orientation distribution for each fracture set, usually inferred from orientation measurements along scanlines (including boreholes) properly corrected for orientation sampling bias, e.g. Terzhaghi, 1965.

- Spatial distribution of fractures, i.e. random (Poisson distribution) or models implying statistical dependence among fractures (usually inferred from fracture positions/spacing measurements along sampling lines or from two-dimensional rock exposure mapping).
- Fracture size distribution. The size distribution should capture all fracture zone sizes ranging from lineaments not included in the deterministic model down to individual fractures. A lower size cut-off is needed, but the allowed cut-off depends on the use of the information and may be different for different applications.
- Volumetric fracture intensity. The fracture intensity, P_{32}, is the ratio between total area of all fractures to the total volume inside which the fractures are generated. P_{32} is linearly correlated to fracture frequency along a borehole or on the rock exposure. The proportionality constant depends upon fracture orientation and distribution of the fracture size. It is a much better measure than fracture frequency (which is orientation dependent) or fracture centre density (which depends on fracture sizes).

The statistical fracture parameters (the DFN-model) can be used to produce realisations of fracture networks using software such as FracMan (Dershowitz et al, 1998). These realisations can, in turn be used for analysing (the statistics of) e.g. key block stability (see e.g. Starzec and Andersson, 2002) or in calculating rock mass deformation properties (see e.g. Staub et al., 2002).

5.4 Confidence assessment

The confidence in a model is the total assembly of motives, indications, and arguments in support of the model, i.e. to what extent I believe that the model, including its parameters with uncertainty, adequately describes the problem to be analysed. High confidence is not the same as low uncertainty. If the uncertainty description is well founded, given the objectives of the analysis, the confidence can be high in the model. Conversely, if a model description with low uncertainty has a poor foundation, the confidence in the model should be low. Confidence in this respect should not be mixed up with ‘confidence intervals’ used in statistical analysis.

Confidence is essentially a qualitative concept, but this does not mean it is not important to consider. The decision analysis will be made using a system description with associated quantified uncertainties. The analysis will be no good if there is a fundamental lack of confidence in the description. Some kind of confidence assessment is needed.

Confidence assessment is qualitative and rests on ‘expert judgement’, but it can still be structured. For example, when assessing the confidence in the description of the rock mass the following questions could be raised:

- How is confidence affected by verification (or rejection) of previous predictions (if earlier descriptions exists)?
- How is confidence related to the information density? The confidence in a geological description is much governed by the overall geological understanding. Confidence in the description could be high even if there are few measurements if geological understanding is high (e.g. if there is a homogenous and evident geology), but could also be low, even with a 'wealth' of data, if the geological understanding is poor.
- How much of the rock volume is really characterised considering both information density and geological understanding.
- Are there measurements or other tests, which could separate between alternatives and enhance confidence?

The confidence assessment thus has a large impact on the evaluation of site investigation data. For example, if the confidence is high regarding the conceptual model (e.g. we 'know' we work in the Stockholm type crystalline rock') only few measurements may be needed to establish a quite good description of the rock. Reasons for low confidence may include that we work in a novel environment (e.g. volcanic rock in Islands) or because we get measurements in conflict with our concept (say that sedimentary rock as found in an investigation in Stockholm).

If the confidence is low one may need very many measurements in order to establish a model of the rock mass with reasonable confidence. This means that it is rather the confidence assessment than the statistical ranges found which would guide the need for further investigations. This is further discussed in Chapter 8.

5.5 Conclusions

Many design situations can be handled by risk based analyses. It implies that the uncertainties have to be expressed in terms of probability. This involves several considerations that have to be addressed. Examples of theses are the issues of the variations of a properties in the space and taken over a certain volume (mean value process). Handling and describing uncertainties is thus essential for proper decision analysis. However, even if the risk analysis requires quantitative uncertainty estimates, there are many decision situations where rough uncertainty estimates suffice.

To a large extent uncertainty in rock properties relate to the fact that rock properties vary, strongly, in space. However, many stability problems depend on the spatially averaged properties. Averaging implies potential for substantial variance reduction – which again in cases reduces the need for extensive data. Still, all problems are not well behaved in this manner, and there may also be a risk if too much bias is introduced. Finally, there are also less quantifiable uncertainty relating to future events (scenarios) and the conceptual understanding of the system. Handling these uncertainties is part of the System analysis described in previous chapters.

Subsequent chapters build on the framework presented in this chapter. Chapter 6 discusses how to estimate probability of failures. Chapter 7 describes how to use probabilities in decision analysis. Chapter 8 discussed how to obtain information on data and uncertainties.

6 System reliability

This chapter discusses means for assessing system reliability and probability of failure. There are also practical approaches, like the β-method and partial coefficient, which need to be considered in this context.

6.1 Reliability and probability of failure

A system, see section 3.2.2, can be defined as a ”composite entity, at any level of complexity, of personnel, procedures, materials, tools, equipment, facilities and software”. The ***reliability*** of the system can then be expressed as the likelihood that it will fulfil this given task or achieve the specific objective, i.e.:

*“**Reliability**. The probability that an item will perform its intended function for a specified interval under stated conditions.” (System Safety Society, 1999).*

For structural reliability, Thoft-Christensen & Baker (1982) give the following definition: “In a narrow sense it is the probability that a structure will not attain each specified limit state (ultimate or serviceability) during a specified *reference period*.” (In engineering one often talks about probability of failure. The following relationship exists between the reliability R and the probability of failure P_f: $P_f = 1 - R$)

As defined above, the system is composed of several components (that may be of very different nature). The system structure can be described graphically using for instance Reliability Block Diagrams, see Figure 6-1.

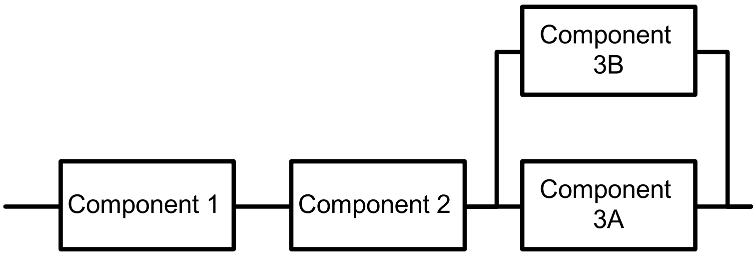


Figure 6-1 *Reliability Block Diagram*

The system in Figure 6-1 will have an adequate reliability if both of the Components 1 and 2 have a sufficient reliability and at least one of Components 3A and 3B has a sufficient reliability. The system can be described using other tools, for instance Fault trees or Success trees, which are Fault trees where the top event is desirable. The system in Figure 6-1 is shown in Fault tree format in Figure 6-2 and in Success tree format in Figure 6-3.

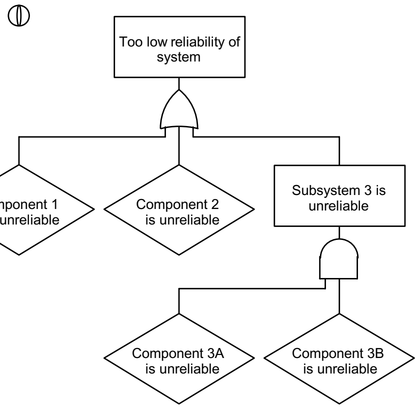


Figure 6-2 *Fault tree*

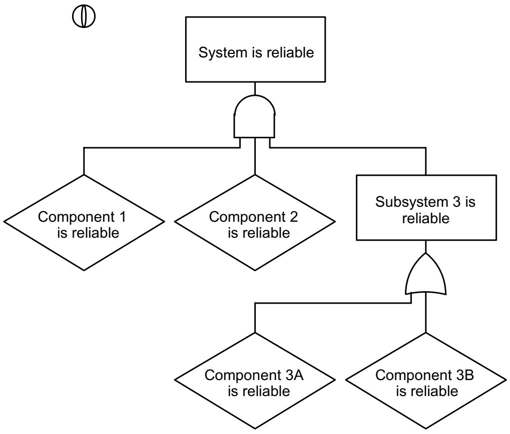


Figure 6-3 *Success tree*

In order to be able to calculate the reliability of a system, the demands must be clearly defined for all system components. Also, one might have to redefine the system components if the components are not independent but interact so that the performance of one component influences the limits for reliable performance of another component. An example is shown in Figure 6-4. The example concerns a hypothetical water pressure tunnel where reliability is governed by the total flow of leaking water. The tunnel will pass through three different rock types and different tunnel designs will be used to fulfil the reliability criterion of not exceeding the total allowed flow. For each rock type (i.e. for each design) the tunnel part can be modelled as one component in a series system.

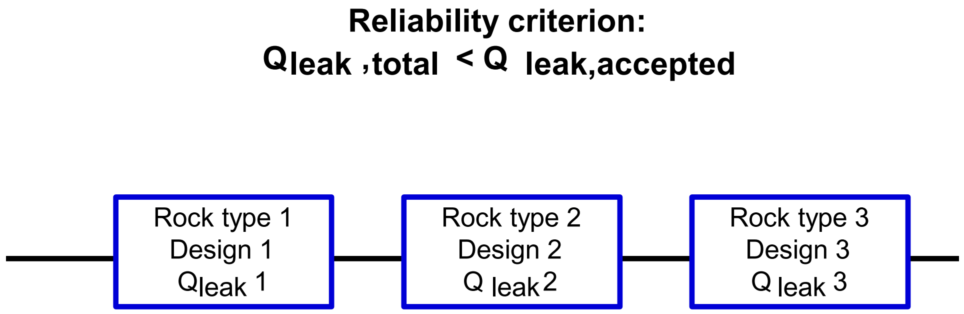


Figure 6-4 *Pressure tunnel system model. The tunnel will pass through three different rock types and different designs will be used to fulfil the reliability criterion.*

However, using this system description a counter-measure against leakage, say a water-tight concrete lining with a membrane, in one “component” will allow a larger leak in the other “components” without the system reliability being jeopardised. It is thus not possible to check the reliability of the components separately as the acceptable reliability of one component will be conditional on the reliability of other components and the system might better be redefined with just one “component”.

The systems that are encountered in rock engineering are most often complex systems composed by several components. This will be further described in section 6.5, which concern the probability of failure of a system. In the next section the basic methods to calculate the probability of failure of a component are described.

6.2 Calculating probability of failure of a component

In order to have a good basis for decisions, it is often necessary to calculate the reliability of different possible designs, construction methods etc. The goal of the reliability calculations is to calculate the probability of failure, (i.e. non-compliance with the limit state function) of the components of the system and thus of the system.

6.2.1 The general problem

For the reliability calculation the following must be known

- An expression $g(X_i)$ of stochastic variables that defines reliable behaviour, in (underground) construction often called limit state functions. This function is written in such a format that $g(X_i) < 0$ signifies failure.
- The stochastic properties of the uncertain variables in the limit state functions.
- The demands on the result accuracy (This is given by the underlying decision problem or in some cases by regulations).

For a simple case, where the limit state can be expressed in terms of a (stochastic) safety margin, i.e. the difference between the resistance and the load effect, the probability of failure is the probability of the safety margin being equal to or less than 0, see Figure 6-5. In the figure, R-S = 0 defines the limit state and the probability of failure is thus given by the shaded area.

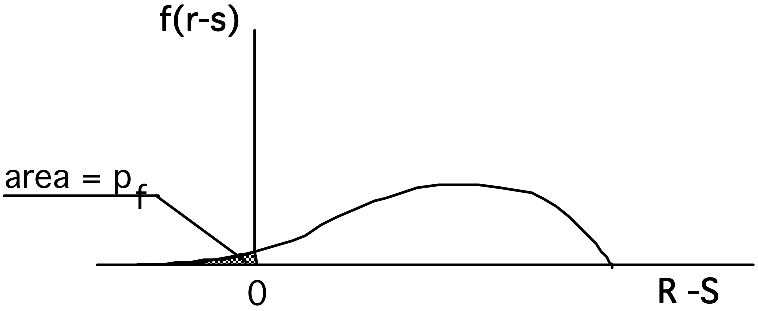


Figure 6-5 *Safety margin and probability of failure*

If the safety margin cannot be expressed as a single stochastic variable, the load effect and resistance might be expressed separately, see Figure 6-6. Failure is defined as Resistance – Load effect < 0 as in the previous case. In this case, the probability of failure is not given by the area where the two stochastic variables overlap, but by the expression:

$$P_f = \int_{-\infty}^{\infty} F_R(x) f_s(x) dx$$

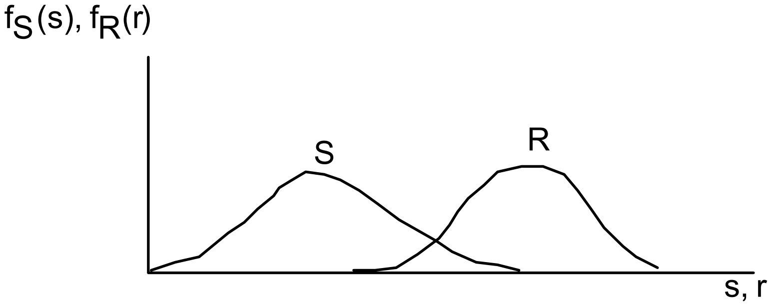


Figure 6-6 *Load effect and resistance*

In the general case, the limit state function is a function of several variables and the limit state function is a multivariate random variable. This is shown, for a bivariate function in Figure 6-7. As can be seen, the probability of failure is defined by the “volume” of the random variable in the failure region.

