

RISK ANALYSIS APPROACHES IN UNDERGROUND CONSTRUCTION

Four papers

STIFTELSEN SVENSK BERGTEKNISK FORSKNING
SWEDISH ROCK ENGINEERING RESEARCH

RISK ANALYSIS APPROACHES IN UNDERGROUND CONSTRUCTION

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FOREWORD

Three projects within SveBeFo's current research programme focus on the problem of making decisions based on limited information. They deal with the engineering geological prognoses as well as the administrative aspects of treating this kind of data in connection with the organising and procurement of large, underground projects and choosing the "right" tunnelling method under different circumstances.

Results from this research have been presented in SveBeFo reports, seminars and international symposia. We have selected some of the conference presentations and compiled them as reprints in this report. They contain direct results from the research as well as experience from the application of tested methodologies in practice. We hope that this report will demonstrate something of what can be achieved by going deeper than usual in the analysis of inherent uncertainties in rock construction, thus giving a more reliable basis for the difficult decisions to be made in different stages of a tunnelling project.

The research has been performed by Robert Sturk, Per Tengborg and Therese Isaksson, who have been supported by senior advisors and colleagues, some of them appearing as co-authors of the papers in this report.

We acknowledge with thanks the kind permission by Balkema, to republish these papers originally printed in conference proceedings.

Stockholm February 1999

Tomas Franzén
Research Director

FÖRORD

Tre projekt i SveBeFos ramprogram 1997-99 behandlar risk- och beslutsanalys i samband med stora undermarksanläggningar. De är koncentrerade på olika delområden, dels ingenjörgeologiska prognoser som måste tas fram utifrån begränsad information (Robert Sturk), dels organisation och upphandling av stora projekt, som kräver en mängd beslut grundade på bedömningar och riskvärdering (Per Tengborg), och slutligen valet av drivningsmetoder som med rimlig säkerhet ska klara de bergförhållanden som påträffas under byggandet (Therese Isaksson).

Resultat från forskningen och erfarenheter från tillämpning i några bergprojekt har redovisats i olika sammanhang, som vetenskapliga avhandlingar, SveBeFo-rapporter och vid konferenser. Vi har bedömt några av konferensbidragen vara av särskilt intresse och representativa för problemområdet. Vi har därför sammanfört särtryck från några konferensvolymerna i denna rapport.

Föredragen har skrivits av SveBeFo-forskarna tillsammans med de andra experter som genomfört de aktuella analyserna.

Vi tackar Balkema som har ställt originalmanus till förfogande för denna publikation.

Stockholm i februari 1999

Tomas Franzén

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Tunnelling in poor ground – Choice of shield method based on reliability

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ABSTRACT: This study deals with a possible methodology for the choice of shield excavation method, based on an economic model. By using a geological/constructability model the robustness of the method can be defined. The robustness of the method can be increased by certain measures. A developed probability-based decision model has been used to estimate expected costs for various shield methods of excavating. Clearly formulated decision criteria are defined: the choice of method should not be based on the lowest standard cost but on the lowest expected total cost. A simulation has been carried out in a case study with three different excavation methods in the Grauholz tunnel in Switzerland. The result shows that the method can be made more robust by implementing additional measures which give less probability of major cost increases.

1 INTRODUCTION

The correct choice of excavation method is decisive for maintaining the cost ceilings and time frames of a tunnel project. Therefore, it is essential to select a method that is robust, and can cope with any type of geology that may occur along the whole extent of the tunnel. The right decision about the tunnelling method should be taken as early as possible in the planning phase. Factors influencing this decision could be geology, length of tunnel, number of tunnels, time schedule, space in front of the tunnel adit, buildings above, availability of trained personnel etc.

To facilitate the decision about the cheapest method of excavation, decision theory can be applied. The decision criterion for excavation is to minimise the risk of cost increases. The willingness of the construction parties to accept risks must also be regarded.

The choice of alternatives for construction is standardly based on earlier projects under similar geological and other conditions. A proper decision analysis, including main tree, fault tree, maximum cost and so on, is very often not carried out due to lack of time and funds. In the absence of a large bank of experience and skilled personnel, it is almost impossible to compete for and realise certain design solutions. In such cases, expensive solutions may be the only reasonable alternative.

This study deals with a possible methodology for the choice of shield method. Robustness, the probability of unwanted events and measures to increase robustness are examined. Certain excavation methods can be excluded directly due to external circumstances. Others are worth analysing further. Research into choice of excavation method has been conducted since the 1970s at Massachusetts Institute of Technology in USA (Einstein & Vick 1974). A simulation program called Decision Aids in Tunnelling (DAT) has been developed and applied to the choice of excavating system by estimating project costs and time (Einstein et al. 1991, 1996), (Salazar 1983).