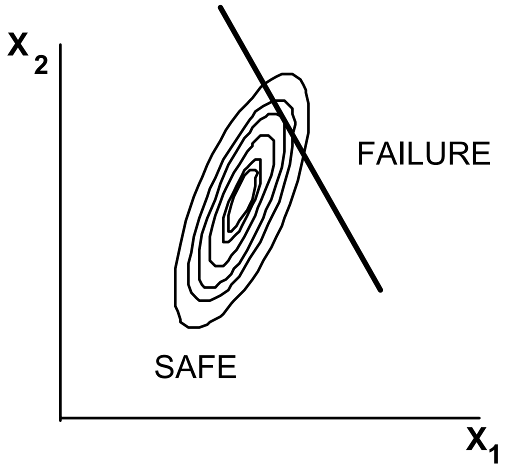


Figure 6-7 *Bivariate limit state function*

This volume is given (for the general n-dimensional case) by

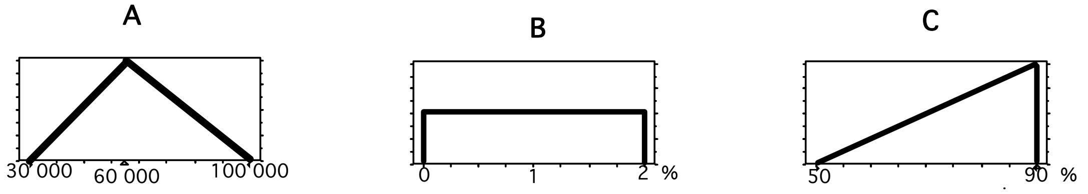
$$P_f = \iint\limits_{failure\ region} \ldots \int f_{X_1, X_2, \ldots X_n}(x_1, x_2, \ldots, x_n) dx_1, dx_2, \ldots, dx_n$$

6.2.2 Calculation methods: Overview

The direct analytical calculation of the integrals defined above is very seldom possible and other calculation methods must be used. Usual calculation methods for the direct calculation of the probability of failure are numerical integration often by using simulation methods, see section 6.2.3. In the construction industry, a proxy safety measure, the safety index β, has come into use, see section 6.3. When the safety index is calculated according to certain principles, the probability of failure can be calculated from the safety index.

6.2.3 Simulation methods

Simulation methods are based on the principle of sampling all the stochastic variables that are part of the function and inputting the sampled outcomes into the function to calculate one possible outcome. An example is shown in Figure 6-8 where the problem is to calculate “Result = A*B*C”, where A, B and C are stochastic variables as shown in the figure.



Calculation round	Outcome sampled from A	Outcome sampled from *B*	Outcome sampled from *C*	Calculated *Result*
1	83138	0,5%	78%	**337**
2	48345	0,1%	83%	**34**
3	69421	1,9%	89%	**1147**
4	96684	0,7%	87%	**544**
•	•	•	•	•
•	•	•	•	•
•	•	•	•	•

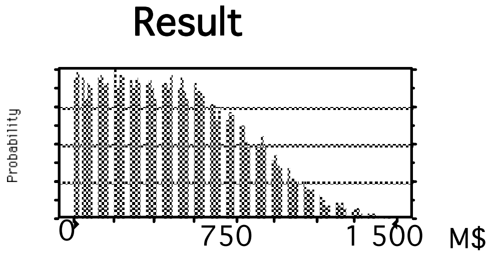


Figure 6-8 *Simulation example.*

It is of course necessary to get representative samples from the stochastic variables. The principle of doing this is shown in Figure 6-9. The stochastic variable is described by its Cumulative Distribution Function. A probability is drawn at random from a uniform distribution and the corresponding outcome is calculated from the CDF.

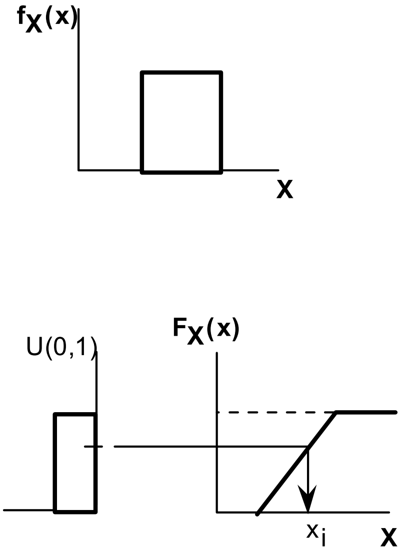


Figure 6-9 *Creating random numbers*

When calculating the probability of failure using sampling methods, two approaches are possible.

- In the first approach, one calculates possible outcomes of the limit state function. This outcome might be safe or failure. If this sampling is repeated a number of times, one will get an estimate of the failure probability as the ratio of failed outcomes/ total number of outcomes. Using normal statistical tools, one can estimate the necessary number of samples to get the required precision in the estimate of the probability of failure.
- The other approach is to write the safety margin as a function of the stochastic variables. Using samplings of the stochastic variables one can calculate the safety margin. If this is repeated a number of times, one can estimate the CDF of the safety margin.

The probability of failure can then be calculated as the area shown in Figure 6-5.

6.3 Safety index *β*

The calculation of the probability of failure is often tedious and some other safety measure is desirable, which is easier to calculate but still is based on the likelihood of failure. Since the distributions of R or S are problem dependent and for some problems are very wide and some other times quite narrow the usual Factor of Safety (R/S) and Safety Margin (R-S) are not satisfactory in this regard. Depending on spread of the R or S distributions different safety factors must be used to get the same probability of failure. A new measure, called the safety index β, was suggested in the 60-ies and has been further developed.

6.3.1 Simple β, mean and standard deviation

The first definition of the safety index β uses the safety margin (resistance – load effetct). The safety index is defined as the distance between the failure limit (= Safety Margin = 0) and the mean (expected value) expressed in standard deviations, see Figure 6-10. The only statistical information used is thus the first two moments. This method is sometimes called FOSM, First Order Second Moment.

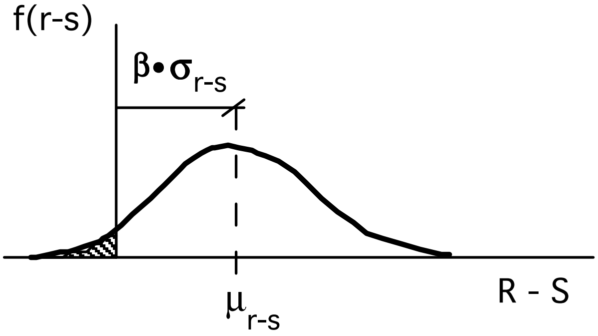


Figure 6-10 *Simple β*

Even though this definition of β is attractive, inter alia due to its simplicity, it has a very serious drawback. There is an unambiguous relation between β and the probability of failure only for the case where the safety margin is Gaussian. This means that for one particular value of β, there can be several values of P_f, depending on the specific problem i.e. the failure limit. In the figure, the shortest distance from the mean to the failure limit is β*σ, and the "volume" outside the failure limit is the probability of failure, P_f. For the same β one can thus have different P_f. This of course makes it impossible to specify general values of β in codes.

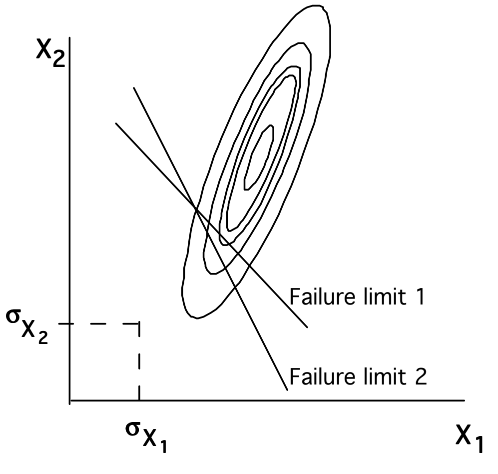


Figure 6-11 *Different failure probabilities with same β*

6.3.2 Hasofer –Lind β

The problem of having different probabilities of failure corresponding to the same β was solved by Hasofer & Lind (1974). They defined a safety index β_{HL}, which is defined as the shortest distance from the origin to the failure surface, in a co-ordinate system where all random variables have been transformed to N(0;1) and the failure surface of course has been transformed into the same co-ordinate system, see Figure 6-12. Due to the rotation symmetry, there will be an unequivocal relationship between β and the probability of failure if the failure surface is a plane. This relationship is given by: $P_f = \phi(-\beta)$; $\beta = -\phi^{-1}(P_f)$. See Table 6-1.

Table 6-1 Relationship P_f - β

P_f	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1,28	2,32	3,09	3,72	4,27	4,75	5,20

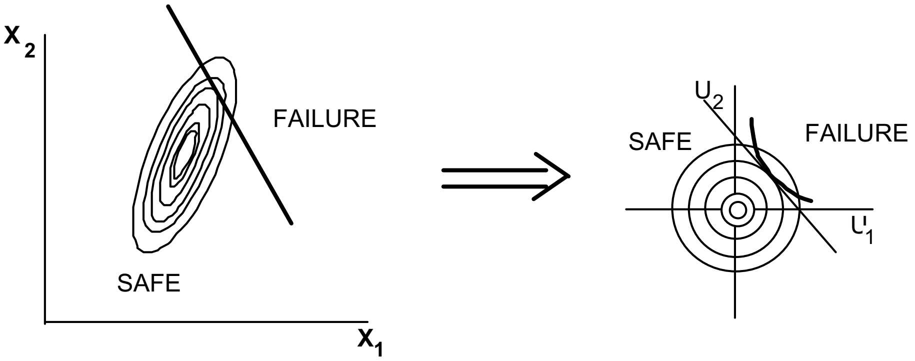


Figure 6-12 *Hasofer-Lind transformation*

6.3.3 FORM

The First Order Reliability Method (FORM) is one method of calculating the Hasofer-Lind safety index. In this method all stochastic variables are defined not only by their moments but also by their distribution function and correlation structure.

For an account of the method, see e.g. Thoft-Christensen & Baker (1982). The calculation of the safety index is done iteratively, usually using the so called Rackwitz-Fiessler algoritm, see Rackwitz & Fiessler (1978). Though simple problems can be solved by hand, for practical problems, special (and rather expensive) software is normally used as the calculation problems are rather tedious involving finding eigenvectors, transformed space and iterations.

6.3.4 Other formulations

There are simpler approaches to the calculation of $\beta_{HL.}$ Low & Tang (1997) point out that an alternative to the usual calculation method one can maximise the multivariate normal probability density function and find the smallest ellipsoid that is tangent to the failure surface, with no need to transform the variables into uncorrelated ones. This calculation can be done iteratively using a spread-sheet e.g Excel, and several soil-and rock mechanics applications have been published, see e.g. Low (1997), Low, Teh & Tang (2001a), Low, Teh & Tang (2001b) and Low (2001). The approach may be valuable for practical use by construction engineers, as less focus is placed on the special mathematics of the usual calculation method.

6.4 Partial coefficients

In order to have a safety measure, which is more nuanced than the conventional safety factor and at the same time simple to use, the concept of partial coefficients has been introduced. The basic difference from the ordinary safety factor is that different partial coefficients are applied to the different uncertain variables in the limit state expression, at least to the load effect and the resistance.

One can find a theoretical relationship between partial coefficients and the safety index β_{HL}. The point on the failure surface closest to the origin (=mean) is usually called the design point. It is defined by the direction cosines α (also called sensitivity factors) and the distance β, see Figure 6-13.

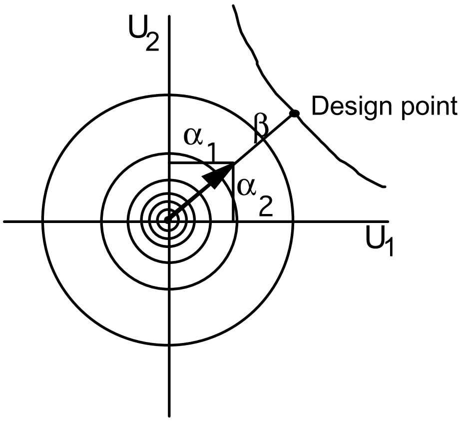


Figure 6-13 *Design point*

One can obtain a construction with the same design point and which thus agree with the safety index if one chooses characteristic values for all the uncertain variables and then obtains design values by multiplying the characteristic values with a partial coefficient γ defined by

$$\gamma_i = \frac{x_{ki}}{\mu_i + \alpha_i \cdot \beta \cdot \sigma_i}$$

x_{ki} is the characteristic value of variable i
μ_i is the mean of variable i
α_i is the sensitivity factor of variable i
σ_i is the standard deviation of variable i

It must be observed that:

- The uncertainty of the calculation model itself can be expressed as a stochastic variable (M = True value/ Computed value) and included in the calculations.
- The characteristic value is characteristic from a statistical point of view, usually the mean or some specified percentile.
- In order to have the same design as when using β_{HL}, all variables must be multiplied with their respective partial coefficient.

It has been suggested that for structural engineering one can use a simplified method to obtain an estimate of the sensitivity factors α_i (Thoft-Christensen and Baker, 1982). A similar approach has been tentatively suggested by Bengtsson et al. (1991). The method is simple to use, but is very sensitive to assumptions made of the relative importance of the variables. It has not been the subject of extensive tests, and should be used with caution.

It must also be observed, that the theoretical expression for the partial coefficients given above is not used in codes. In the codes, one prefers to multiply the actions (loads) and to divide resistance with the partial coefficients. It is also often prescribed that resistances should be considered to have a Lognormal distribution.

Assuming a Lognormal distribution and transforming it to a Normal distribution his leads to the following expression for the partial coefficient for resistance, see e.g. Alén (1998):

$$\gamma = \frac{R_k}{\mu * \exp(-|\alpha|\beta V)}$$

where R_k is the characteristic value of the resistance and V is the coefficient of variation (σ/μ).

6.5 Calculation of the probability of failure of a system

Systems are built up with component that can be arranged in different combinations. The components influence the behaviour of the system through their properties (e.g.

load-deformation curve, post failure behaviour). The two main system configurations are *series systems* and *parallel systems* and also *combinations* thereof.

6.5.1 Series systems

A series system is of the weakest link type. It fails as soon as one component fails, see Figure 6-14. For the simplest case, where the components are independent, the probability of failure can be calculated with the following expression:

$$P_f = 1-\Pi(1-p(\phi_i))^{n}$$

which says that the probability of failure is equal to 1 minus that no component will fail. However if the components are dependent this relation will be modified.

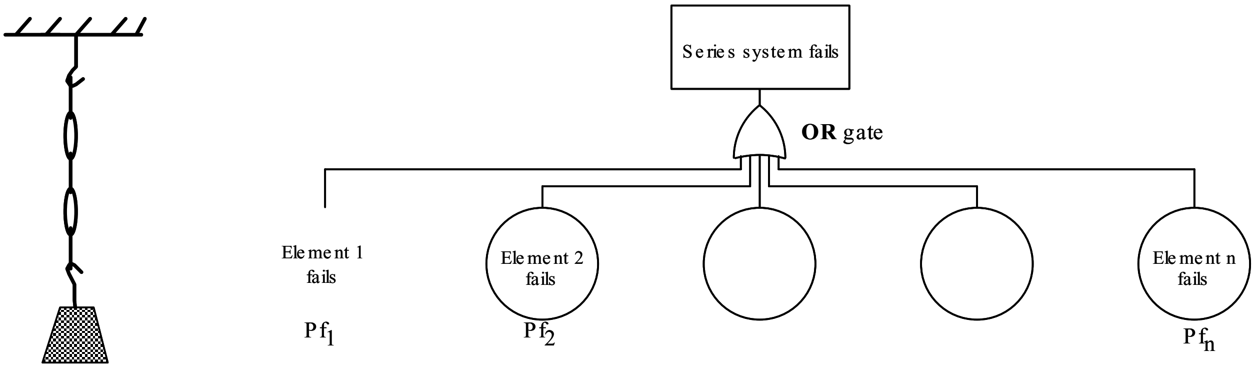


Figure 6-14 *Series system and its corresponding fault tree*

In general, the behaviour of a series system is governed by the number of elements, the failure probability of the elements and the correlation between the elements. This is shown in Figure 6-15, which shows the probability of failure of a series system where all elements are designed to have the same probability of failure ($p_f = 0.01$) and are equally correlated.

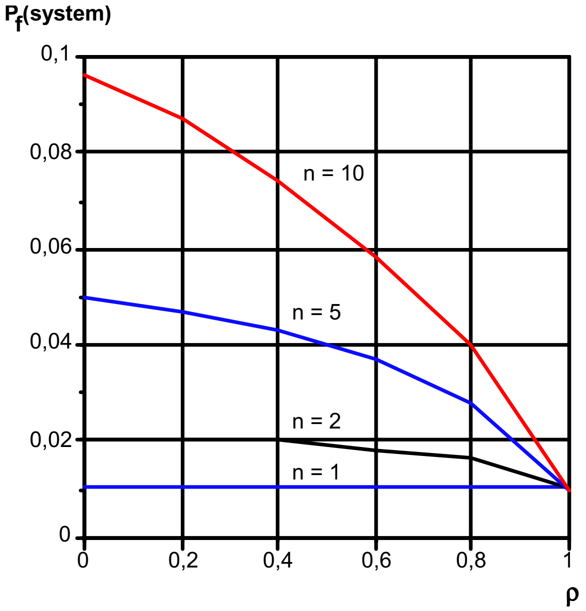


Figure 6-15 *Series system behaviour as a function of correlation (ρ) between components and the number of components (n) where all components have an individual* p_f*=0.01.*

As can be seen from Figure 6-15 the probability of system failure decreases with the correlation between the elements and increases with the number of elements.

6.5.2 Parallel systems

A parallel system fails when all components fail, see Figure 6-16. For the simplest case, where the components are independent, the probability of failure can be calculated with the following expression

$$P_f = \Pi p_f(\phi_i)^{\,n}$$

In general the behaviour of a parallel system is governed by the number of elements, the failure probability of the elements and the correlation between the elements and also by the system for load sharing between the elements. The load sharing can be such that the load is shared equally between the elements, but it can also be deformation governed.

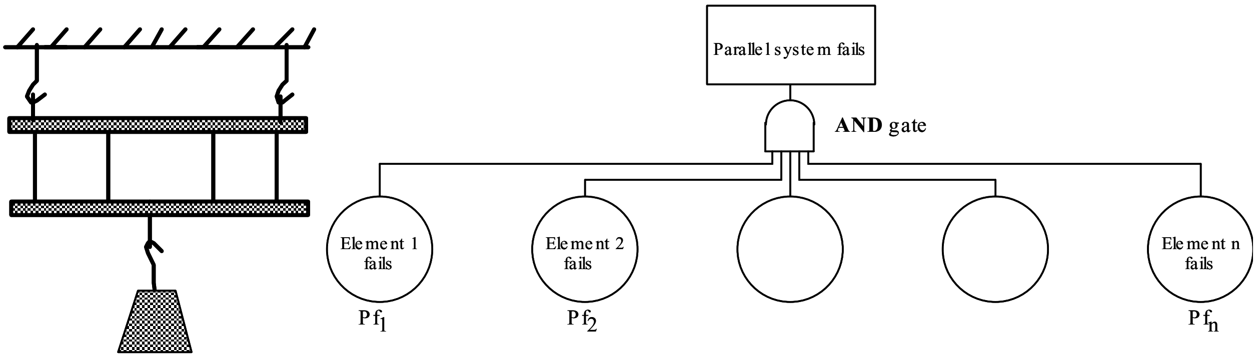


Figure 6-16 *Parallel system and its associated fault tree*

The behaviour of a parallel system is governed by the number of elements, the failure probability of the elements and the correlation between the elements and also by the system for load sharing between the elements. The load sharing can be such that the load is shared equally between the elements, but it can also be deformation governed.

For a parallel system with equal load sharing, the behaviour is illustrated in Figure 6-17 showing the probability of failure of a parallel system, where all elements are designed to have the same probability of failure ($p_f = 0{,}01$) and are equally correlated.

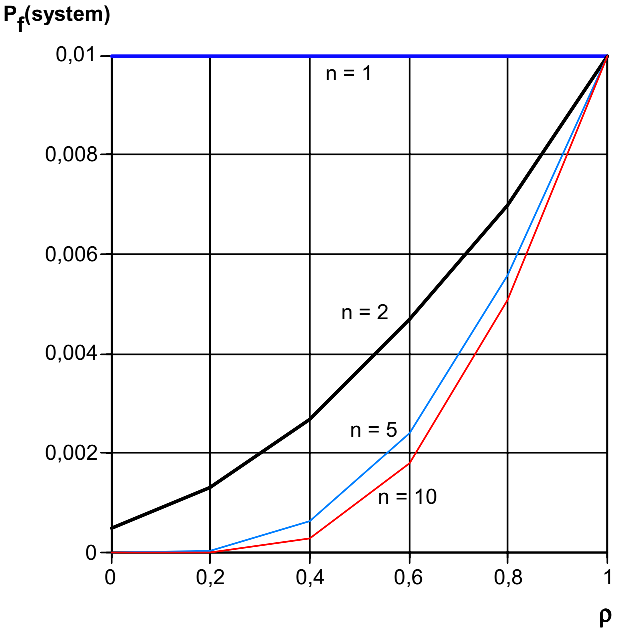


Figure 6-17 *Parallel system behaviour as a function of correlation (ρ) between components and the number of components (n) where all components have an individual p_f=0.01.*

As can be seen from Figure 6-17 the probability of system failure for a parallel system decreases with the number of elements and increases with the correlation between the elements.

6.5.3 Complex systems of reality

The systems that are encountered in real life rock engineering problems are most often complex combinations of parallel and series systems. A complex system may be described by a fault tree, where parts are in series and other parts act in parallel. This of course has a great influence on the fault trees that are used to depict the system.

The tree methods described in sections 4.3 and 4.4 might be used to assess the probability of failure of a system. If the top event in a fault tree is "System fails" the probability of failure may be calculated if the tree is correctly quantified. (It might also be possible to calculate the probability of failure from an event tree, using the path probabilities of paths leading to "system failure".)

6.6 Time variant reliability

Usually, when underground structures are designed, the design is made under time invariant considerations. However, real conditions affecting the reliability are not necessarily invariant. Both load actions and resistance may vary. Although for underground constructions load actions often are more or less invariant, for general geotechnical constructions loads can vary, e.g. wind loads carried down to foundations or varying water pressures in a tunnel. Also, the resistance may vary, due to deterioration of the material in the construction, e.g. shotcrete and rock bolts. This is often illustrated using the so called "bathtub curve" which shows the hazard rate (conditional probability of failure per unit of time) for a construction, see Figure 6-18.

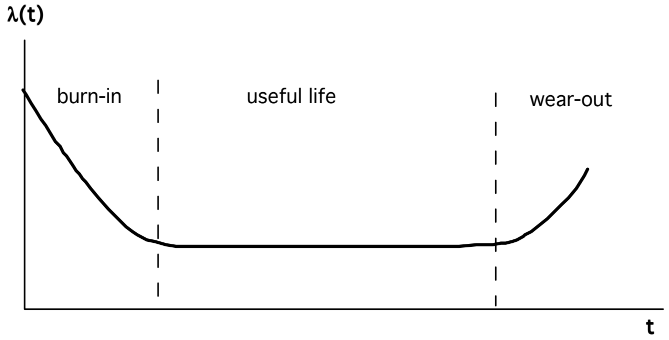


Figure 6-18 *Bathtub curve*

When calculating the reliability, the time frame must be taken into consideration. Often in codes the demands are stated both for the intended lime time of the construction (the design working life) and for the required reliability for different reference periods, see Table 6-2. In principle it can be looked upon as being a series system.

Table 6-2 Required safety index β (from EN 1990).

Reliability Class	**Minimum values for β**	
	1 year reference period	50 years reference period
RC3	5.2	4.3
RC2	4.7	3.8
RC1	4.2	3.3

NOTE A design using EN 1990 with the partial factors given in annex A1 and EN 1991 to EN 1999 is considered generally to lead to a structure with a β value greater than 3.8 for a 50 year reference period. Reliability classes for members of the structure above RC3 are not further considered in this Annex, since these structures each require individual consideration. (From EN 1990. Eurocode - Basis of structural design)

The concept of time variant reliability is rather new and partly at the research stage, see e.g. Kuschel & Rackwitz (1999) who discuss Reliability-Based Cost Optimization (Minimization of total cost subject to reliability of the structural system and other constraints.)

Time-dependent models are discussed in e.g. Hasofer & Rackwitz (1999), reliability changes due deterioration is treated in e.g. Enright, Frangopol & Gharabeih (1999) and the assessment of existing structures is discussed by Val & Stewart (1999).

6.7 Codes

The codes which will have the largest influence on future Swedish underground construction is the so called Eurocode. This consists of two general parts: Basis of Structural Design and Actions on Structures, respectively and eight material related parts of which part 7 deals with Geotechnical design. Below some important concepts of the codes are discussed.

- Design is made for two limit states: The *ultimate limit state* which concerns the safety of people and/or the safety of the structure and the *serviceability limit state*, which concerns the functioning of the structure under normal use, the comfort of people and the appearance of the construction works.
- Reliability management. The reliability required shall be achieved by design in accordance with the Eurocode and by appropriate execution and quality management measures
- The design working life should be specified
- Limit state design Verifying that the demands that no limit is exceeded can by done by:

- Geotechnical design by calculation. Limit state design can be done using the partial factor method as described in the Code. As an alternative a design directly based on probabilistic methods may be used for which target values of the safety index β are given. A bayesian approach is allowed
- Design by prescriptive measures. These are conservative, nationally rules that can be applied where calculation methods are not available or not neecessary.
- Load test and tests on experimental models. Design can be justified using results of load tests or tests on large or small scale models.
- Observational method (see section 8.3). In this method the behaviour of the construction is monitored during work and a comparison is made with predefined limits.

6.8 Conclusions

The reliability of a system can be expressed as the probability that it will fulfil its given task or achieve its specific objective. There are various tools for exploring reliability. Of particular importance is whether the system is a parallel system, a series system or a combination thereof.

In order to have a good basis for decisions, it is often necessary to calculate the reliability of different possible designs, construction methods etc. Exact solutions generally imply solving multiple integrals analytically and are thus seldom searched for. Usual calculation methods for the direct calculation of the probability of failure are numerical integration often by using simulation methods. In the case where a high degree of accuracy is not called for, one might use risk analysis methods to calculate the probability of the occurrence of an undesired event (i.e. the failure). In the construction industry, a proxy safety measure, the safety index β has come into use. When the safety index is calculated according to certain principles, the probability of failure can be calculated from the safety index. In order to have a safety measure, which is more nuanced than the conventional safety factor and at the same time simple to use, the concept of partial coefficients has been introduced. The basic difference from the ordinary safety factor is that different partial coefficients are applied to the different uncertain variables in the limit state expression, at least to the load effect and the resistance.

As pointed out in the previous chapters the concept of probability is essential to describe our uncertainties and to guide the different decision that have to be taken. In this context both the probability of different scenarios and the probability of failure of a certain system given a scenarios has to be discussed.

7 Decisions and decision aiding tools

This section first presents how decision trees can be used to aid decisions made under uncertainty. It then also briefly discusses some other decision aiding tools. Furthermore, just by structuring the problem to be analysed as a decision tree helps in defining the problem (see chapter 3). Thus, it is not only the numerical outcome of the decision analysis, but also the very decision analysis itself, which eventually guide the decision making. In fact, even when the formal and quantitative decision analysis is performed it is always advisable to assess the outcome on it own merits. Does the decision make sense? Is there a logic, apart from the formal analysis, which can be used to support the decision).

7.1 Decision trees

7.1.1 General principles

Decision trees are useful in those cases where all possible outcomes can be expressed in the same quantity e.g. money and the goal of the decision is to minimise costs (or equivalent: to maximise profit). They are a graphical method to depict the decision situation with possible decisions, uncertainties and outcomes.

A decision tree is built from the following components, see Figure 7-1:

- Decision nodes, where there exists a choice to be made.
- Chance nodes, where there is a possibility that events can follow one path or another, but the path followed is governed by chance.
- Terminal nodes which describe the outcome if a certain path is followed

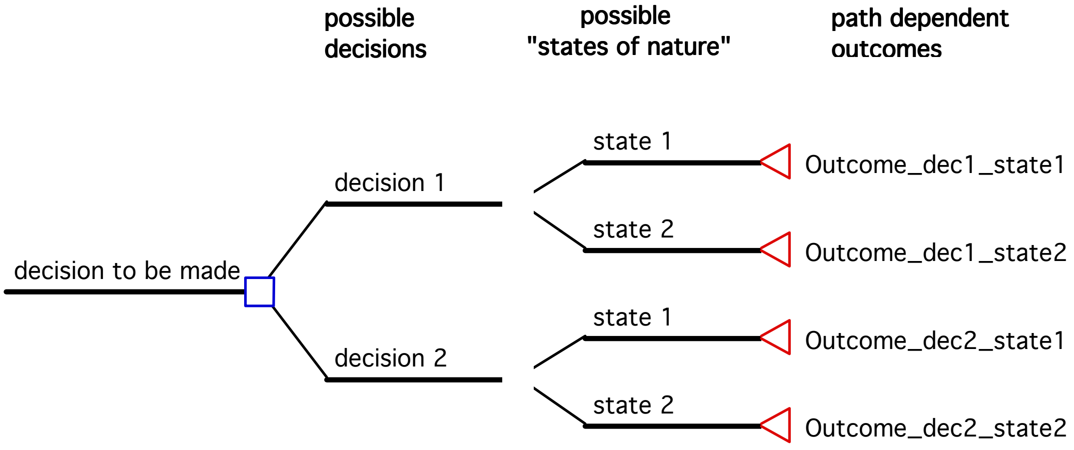


Figure 7-1 *Decision tree components*

Such a tree is often called "qualitative" as uncertainties and outcomes have not yet been enumerated. When that is done, one can talk about a quantitative decision tree, which can be analysed and used as a base for decision making, see Figure 7-2.