This article is part of a scientific project at the Division of Soil and Rock Mechanics at the Department of Civil and Environmental Engineering, Royal Institute of Technology (KTH) in Stockholm, Sweden.

2 THEORETICAL APPROACH

2.1 Simulation model

A probability-based decision model is used to estimate expected costs for drilling with different shield machines. The advance rate varies depending on constructability state, that is, ability to cope with the geology, which affects the construction time when estimating the costs. Constructability state I

means that problems arise, state II means standard operation and state III means that work is progressing very smoothly.

The simulation is based on an economic model. The costs of every excavation method in every geological zone and for every constructability state consist of standard costs and a risk factor; see equation (1). To obtain a probable cost, including the risk of the method working poorly, the product of the costs and the probability of a certain constructability state is estimated in a given zone; see equation (2). Then the probable costs for every zone are added together. The parameters included in the cost model, for instance, advance rate, are expressed as stochastic variables which are modelled as triangularly distributed. A Monte Carlo simulation of the total implementation costs displays the distribution of costs.

The robustness of the method can be increased through measures. If the method is more robust when applied to a certain geological formation, the probability of a problem arising is decreased. Expected costs are estimated according to these formulas:

- The cost at a given constructability state in a given zone

$$C_{zone,i} = C_n + P_f * C_f \quad (1)$$

- The total cost of the whole tunnel

$$C_{tot} = \sum_{all\ zones} \sum_{all\ states} (C_{zone,i} * P(state)) \quad (2)$$

where C_n = standard cost for one zone, P_f = probability of an unwanted event, C_f = cost consequences of this event and $P(state)$ = probability of the constructability state.

The decision criteria for the choice of method is, consequently, not only the minimum standard costs $\min \sum_{all\ zones} C_n$ but the minimum expected total cost

$$\min \sum_{all\ zones} \sum_{all\ states} (C_{zone,i} * P(state)).$$

The following parameters are necessary for the simulation of the costs:

- advance rate
- standard cost for excavation and support
- probability of an unwanted event in the given constructability state
- cost consequence of this event
- probability for geological/constructability state

The methodology to determining these parameters is described below.

2.2 Methodology to calculate advance rate for shield machines

A study of tunnelling operations and how these are affected by disturbances has been carried out to provide a basis for calculating the advance rate. This can be done if the geology is constant throughout a section of the tunnel (zone) and is obtained from a subjective estimation and follow-up data from earlier projects. The advance rate is then calculated according to the following formula:

$$y = \frac{T * \lambda}{(tb + tf + tk + td)} \quad (3)$$

where T = working hours per day, λ = round length which means the length at maximal extended cutter head, tb = time for excavation, tf = time for installing concrete segments, tk = time for change of cutter, td = various down time. These time parameters express the numbers of hours for one round of length λ .

$$tb = \frac{\lambda}{(v * rpm * 0,06)} \quad (4)$$

where rpm = rounds per minute of the cutter head, v = penetration rate per round.

$$tf = ts * seg + to \quad (5)$$

where ts = the time to install a segment in the ring, seg = the number of segments per ring, and to = time for changeover between previous operation and commencing the installation.

$$tk = MTTR * \frac{\pi^2 d \lambda}{(MTTF * 4n)} \quad (6)$$

where $MTTR$ = mean time to repair cutters, $MTTF$ = mean time to fail, and n = number of cutters on the cutter head.

An estimation of down time (td) can be made with fault tree analysis. In a main tree, the principal factors that cause down time are defined. Reasons for down time in the respective main trees are illustrated with sub trees. As a basis for estimating the probabilities in the case of each initial event in the following example, data from the Grauholz tunnel has been used: (Aebersold 1994).

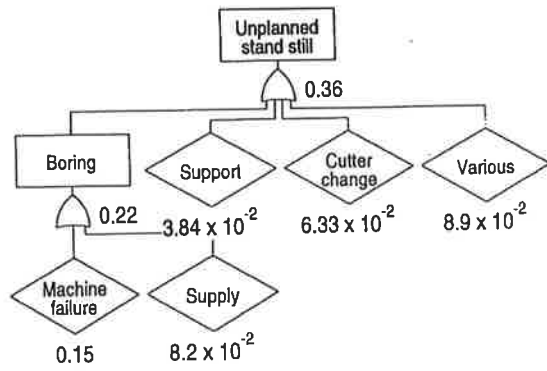


Figure 1. Main tree for unplanned down time

2.3 Methodology for estimation of standard costs

Standard costs are estimated for different methods of shield excavation. The costs depends of the tunnel diameter and consists of:

- Fixed costs
- Time-dependent costs

The following equation is used to estimate standard costs for the entire tunnel using shield excavation.

$$C_n = \sum C_{fix} + \frac{\sum C_{tid} * i * \lambda}{y * dm} \quad (7)$$

where C_{fix} = fixed costs, C_{tid} = time-dependent costs, i = number of rounds along the whole tunnel, λ = round length, y = advance rate and dm = number of days per month.