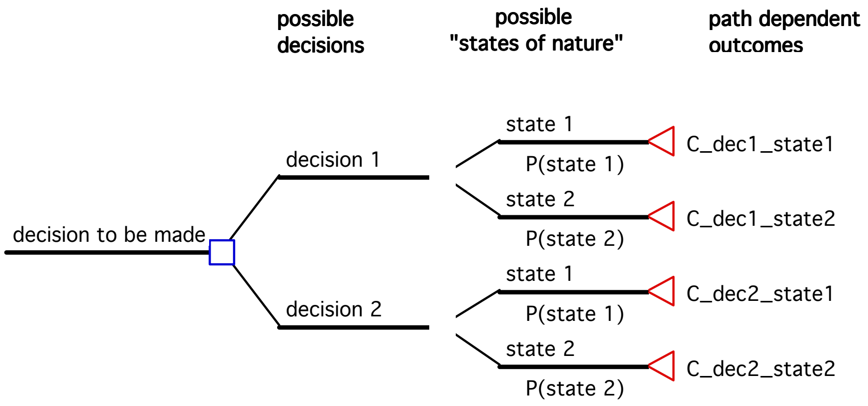
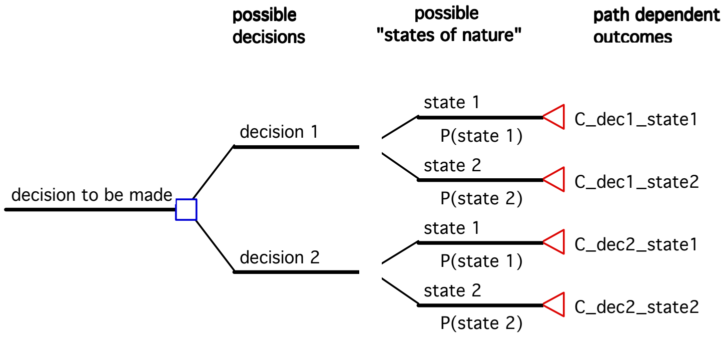


Figure 7-2 *A quantified decision tree*

In order that the tree shall be useful for decision making, one must have a criterion for which decision is the best. One such criterion is called the "subjective expected utility" criterion (also known as the Bayes criterion). It takes its name from the following observations:

- Probabilities are subjective
- The value to be attached to a certain outcome must reflect the decision makers opinion of their desirability. Thus these values are subjective too.
- The best estimate is the expected value

The evaluation of a decision tree is made by a so called roll-back where starting from the outcomes the expected value of following each branch is calculated, see Figure 7-3.



EC (decision1) = P(state 1) x C_dec 1_state1 + P(state 2) x C_dec 1_state2
EC (decision 2)= P(state 1) x C_dec 2_state1 + P(state 2) x C_dec 2_state2

Figure 7-3 *Roll back principle*

In accordance with the principles the decision with the lowest estimated cost is the correct one. Putting some (fictitious) values into the tree gives the roll-back in Figure 7-4.

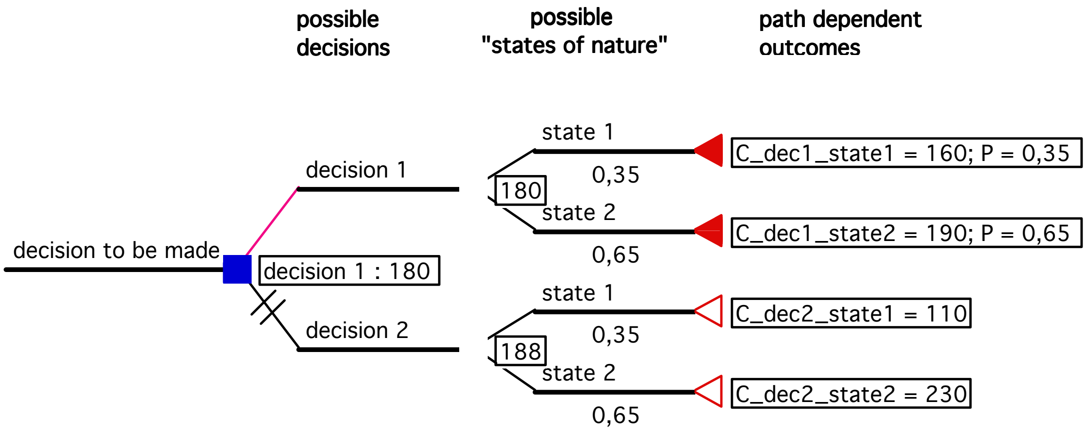


Figure 7-4 *Roll-back*

(As can be seen from the tree in Figure 7-4, the correct decision is decision 1,with an expected cost of 180)

7.1.2 Quantifying outcomes

Usually the outcome of a decision is calculated in monetary terms, but there are two cases where there is a need for special considerations.

Utilities

It might not be sufficient for the decision-maker to use a straight monetary value when quantifying the outcomes. He might for instance wish to avoid large losses, so such losses should be "exaggerated" in the calculations. Some values should be used that reflect his subjective preferences. These are usually called utilities and are assessed by the decision-maker.

For a description of the procedure see e.g. Ang & Tang (1984). The conversion between monetary values and utilities is usually shown in a graph, see the example in Figure 7-5.

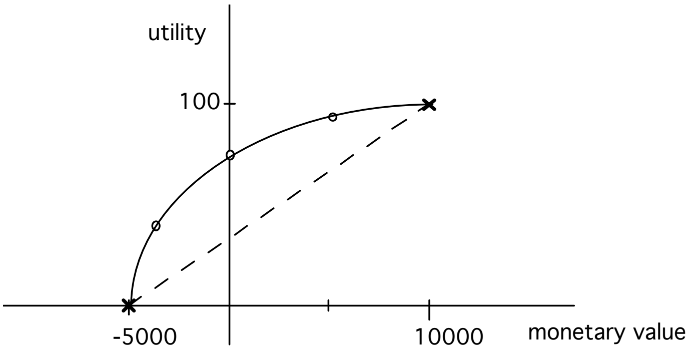


Figure 7-5 *Utility curve*

Multi-attributive utility

Sometimes one wishes to reach several goals at once with the decision, for instance at the same time minimise cost and minimise environmental impact. This is a case of multi-objective decision analysis. For such problems a special utility function is needed, a so called multi-attributive utility. For a discussion of this problem, see e.g. Ang & Tang (1984), Keeney & Raiffa (1976).

7.1.3 Constructing a decision tree

The construction of a decision tree should be done in a systematic manner. Some suggested steps in the construction of a decision tree are:

- Define and delimit the problem
- Identify the alternatives
- Calculate outcomes of the alternatives
- Choose variables
- Structure the decision, construct decision tree

- Determine probabilities
- Evaluate the tree (rollback)
- Run sensitivity test

More detailed accounts for the process can be found in the literature, see e.g. Ang & Tang (1984), Olsson & Stille (1980).

7.1.4 Decision in stages

There might often be the case that the decision process calls for decisions at different stages in the tree. This means that the primary decision to be evaluated will depend on decisions taken later on and thus unknown at this stage, they might be compared to chance nodes. This problem is handled assuming that the decision-maker is logical and follows the principles above, i.e the later decisions are those that are optimal in the roll-back.

7.1.5 Adding information

In the examples above, the decision has been based on existing information, so called prior analysis. The decision depends on the possible consequences and on the probabilities of the branches. These probabilities might be based on a small amount of (prior) information.

Often there is a possibility for gathering more information to be included in the decision process by updating the branch probabilities and repeat the analysis, a so called posterior analysis. ("Posterior" refers to the gathering of additional data.) As a rule, this information gathering has a price, and the question is what the value of the added information is. This value of course is expressed in terms of a lower expected cost of the decision. There is a possibility of assessing the value of gathering more information before it is really available (so called pre-posterior analysis). Thus it is possible to make a decision e.g. on whether an extensive soil investigation should be made or if a less extensive one is more cost effective. This is done by comparing the expected cost calculated with only the original information (probabilities) with decisions made with the updated probabilities. We have thus a new decision to make: the decision whether to gather more information or not. The decision tree for the new situation is shown in Figure 7-6.

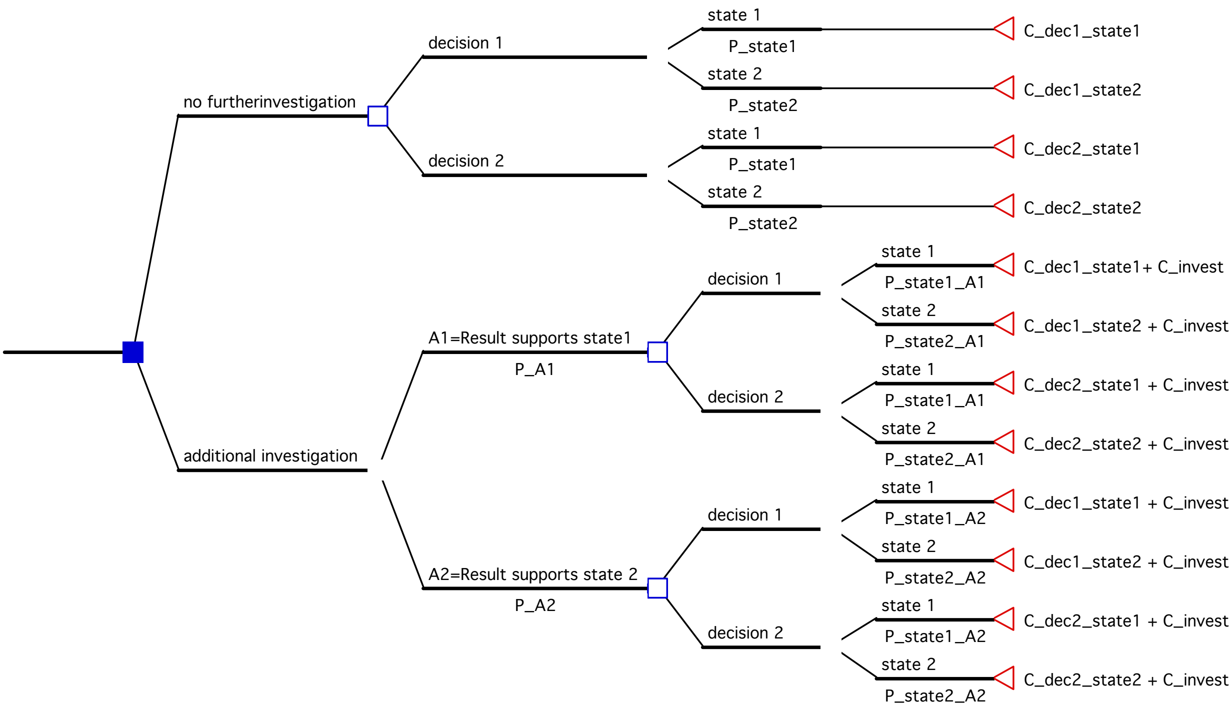


Figure 7-6 *Decision tree for choosing investigate or not*

In the tree the outcomes are as before, with additional investigation cost. In the case of an investigation, the probability of each state depends on the investigation result and its information value.

Perfect information

If we at first make the assumption that we can acquire perfect information, i.e. that we can predict the unknown states of nature with absolute certainty, we talk about the value of perfect information. In this case, if the investigation supports state 1, then state 1 is the true state (probability = 1) and state 2 has a probability of 0.

What remains to assess is the probabilities of the different test results. These are the prior probabilities of the corresponding states of nature. The resulting tree and roll-back is shown in Figure 7-7 (As we wish to assess the value of a perfect information, no investigation cost is entered in the tree)

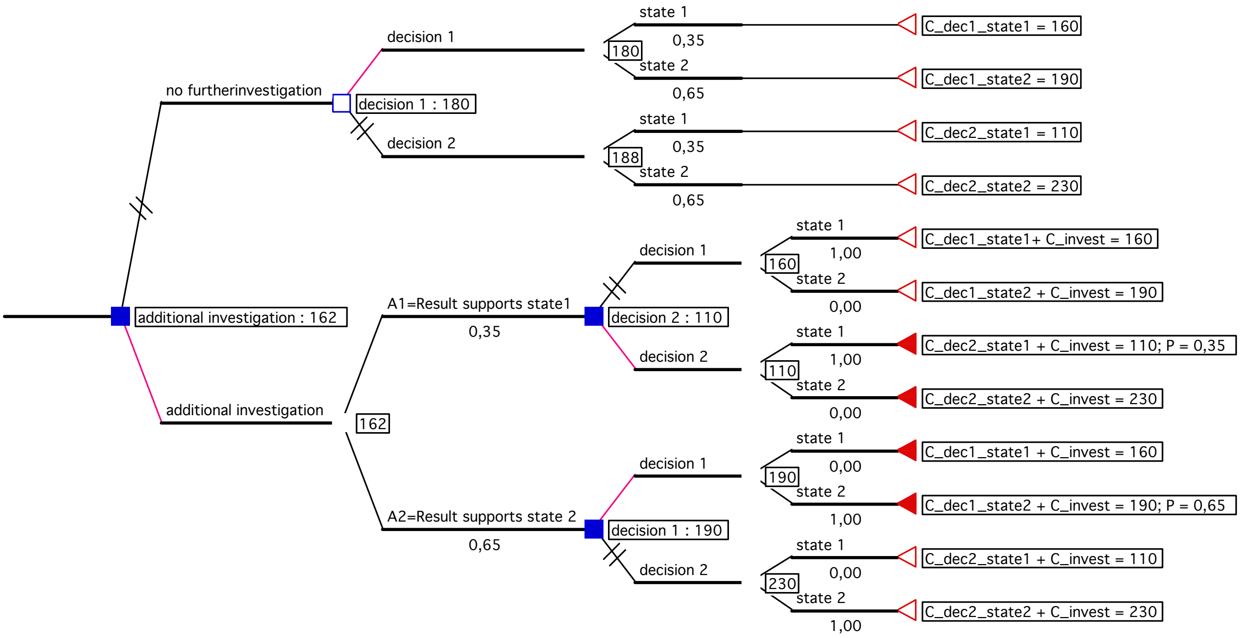


Figure 7-7 *Expected value of perfect information*

From the tree it can be seen that the expected cost with the perfect information has decreased from 180 to 162. This means that. perfect information is worth 10% of the cost. Also the best decision has changed from decision 1 to the decision to investigate and then the best choice is decision 2.

Imperfect information

If the expected value of perfect information is such that it well covers the cost of a real investigation, one might proceed to calculate the value of imperfect investigation. In this case, one must estimate the precision of the investigation and state that e.g. in a reliability matrix. Such a matrix might look like in Table 7-1.

Table 7-1 Reliability matrix for rock investigation

Exploration result	**State of nature**	
	State 1	**State 2**
A1	0,8	0,3
A2	0,2	0,7

From such a reliability matrix and the prior probabilities for the different states of nature it is possible to calculate the posterior probabilities for the states of nature and also the probabilities to get the different exploration results, see Table 7-2 and Table 7-3.

Table 7-2 Posterior probabilities given different exploration results

Exploration result	**Posterior probabilities given result**	
	P''(state1 | result)	**P''(state2 | result)**
A1	0,59	0,41
A2	0,13	0,87

Table 7-3 Probabilities for different exploration results

Result	**Probability of result**
A1	0,475
A2	0,525

These figures can then be entered in the decision tree and the value of the imperfect information can be calculated, see Figure 7-8.

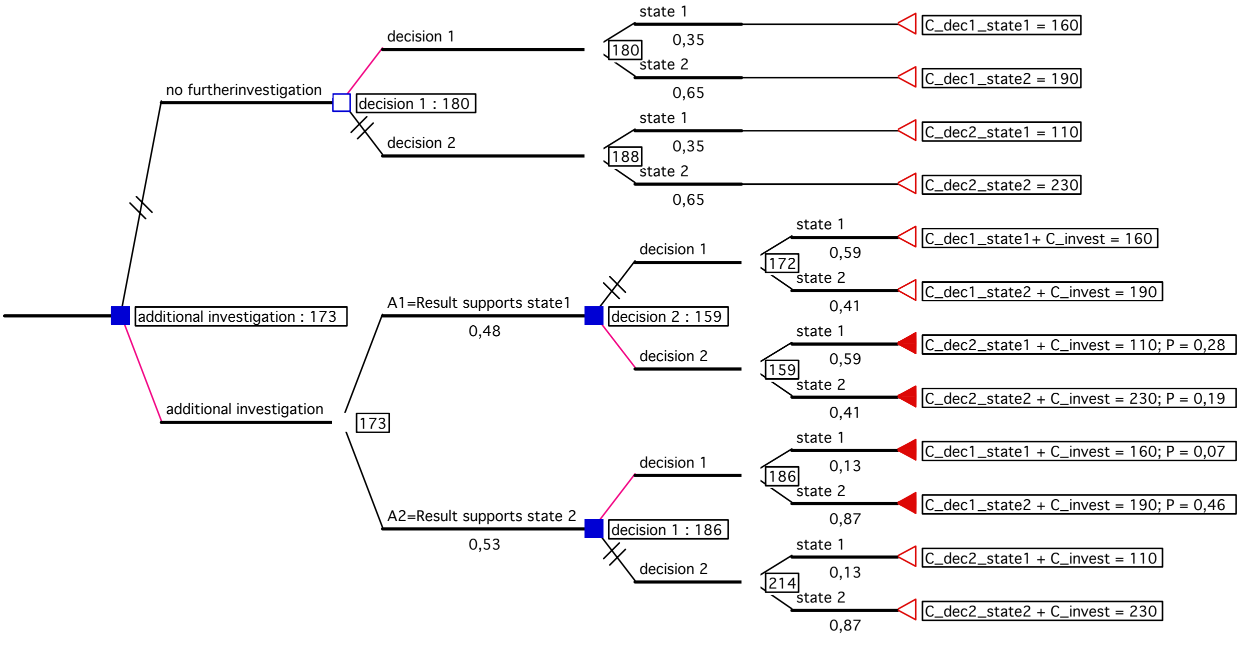


Figure 7-8 *Decision tree with imperfect information*

From the tree it can be seen that the expected value of the exploration is 180 –173 = 7 i.e. < 4% of the cost. An exploration program with the stated reliability should thus be undertaken if the cost is less than that.

7.1.6 Uncertainty in the outcomes

It is often the case that one cannot state the outcomes exactly, but rather as an interval or perhaps in the form of probability density function.

This can be handled by representing the interval or the PDF by a set of discrete values with the corresponding probabilities and adding these as end-branches from a chance node.

7.2 Probabilities in decision analysis

Probabilities as a way to quantify uncertainty have been discussed more in detail in Chapters 5, 6 and 8, where also the concept of Bayesian updating is discussed. The probabilities needed in decision analysis are the probabilities of each "state of nature" and the probabilities of failure given a certain state of nature. As has been mentioned earlier, fault tree analysis is a tool that can be used for calculating the probabilities of certain events.

7.2.1 Assessing prior probabilities

All assessing of subjective probabilities may be "wrong" due to psychological factors such as anchoring and overconfidence. For an overview of these problems and some suggestions on how to counteract them, see e.g. Ayyub (2001), Olsson (2000), Vick (2002).

7.2.2 Assessing information

The value of new information must be expressed in a suitable format. This applies both if the information comes as an expert's opinion or from an investigation programme. Evaluating expert opinion is treated in the literature, see e.g. Mosleh & Apostolakis (1985)

The assessment of the value of information of ground investigations can be done subjectively and with the application of bayesian statistics if you consider the reliability matrices as sample likelihoods. See e.g. Olsson & Stille (1980), Winkler (1972), Einstein et al (1978).

7.2.3 Simulation in decision tree analysis

In several cases one might wish to specify probabilities and consequences as stochastic variables and also to have the expected cost as a stochastic variable. This can be handled by using Monte Carlo simulation. This is possible in some decision tree software, but another solution is to model the tree in Excel and to use a simulation add-in such as CrystalBall or @Risk. These have a wider range of simulation possibilities than what is usually present in the decision analysis software.

7.3 Ranking methods

7.3.1 The Analytic Hierarchy Process

In some decision problems it is very difficult to evaluate the consequences and thus to use an expected value as a decision criterion. In these cases one might instead use some sort of a ranking scheme, where the different alternatives are compared to each other and ranked according to their judged desirability (without calculating the possible outcomes.)

This judgement and the ranking should be made in a systematic and stringent manner in order to avoid psychological biases etc. One method to do such rankings is the Analytic Hierarchy Process (AHP) see Saaty (1990).

7.3.2 AHP principles

In the AHP the following steps are taken to solve the decision problem:

a) Define the problem. Identify alternatives and criteria

b) Eliminate infeasible alternatives

c) Build a structured AHP model

d) Make judgements

e) Evaluate

f) Examine, verify and document

Define the problem

The definition of the problem, including the goal to be reached, and the identification of alternatives is a system analysis problem, which has been described in Chapter 3. The criteria to be used when judging the alternatives may also be seen as part of the system identification.

Eliminate infeasible alternatives

Some alternatives may not satisfy some minimum requirements. They should be eliminated to simplify further analysis.

Building the AHP structure

In AHP the decision problem is structured in a hierarchic tree format using the elements GOAL, CRITERIA and ALTERNATIVES, see Figure 7-9. The GOAL might for instance be: Chose best method to build a certain tunnel The ALTERNATIVES might be: TBM and Drill and blast and the chosen CRITERIA.: Construction time, Environmental impact and Method reliability

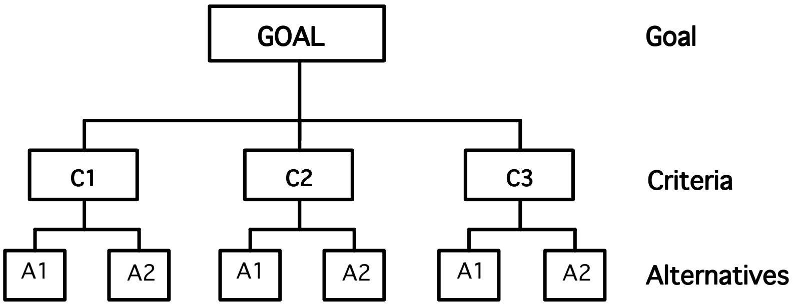


Figure 7-9 *AHP basic structure*

Making judgements.

When using the AHP approach, all judgements are maid as pair-wise comparisons between the elements at one level of the tree. This comparison is made with regard to each element on the next level. In the example above the comparisons would be

“Which alternative TBM or Drill and blast is preferable

- With regard to Construction time?
- “With regard to Environmental impact?”
- “With regard to Method reliability?”

and on the next level:

“What is more important for the goal:

- Construction time or Environmental impact?”
- “Construction time or Method reliability”
- “Environmental impact or Method reliability?”

The preferences are described using verbal expressions that for computations are translated using a special scale, see Table 7-4.

Table 7-4 Verbal expressions and corresponding numerical values used in AHP (Saaty 1992)

Intensity of importance	**Definition**	**Explanation**
1.0	Equal importance	Two elements contribute
3.0	Weak importance of one over another	
5.0	Essential or strong importance	Experience and judgement slightly favour one activity over another
7.0	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9.0	Absolute importance	The evidence favouring one activity over another is of the highest order of affirmation
2.0, 4.0, 6.0, 8.0	Intermediate values between adjacent scale values	When compromise is needed

Evaluation of judgements

Evaluation of the judgements is usually done using a computer using software such as ExpertChoice. For the mathematical principles, see Saaty (1992). As a result from the evaluation, one gets a ranking of the alternatives (with regard to the Goal) and also the importance of the various criteria. (These results are given on a ratio scale)

7.3.3 AHP example

An example of the application of AHP to underground projects can be found in Olsson & Sandstedt (1992). The goal was to make a comparison between different concepts for the underground storage of spent nuclear fuel using an expert panel.

The alternatives were:

- KBS-3. Deposition of canisters with spent nuclear fuel in deposition boreholes drilled in the floor of tunnels at a depth of about 500 m below ground surface.
- Medium Long Holes (MLH). Horizontal depositions of the same canister as for the KBS-3 concept in parallel tunnel system, each tunnel with a length of about 250m.
- Very Long Holes (VLH). Deposition of the spent fuel in fairly large canisters in several km long horizontal, bored tunnels.
- Very Deep Holes (VDH). Deposition of canisters with spent nuclear fuel in deep boreholes at a depth of between 2000 and 4000 m below ground surface.

The hierarchy used is shown in Figure 7-10. The result is shown in Figure 7-11, where is shown both the weight of the different concepts relative to the goal and the relative importance of Level 1 objectives. It should thus be noted, that one use for the AHP is to find what factors are important in fulfilling a goal, not only to choose between alternatives.

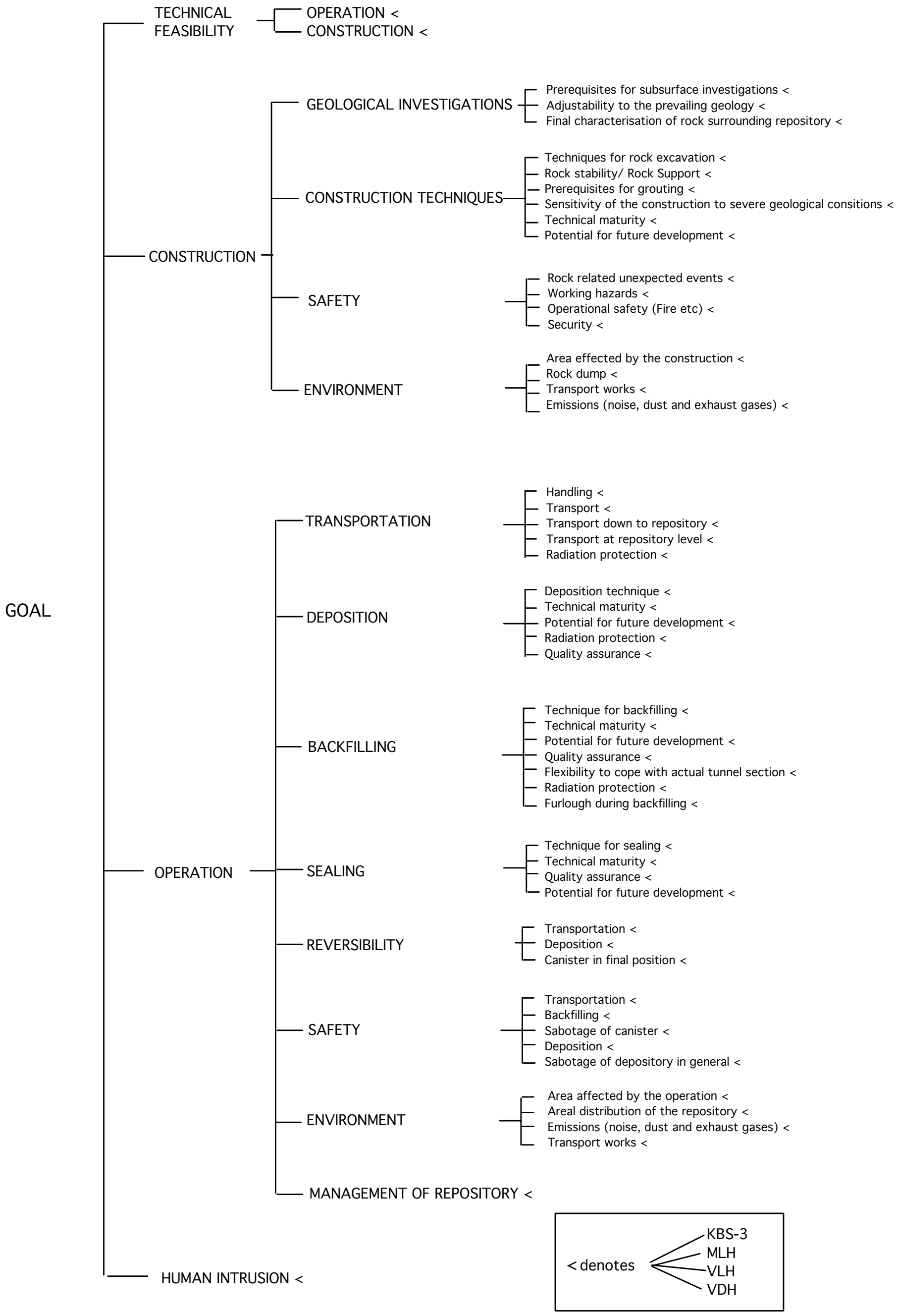


Figure 7-10 *AHP-hierarchy*

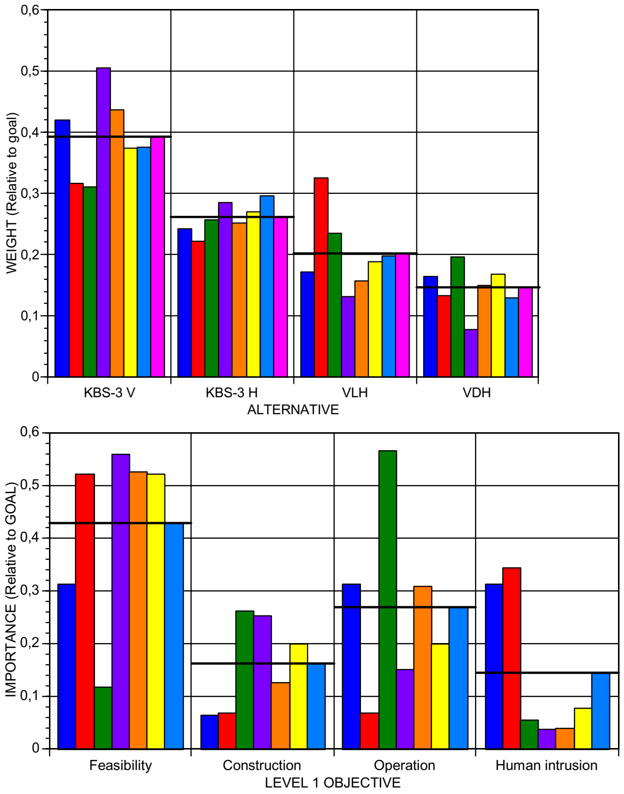


Figure 7-11 *AHP results*

7.4 Sensitivity analysis and reporting

After the formal decision analysis it is necessary to assess its reasonableness, its sensitivity to various assumptions and data and to report the findings. The sensitivity analysis should tell whether the decision is robust or very sensitive to uncertainties in data. The findings of this need to be reported along with results of the actual decision analysis. In the end it needs to be remembered that decision analysis does not replace the decision-making – it provides support for decision-making. Also decisions resulting from a decision analysis needs to be reasonable and logical. However, reason and logic are usually more subjective than one usually admits. The formal analysis will usually provide good insights into how to logically argue (or argue against) a decision.

7.4.1 Sensitivity

After the decision analysis has been done, a sensitivity analysis should be made to investigate the influence on the decision of different assumption about e.g. prior probabilities and investigation reliability matrices. If the decision is not very sensitive to changes in data, i.e. it is robust, a very detailed assessment of these data is not necessary. On the other hand, if it is very sensitive to data with poor support, there may be a need to acquire more information before reaching a decision. It should be noted, that a decision might be quite robust, even if the data in the decision analysis may be very uncertain. Decision analysis concern comparing options – not predicting the actual outcome of a decision.

The sensitivity analysis is done stepwise by modifying these data repeating the roll-back and analysing the results. Often this is a built-in feature of decision tree software. This is illustrated in Figure 7-12 where the dependence of the decision on the prior probabilities is shown. The diagram shows the expected cost for two competing decisions as a function of the probability P_state. There is a change of which decision is the best at P_state = 0,44. If the estimated value of P_state is in the vicinity of this value, a further analysis of it might be called for.

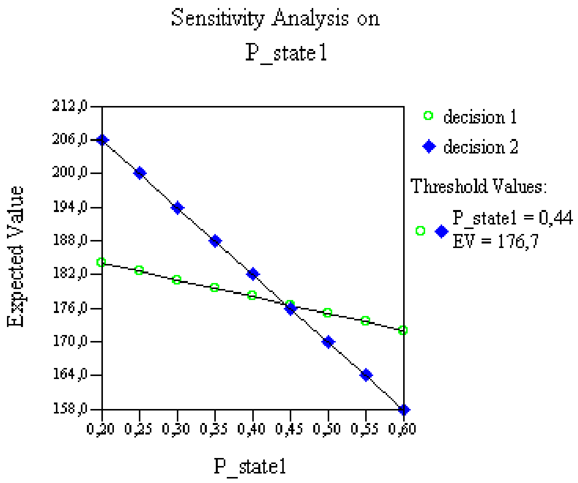


Figure 7-12 *Sensitivity analysis*

7.4.2 Reporting results of decision analysis

The decision analysis and its findings needs to be reported! This issue is most important, and is a fact a corner stone of an information based design in rock engineering. As has been pointed out the flow of undisturbed and relevant information through the project and its different stages is a key factor to a successful project. Not only should the best decision and its cost be reported, but one should also report all risks, e.g. possible outcomes with their probability.

7.5 Conclusions

Decision trees can be used to aid decisions made under uncertainty. Furthermore, just by structuring the problem to be analysed as a decision tree helps in defining the problem. Thus, it is not only the numerical outcome of the decision analysis, but also the very decision analysis itself which eventually guide the decision making. In fact, even when the formal and quantitative decision analysis is performed it is always advisable to assess the outcome on it own merits. Does the decision make sense? Is there a logic, apart from the formal analysis, which can be used to support the decision)

In some decision problems it is very difficult to evaluate the consequences and thus to use an expected value as a decision criterion. In these cases one might instead use some sort of a ranking scheme, where the different alternatives are compared to each other and ranked according to their judged desirability (without calculating the possible outcomes.) This judgement and the ranking should be made in a systematic and stringent manner in order to avoid psychological biases etc. One method to do such rankings is the Analytic Hierarchy Process (AHP).

After the formal decision analysis it is necessary to assess its reasonableness, its sensitivity to various assumptions and data and to report the findings. The sensitivity analysis should tell whether the decision is robust or very sensitive to uncertainties in data. The findings of this need to be reported along with results of the actual decision analysis. In the end it needs to be remembered that decision analysis does not replace the decision-making – it provides support for the decisions to be made.

8 Acquiring information

The basic problem of the design process is to be able to predict the future behaviour of the system under consideration. If we can do this, we do have the necessary basis for making a decision on which design to choose. As has been pointed out in the previous chapters, we are not able to make an exact prediction so our decisions have to be made under uncertainty or under risk. This chapter discusses the acquiring of information from a decision-analysis perspective. Connected to this is the application of the observational method.

8.1 Information needs in the design process

The predicted system behaviour depends on several factors. As shown in Figure 8-1 the predicted behaviour of the system depends not only on data, but to a larger extent on how we model different influencing factors.

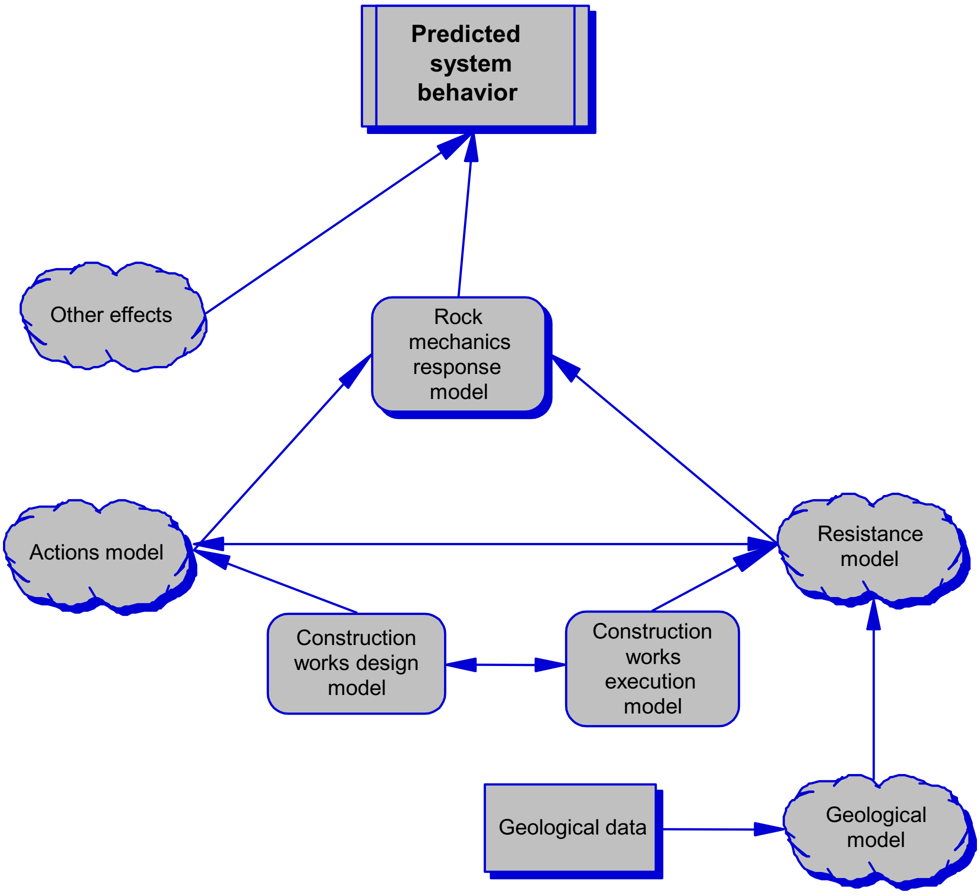


Figure 8-1 *Factors influencing predicted system behaviour*

Modelling concerns “technical” models such as the geological model, the mechanical response model but also models describing the construction procedure (including the organisational factors). The actions model describes the actions that the underground construction must be able to resist during its lifetime and must consider variations over time and also include time dependent factors like degradation. As we do not have perfect knowledge of these factors, we must always consider if there is a demand for further information to lessen the uncertainties.

From a decision perspective additional information is needed when the best decision is not clear-cut, e.g. when a sensitivity analysis shows that small changes in input data can shift the best decision. A special case is when there exist differing models, geological or computational or, and one wants to prove one of them as being better than the other. The system description and delimitation itself is a model and can also contain large uncertainties and thus demand more information.

It should be remembered that in design work the main purpose of modelling is not to have an exact representation of the nature (as for scientific inference purposes). Rather, the model used should serve as an efficient basis for decision-making and they should account for uncertainties in this respect – and not in general.

8.2 Sources of information

The type of information needed for the modelling and decision-making depends on what purpose it is going to be applied. In the first phases of a project e.g. during system definition, one needs information of a descriptive, qualitative kind for instance about geological processes and other models. Later on also quantitative information is needed, e.g. data about the rock properties. Section 5.1 discusses various aspects of uncertainty in models and data. These concepts should be considered when assessing information.

Both for qualitative and quantitative information, the decision process governing the design needs estimates about how reliable the information is. These estimates should be given in probabilistic terms. For data, this can be done using statistical descriptions using e.g. statistical distribution and parameters, see Sections 5.2 and 5.3.

Information can come from different sources:

- subjective information from one or more experts, from (published) data from similar projects or similar geological regimes
- measurements of the parameter in question. (A special case is where additional information is obtained from observations of the behaviour of the construction while it is being built)

8.2.1 Expert knowledge

To be useful in geotechnical design, expert knowledge should be expressed in terms of probabilities, e.g. the probability that a certain model is correct, reliability matrices (c.f. Section 7.1.5), prior distribution and likelihood in Bayesian analysis.

Assessment of expert knowledge

Expert knowledge is often used in underground construction design, though most often it is assessed in an informal way. This is somewhat unfortunate as there are several sources of errors that should be minimised.

For a discussion of these errors, among them psychological biases, and methods to counteract them when assessing subjective probabilities, see Kirwan (1994), O'Hagan (1998), Rahman & Shresta (1990), Roberds (1990), Stael von Holstein & Matheson (1978).

Olsson (2000) gives an overview and suggests methods for assessing probabilities that do not require the presence of a separate analyst. It is suggested that the expert doing the assessment on his own should fill in quality assurance forms, in order that the expert is made aware of possible biases and also in order to document the assessment.

Combination of expert knowledge

In the case where one has several experts' opinion on the same uncertain factor, one can handle this in a manner equivalent to the case with competing models. One can discriminate between the experts and just use the "best" expert or one can combine the opinions as a weighted linear combination. The weights can be assessed subjectively. Zio & Apostolakis (1996) suggests the use of the AHP method (c.f Section 7.3) to determine the weights, considering expertise, biases and other factors.

Updating using expert judgements.

When one obtains experts' judgements, they can be used to update prior knowledge using Bayes' theorem in the same way as when one obtains measurement data, see Section 5.2.8. Of course, one needs a prior estimate and also a likelihood, which in this case describes the experts' ability. This likelihood can be given in the form of a reliability matrix and the prior estimate can for instance be the decision makers own.

8.2.2 Measurements (geotechnical investigations)

All geotechnical investigations are basically bayesian in their nature, as one always has some knowledge or conception of the conditions, from experience. This experience should of course be used, as it contributes to the total information. This can be done formally using Bayesian statistics as has been shown in Section 5.2.8.

The purpose of the investigation can be seen as three-fold:

- To verify or update the assumed geological model
- To determine the geological stratigraphy
- To measure important parameters, such as RQD

There are also other measurements, for instance when monitoring the behaviour of the construction.

Measurement accuracy

There are several error sources that can cause low accuracy of the measurements as such. Among these are

- Measuring equipment bias and imprecision
- Gross errors made by the operators
- Disturbance of the soil or rock sample

Most measurement equipment is based on a physical model (for instance sounding resistance) which is translated into a geotechnical parameter and then used in calculations. There can exist a substantial error in this translation, an error that can be further aggravated if the calculation model has another underlying physical model so that the measurement cannot be seen just as a small scale test of the same type as the real problem.

Investigation accuracy

Apart from the accuracy of the measuring method and equipment, the investigation programme itself can cause lack of accuracy. Some sources of error are:

- ***Addressing wrong problem***. If the investigation is made before one has made a thorough system analysis, it might be the case that the investigation focuses on other problems than what later shows to be the important ones.
- ***Non representative location***. It is important that the location of a drilling is chosen such that the results can be used to discern between competing models. Figure 8-2, after Baecher (1979), shows a schematic example on how there can be alternative hypotheses that explain observations. In bayesian terms, the likelihood matrix of this investigation programme, (c.f. Olsson & Stille 1980), is such that it cannot discern between the two hypotheses.
- ***Too small range***. If there is a spatial variation, the autocorrelation distance (or scale of fluctuation) can be so small that measurements at one location do not add specific

information about the variation between measurement points. Sturk (1998) gives an example of this for two horizontal core drillings for the Hallandsås tunnel project.

- ***Spatial variability***. If there is, or if one presumes, spatial correlation, the investigation must be designed so that this can be determined, as the spatial variability has a large impact on the uncertainty (variance reduction, see Section 5.3.2). When designing an investigation programme to include this, one must consider both the small and the large scale so that measurement noise can be detected and considered, see e.g. Baecher (1982), Vanmarcke (1979). It should also be pointed out, that if there is a spatial variability, this must be considered when determining the mean. If boreholes are close together and there is a spatial variation, the mean of all bore-holes should not be used as they are not random samples. Some technique like declustering must be applied. (cf. bias in section 5.1.3).

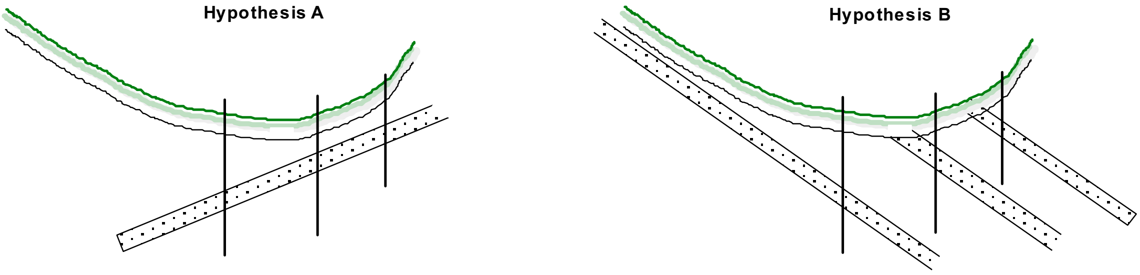


Figure 8-2 *Alternative hypotheses explaining observations. (After Baecher 1979*)

8.2.3 Monitoring

Monitoring, e.g. measurements made during the course of construction can be used in two ways:

- Back calculation to determine the parameters of a calculation model, which is often a difficult problem with large uncertainties.
- Direct decisions on changes in the design or construction process (the observational method), see section 8.3.

8.2.4 Assessing the uncertainties in the information

The uncertainties in the information should be assessed while considering the remarks in previous sections. It needs to be judged whether uncertainties are low enough to allow a decision or if more information would be needed or useful. In the latter case, consideration of applying the observational method or other surveillance systems may be an alternative to directly acquiring more information.

8.3 The observational method and surveillance system

Geotechnical design and construction is associated with large uncertainties, and it is usually the case that enough information cannot be gathered until after construction has started. Such late-coming information is then used to modify the original design and construction procedures to comply with the actual geotechnical conditions. Often in underground construction the so-called “active design” approach is applied. This method is based on a previous analysis of the problem and the determination (in advance) of modifications of the construction procedures to be taken, based on observations made, Bredenberg, Olsson &Stille (1981), This approach is also called” the observational method” Peck (1969).

In the Eurocode 7 the observational method is one method that can be used to ascertain that a geotechnical design will not exceed the limit states, see below.

““2.7 Observational method:

(1)P PER When prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as "the observational method", in which the design is reviewed during construction.

(2)P REQ The following requirements shall be met before construction is started:
- the limits of behaviour which are acceptable shall be established;
- the range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits;
- a plan of monitoring shall be devised which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage; and with sufficiently short intervals to allow contingency actions to be undertaken successfully;
- the response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system;
- a plan of contingency actions shall be devised which may be adopted if the monitoring reveals behaviour outside acceptable limits.

(3)P REQ During construction, the monitoring shall be carried out as planned.

(4)P REQ The results of the monitoring shall be assessed at appropriate stages and the planned contingency actions shall be put in operation if the limits of behaviour are exceeded.

(5)P REQ Monitoring equipment shall either be replaced or extended if it fails to supply reliable data of appropriate type or in sufficient quantity.” (Eurocode 7) “

The abbreviations used are, PER, for permission, (verb: may), REQ, for requirement (verb: shall), P for Principles. The Principles comprise: general statements and definition for which there is no alternative; -requirements and analytical models for which no alternative is permitted unless specifically stated.

8.3.1 Alarm threshold. Basic principles.

One fundamental concept is the alarm threshold. The alarm threshold is a pre-determined value of a single or of a combination of several observation results, which, if exceeded will trigger pre-determined measures in order to avoid damage. It is not even necessary that the alarm threshold be expressed in numbers. A threshold limit might be formulated in terms of a series of events like "*The rock mass is heavily jointed and the water inflow is great and increases with each blasting round*". Such an alarm threshold would obviously be used to indicate the need to switch to a more careful excavation method.

A very clear distinction must be made between the *alarm threshold* and *the critical limit*, the *target value* and the *expected value.* The critical limit is the limit where damage is expected to occur with an unacceptable probability. The target value, which is a guide to efficient and safe work, might for instance be a value of vibration during blasting and is set so that blasting can be carried out with as large rounds as possible, but at the same time with a sufficiently low probability of exceeding the alarm threshold, see Figure 8-3. The chosen alarm threshold may in turn govern the choice of the target value, i.e. the value that is optimal from an economic and safety point of view. This is the value that will permit an efficient work strategy while taking into account the costs and inconvenience connected with exceeding the alarm threshold. The expected value, finally, is the value most likely to occur for a given design and construction process.

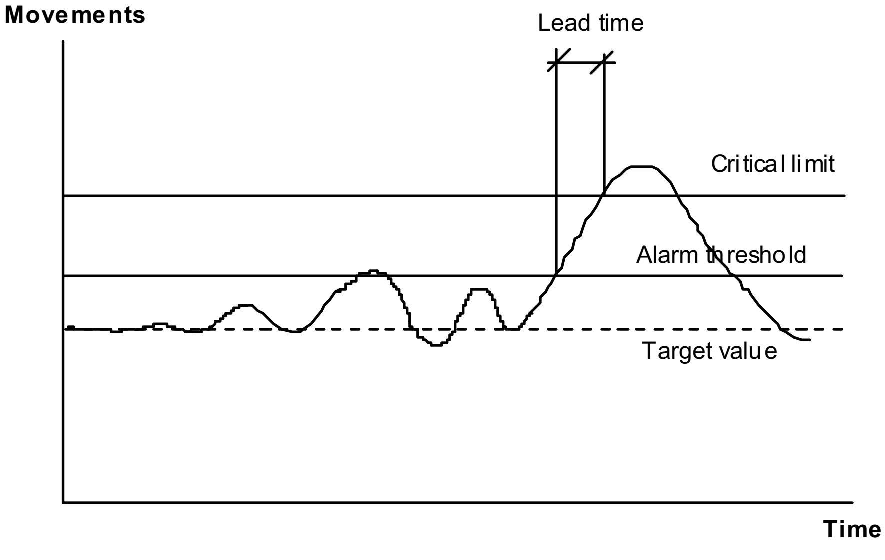


Figure 8-3 *Alarm threshold and lead time. (After Paté-Cornell & Benito-Claudio 1987.)*

The choice of the alarm threshold incorporates most of the demands made in the Eurocode when done in a stringent way. The problem of the choice of an observation system including the alarm threshold can be illustrated using a decision tree, see Figure 8-4.

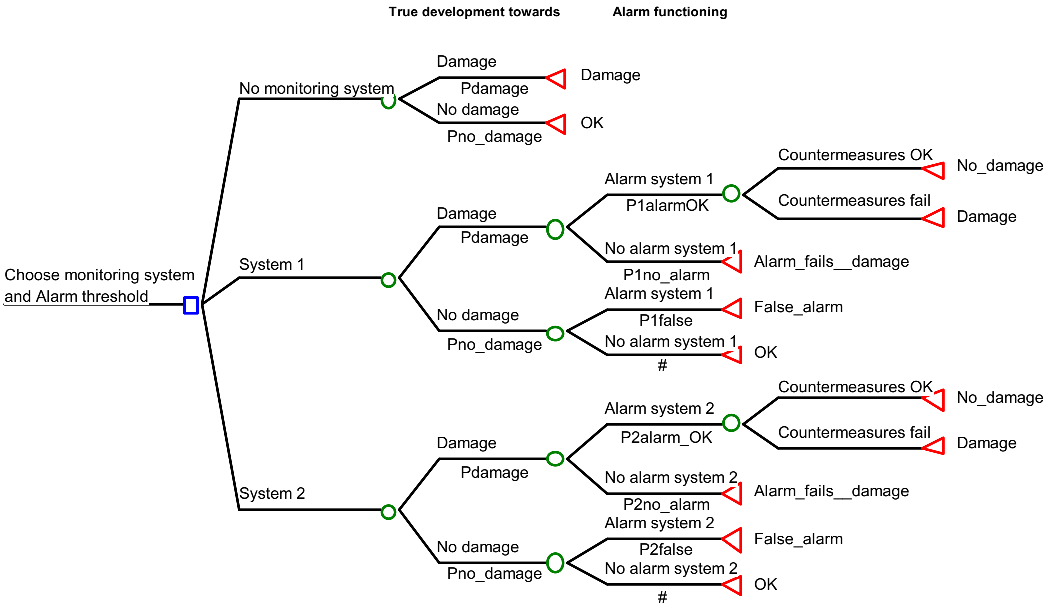


Figure 8-4 *Decision tree for choice of alarm threshold*

As can be seen from Figure 8-4, there are several factors that affect the choice. These are:

1. The consequences of each outcome.
2. The cost of each monitoring system
3. Probability of each branch, including the overall probability of damage with the design chosen.

This leads to the observations that

- the effectiveness of the observation system and the chosen alarm thresholds is described in the form of probabilities (of giving a correct alarm or a positively or negatively false alarm)
- if the consequences are small, an expensive monitoring system is not motivated.
- if the chosen design is safe (small P[damage]) a monitoring system might not be motivated

- if the probabilities are very small, even a very large consequence will have a small expected cost. On a purely economical basis it will not motivate the cost for a monitoring system.

8.3.2 Basic procedure for designing an observation system with alarm thresholds

A systematic procedure should be used in designing the observation system with alarm thresholds and the basic requirements should always be met. This procedure depends on the “degrees of freedom” of the building project. (Can the location be changed to one with fewer problems? Is the design final? Are there other construction methods?) For the case where the design and location are final and the construction method has been decided on, a proposed procedure is briefly presented below (for a more comprehensive treatment, see Olsson & Stille, 2002a, 2002b):

- Identify the sensitive functions that are to be protected
- Identify the damage mechanism and the critical limits for those functions and find suitable direct countermeasures
- Find observable/measurable indicators that are related to the damage mechanism and determine the critical limits expressed in those indicators
- Identify the construction work steps that can disturb the functions. Determine work procedure-related countermeasures
- Predict the behaviour of the rock, including the expected type of behaviour for these construction steps
- Determine alarm thresholds considering countermeasures and the necessary lead time
- Make a detailed design of the observation system
- Implement, observe, follow up and update. Make changes if necessary.

Identify the sensitive functions that are to be protected

The fundamental idea of the alarm thresholds is to stop work before it can cause damage to any essential “functions”. This means that all functions must be identified. For this a comprehensive analysis is needed using tools such as system analysis and risk analysis (e.g. fault tree analyses). In order to do this it is necessary to adopt a risk analysis approach that also includes a system analysis to ensure that nothing is overlooked and safety surveys of those threatened establishments that have been identified

Identify the damage mechanism and the critical limits for those functions and find suitable direct countermeasures

Once the sensitive functions (primary and secondary) have been found, the damage mechanism and critical limits must be identified. This work must be based on sound engineering know-how, and risk analysis tools can be helpful. Identifying the damage mechanism is a more or less straightforward procedure based on engineering knowledge. It may, however, be rather difficult sometimes to find the critical limit, i.e. the limit above which unacceptable damage is expected to occur. One reason for this is that designers are not accustomed to considering the critical limit but instead a "safe limit" according to codes.

It should be noted again that the critical limits are to be entered into a decision process in which different construction alternatives must be studied, changes made, the decision process repeated, etc. This decision loop is dependent on the parameter values, both in the form of probabilities and in the form of costs. If these factors are likely to be important, a risk information effort at an early stage can help identify them.

The observation system is not complete without predetermined countermeasures to be adopted if the alarm threshold is exceeded. These can be of two different types: Direct, and work procedure-related. Direct counter-measures are applied at the threatened object itself. Examples of this are vibration isolation of sensitive equipment, truing up of movements in tracks, machine beds, etc.

Finding observable/ measurable indicators related to the damage mechanism and critical limits for those indicators

The quantities that we observe, and that have to be a part of the output of our predictive modelling of future behaviour, we will call measurable (or at least observable) indicators. As has been stated earlier, such an indicator can consist of one or a combination of measurements. All these components must of course be observable, otherwise another indicator must be chosen. The general problem of choosing suitable indicators has been discussed in the literature, see e.g. Krauland (1982) and Stille et al. (1981).

Identify the construction work steps that can disturb the functions. Determine work procedure-related countermeasures

The identification and evaluation of these steps is a rock mechanics and/or a rock dynamics problem where a prediction must be made about future threats to the sensitive functions. Related to this is the problem of finding work procedure-related countermeasures. These are of two kinds: those aimed at protecting some identified sensitive function and those aimed at protecting the construction process itself.

Predicting the behaviour of the rock, including the expected type of behaviour for these construction steps

In order to predict if we are approaching a critical limit for a function, we need to predict future disturbances of this function. For this prediction, a prediction model is needed that has certain properties:

- It can handle the uncertainties that are inherent in the rock mass properties and in the execution of the construction work.
- The output of the model must be in the form of observable quantities, otherwise it is not useful.
- It should permit verification of the model through the observations.

Different types of models can be used to predict rock behaviour and whether a dangerous condition is approaching. The main model types are:

- Measurement-based models
  (Expected deformation is compared to actual measurements)
- Type-of-behaviour models
  (If the rock is expected to behave in an elastic manner, and if it starts to behave in a plastic fashion, measures must be taken.)
- Type-of-behaviour plus rough deformation check models
  It is used when it is important not only that the rock behaves elastically, but also that the deformations do not get so great that they cause damage
- Behaviour pattern models
  Used to check that rock movements do not continue when the load is constant (the excavation is finished) and that movements do not accelerate
- Classification models
  Classification models are not used to predict deformations etc. but to classify the rock excavation procedure combination as “safe” or “unsafe”.

Determine alarm thresholds considering countermeasures and the necessary lead time

As many parameters influence the design of the system and thus the choice of alarm thresholds, there is no fixed way of determining this design. Determination of the alarm thresholds must be treated as a decision problem, which is influenced by several factors. The necessity of performing a risk analysis that includes organisational factors is stressed.

Make a detailed design of the observation system

The detailed design of an observation system includes both the instrumentation and the gathering and processing of the observations. The design of the observation system should consider not only the hardware, but also the organisation, as it is the overall accuracy of the system that governs the outcome. The option of making the design and construction of a project more robust should always be considered (smaller probability of failure), reducing dependence on a monitoring system.

Implement, observe, follow up and update. Make changes if necessary

When the observation system is running and you start to get data, these shall be used to verify the chosen alarm thresholds. Usually the assumptions made are fairly uncertain, and one must not consider the alarm limit as being static and unchangeable. When you get (site specific) data you should consider an updating of it.

8.3.3 Using the alarm system for design purposes

It must be stressed that unless you have a thorough understanding of the physical damage mechanisms and also the design situation, alarm systems should not be applied. They can in such situations do more harm than good by giving a false sense of security or by creating an unnecessary deadlock between the parties of the contract.

However, if correctly used, the observation system approach can give less expensive designs and construction work. This is because the risk is lessened both through lower probability of failure and by smaller consequences through the early warnings. Also, in the opinion of the authors, it may be the most viable way to apply the Eurocode to rock mechanics design.

8.4 Conclusions

From a decision perspective additional information is needed when the best decision is not clear e.g. when a sensitivity analysis shows that small changes in input data can shift the best decision. The additional information can be both related to the result from further pre-investigation or information obtained from observation carried out during the excavation.

The cost from getting the additional information shall always be compared to the benefit from the additional information. Decision theory can be used to evaluate this issue before any investigation has been carried out based on the cost and the reliability of the method to be used.

Often in underground construction the so-called “active design” or “observational method” approach is applied. This method is based on a previous analysis of the problem and the determination (in advance) of modifications of the construction procedure to be taken, based on the observation made.

A special type is the use of an observation system with predefined alarm threshold. The alarm threshold is a predetermined value of a single or a combination of several observation results, which if exceeded will trigger pre-determined measures in order to avoid damage. In order to avoid unnecessary alarms or get failure without any warning it is essential to define the threshold in an appropriate way.

9 Project management and quality control

In the light of the discussion in the previous chapters of the uncertainties involved in underground projects it is obvious that the need for a quality systems 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. The cost for the quality system shall be related to the benefit of using it i.e. a typical decision problem.

During the last decades major parties within the underground construction industry, i.e. clients, consultants and contractors, have introduced different quality systems. These systems are often tailor-made for the specific organisations but to a large extent based on the European Standard EN ISO 9001:1994 (referred to as ISO 9001).

This chapter discusses quality work within the underground construction industry and focuses upon a broader definition of the concept of quality including a risk management approach. The factors influencing quality are discussed together with shortcomings in present quality systems. Finally some proposals for improvement of quality work within underground projects are given. This chapter is mainly based on a paper of Stille et al (1998) where these issues are discussed.

9.1 Underground projects and quality

According to 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 society in the building codes.

Given these basic principles it is obvious that quality and risk management are related. 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 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.

It is interesting to note that demands on sufficient quality can be found both in current Swedish laws and in the coming Eurocode, which both require that the finished structure should remain fit for the use for which it is intended for its intended life and in an economic way.

Quality work should always be focused 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. Recently, some large projects have been completed without any major damage, even though substantial geological or environmental hazards existed. The Uri Hydro Power Project is one of the first major projects carried out in the Himalayas without any time delay (Brantmark 1997). Weak rock with severe squeezing was treated with great respect and successfully even though some tunnel failures took place during construction.

The Arlanda Link includes railway tunnels and stations excavated under the Arlanda airport in a partly low quality mica schist and with very low rock cover. Careful excavation and an active follow up during the excavation guaranteed a successful completion (Forhaug & Moen 1996). Another difficult project is the Hvalfjördur Tunnel which is a subsea road tunnel in a thermal active area on Iceland (Eriksson 1997, Brantmark et al. 1998). High water temperature (60°C) and high water inflow (800-2000 l/min) was treated successfully and the tunnel excavation could be completed six months before the agreed completion time. High competence, effective organisation and risk analysis were important factors for the successful completion.

9.2 Important factors influencing quality

As mentioned earlier, quality work should be focused upon important factors and problems, where the greatest concern are related to loss of money, time or goodwill. The first two aspects are obvious. However, the third aspect, loss of goodwill, has become a critical issue especially if it is related to a third party or the environment.

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

- to identify the hazards connected to the project and

- to use a manufacturing process which eliminates or reduces the probability of potentially damaging initiating events.

If damage is unacceptable or 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. Different types of obstacles have been described previous in chapter 2.

Most of the quality systems used today, certified according to 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.

9.3 *The dualistic quality system*

Quality is to give the customer what he needs, wants and hopes for, and still more, i.e. to fulfil stated and implied needs. But in order to reach this goal, the supplier (for example a contractor) must begin with 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 see to it that it is done or built right. Otherwise there is a probability of handing over a substandard product, with heavier demands 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” and they must both be handled by the quality system.

In many aspects the idea of TQM (Total Quality Management 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.

9.3.1 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 serve to 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 for this 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 precise project models, risk analysis, system analysis, technical audits and team qualification are important quality tools 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.

9.3.2 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 faults. The overall understanding of quality work as a 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. 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.

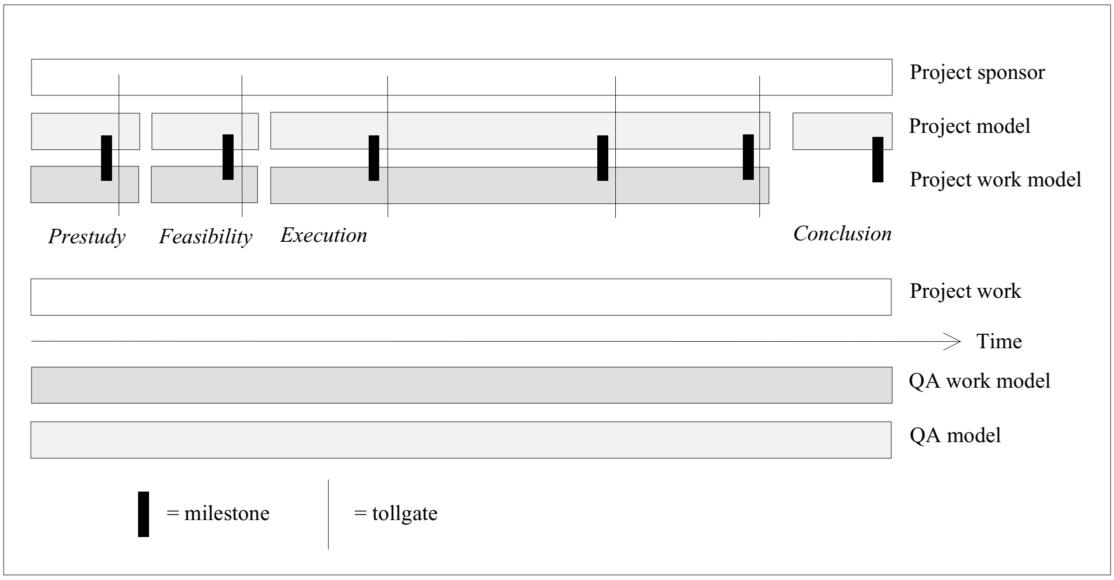


Figure 9-1 *Project model, based on PROPS, and QA-model (after Stille et al 1998).*

9.4 Quality tools

9.4.1 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 the Ericsson Company Group (1994). 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,see Figure 9-1. 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, see Figure 9-1. The quality work is then connected to the activities within the project.

9.4.2 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 (Sturk 1998). 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 (Olsson & Sandstedt 1992).

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 (Sturk, 1998).

One concept that can be applied to civil engineering is that of robustness (Taguchi 1986), 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 (Isaksson 2002).

9.4.3 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.

9.4.4 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.

9.4.5 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.

9.5 Conclusions

In this chapter it is shown that based on experience from underground projects, often characterised by a ”one off” situation, it is difficult to achieve satisfactory quality only using quality systems limited to the ISO 9001 standard. More detailed work has to be committed to identifying and defining customer demands and also identifying hazards threatening the fulfilment of these demands. This way of making sure of doing or building the right things should be started in early project stages and continue throughout the whole project. By applying the proposed dualistic quality system, including the presented quality tools, it is envisaged that the underground construction industry can reach a quality level giving customer satisfaction.

10 Concluding remarks

Handling information is key to effective design of underground excavations. One aspect of information management is the risk based/information based perspective presented in this report. In general, design work concerns information management where the decisions made during different stages of the process play a central role.

A solution to a design problem is normally built up by different components in a more or less complex interaction and different solutions may exist. An essential tool for handling these components and interactions is to describe them as a system, which will enable a reliability analysis. The hazards, outer requirements, the limits in the detailed understanding of the rock mechanics and the spatial variability and uncertainty in the rock itself all very specific for underground project and have to be taken into account in the design work. The complexity and involved uncertainties characterise the design process. Consequently, in many designs situations in rock engineering decisions have to be made under uncertainty. This also implies that a good design management and quality assurance are essential.

In accordance with our stated objectives we have presented a methodology for *information-based design* of underground excavations, which should meet these demands. This methodology should be applicable in various phases of the design work ranging from the *feasibility studies* until the management of the *operational phase*. According to the methodology the following seven steps should be applied at each phase:

- Problem analysis and system identification.
- System analysis.
- Analysis of the uncertainties and probabilities connected to the parameters of the system.
- Reliability analysis of the system.
- Decision analysis based on estimated probabilities and consequences
- Assessment of the information needs.
- Design management and quality assurance.

In the document, the focus is on the overall logic and structure, rather than on describing every detail of the governing probabilistic theory behind. Still, we believe that the methodology presented is complete in the sense that it should be generally applicable. Also, it should be noted that in instances, applying the methodology does not necessarily require extensive calculations or complicated elaborations, although some project are complex enough to require such extensive analyses. The overriding theme of the methodology is to provide structure and logic to the thinking. Of course there are also several issues that have to be further studied before a more general use of the methodology can be used.

10.1 Some recent examples where risk based methods have been used the latest years

According to our experience it seems that the methodology, or elements of it, has found increased use the last years for analysis underground projects. In the future, we believe that the methodology will be a normal part in the design work for underground openings. Below we refer to some projects were the authors have been involved, but risk analyses methods are of course also used in other projects.

The methodology was first used by the authors in connection to tunnel excavation work of some projects where the risk situation was more pronounced. The emphasis was on the execution of the work and to describe the risk situation to get a safe working environment. Two examples of this are the road tunnel in Iceland north of Reykjavik passing under a bay of the Atlantic ocean called “Hvalfjördur” and the sewage tunnel under the harbour of Hongkong, where the tunnels pass under open water and thus an uncontrollable ingress of water should give a very dangerous situation. In both cases a system analysis was carried out based on fault trees analysis with quantification of different geological scenarios and probability of occurrence of different unwanted events like tunnel collapse and large ingress of water. Adequate observations systems were also identified in order to get an early warning of dangerous situations. Examples on such observation measures were measurements of water temperature, water pressure, and inflow of water to pre sounding holes. Other important indicators were changes in geology and quality of ground water. Based on the system analysis, working procedures with detailed information to the tunnel workers were elaborated. When the warnings bells were ringing during the tunnel excavation predefined counter measures were brought into action. By strictly follow the working procedure the two projects could be completed without any incidences.

The expansion of the Central interim storage facility for spent nuclear fuel (CLAB2) in Sweden, by the construction of a new underground cavern beside the existing one, is another interesting example. The new cavern should be excavated some 40 m from the existing cavern. The requirements regarding the non-disturbance of the existing cavern for spent fuel were rather tough both regarding allowable deformation, vibration and different environmental aspects. In order to meet these requirements a risk analysis was carried out. For the excavation work a special risk group was established with the objective to follow up the risk analysis and identify different hazards and initiating events. The experiences of the work of the group was very positive and only very minor disturbance on the existing repository and the work with the spent fuel was recorded even when the new cross tunnel between the old cavern and the newly excavated one was blasted and excavated.

Analysis of different design options have been used in connection to the Rio Esti Hydro power project in Panama using the decision theory based on a reliability analysis. In this project the contractor had to take the full responsibility of the design and the requirements are related to the function of the power plant. With this responsibility the use of decision theory and reliability analysis have been shown to be very useful tool for many different design issues. The diameter of the penstock was checked by a probabilistic analysis of the head losses in the tunnel for different tunnel diameter and the corresponding cost for excavation and risk for not fulfil the requirements of produced power effect. A special study was also carried out to check the risk for hydraulic jacking of the pressure tunnel.

Another project where information based design have been used to some extent is the LCC analysis of different concept of lining and drainage system for the road tunnels of the Southern Link in Stockholm. The analysis illustrated the important coupling between construction cost and costs for further maintenance and repair.

10.2 The way forward

Information based design is already a working methodology applied in underground excavation projects. Still, further developments would be fruitful.

The next step forward is to apply this concept of information based design on different projects in order to fully demonstrate the potential of this methodology. Several of the coming major infrastructure projects in Sweden could benefit from this type of design in order to find the suitable extent of the pre investigation and a more optimal design based on clear requirements of function and future cost for maintenance and repair.

Another important task is to further spread the knowledge of the information based design methodology to the working engineers and designers. Education is the key word in this context.

There are of course many aspects that have to be further developed in coming research work. Proposed research projects in this field include: exploring the accuracy of our pre investigation methods, assessing uncertainties related to our empirical design methods, questions related to spatial variability, scale and variance reduction, development of observational methods and uncertainties in our estimation of the rock mass properties.

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