The fixed costs consists of:

- site establishing and de-establishing
- material costs according to the following formula:

$$C_{fix_2} = \left[\frac{\pi * d^2}{4} (E + S + B) + \pi * d * (I * tj * 1.3 + M * t) \right] * i * \lambda \quad (8)$$

- shield and back-up system according to the following formula:

$$C_{fix_3} = (1 + R)^N * d * \left(\frac{Re + A}{2} \right) \quad (9)$$

where d = tunnel diameter, E = running costs, S = wear costs, B = bentonite consumption, I = grouting between segment and rock, tj = space between segment and rock, M = costs for support, t = segment thickness, A = purchase price for shield machine and back-up system, Re = scrap value of shield and backup, R = annual interest, N = depreciation time.

The time-dependent costs include:

- site office with personnel
- machine costs
- wages for workers

2.4 Methodology for estimating probability of constructability state

Probabilities for various constructability states depend on the geology and on the robustness of the method, that is to say its sensitivity to variation in geological factors such as water and clay content in the soil or the occurrence of boulders.

- *State I* means that the method cannot handle the problems. The probability of unwanted events is high.
- *State II* is the optimal method under given circumstances. Low probability of unwanted events.
- *State III* means that excavation with a cheaper method could be conducted without increasing the risk that problems will occur.

To be able to estimate the probability for constructability state, the probability of geological factors must be assessed. The geological factors could be designated A, B and C. A geological factor of type A could, for example, signify a high water content, B a high frequent occurrence of boulders, and C soil with a high clay content. The probability of a certain factor occurring could be estimated starting from, for example, pre-investigation results.

Table 1. Examples of probability of the occurrence, or non-occurrence of a geological factor

Geological factor	Occurrence	Non-occurrence
	+	-
A	0.9	0.1
B	0.8	0.2
C	0.5	0.5

The excavation method can be rendered less sensitive to interference and the costs lowered if a method is chosen that is not sensitive to variation of the parameters that could vary over the entire length of the tunnel. Preventive steps can also be taken to reduce the sensitivity and thus, the probability of an unwanted event. The steps, or combinations of steps, that are the optimum choice in an actual case depend on a number of factors. Knowledge of technical possibilities and ability to judge how the rock will behave is necessary for the correct steps to be taken.

Table 2. Examples of steps to increase robustness in shield machines

Cause	Steps to increase robustness in shield machines
Boulder occurrence	Integrate stone crusher
Inflow of water	De-watering measures
High clay content	Centrifuges/separate centre head

When there is a risk of disturbance, it is very important to implement robust excavation systems. The diagram below illustrates an example of how costs can rise drastically when a geological factor increases.

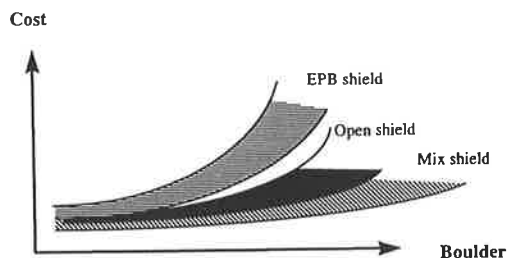


Figure 2. Example of disturbance sensitivity of various types of machine to boulder frequency in the soil.

Table 3. Examples of how occurrence of geological factors will give the probability of the constructability state for a certain method of excavation with or without steps taken to increase the robustness.

A	B	C	State of constructability without steps taken	State of constructability with steps taken	P(state)
+	-	-	III	III	0.09
+	+	-	II	II	0.36
+	+	+	I	I	0.36
-	+	+	I	II	0.04
-	-	+	I	II	0.01
-	-	-	III	III	0.01
-	+	-	II	II	0.04
+	-	+	I	II	0.09

By means of table 3 probabilities for different states can be estimated. It is evident that the occurrence of factor C during excavation with a certain shield machine without measures involves problems. With measures, however, the geological factor C could occur without major problems.

By adding up the probability figures in table 3 for different states of constructability, the figure below will be obtained.

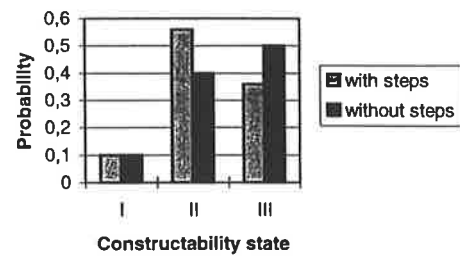


Figure 3. Example of probability for different states of constructability, both with and without steps taken for certain shield method.

2.5 Methodology for risk estimation

The risk of unwanted events can be expressed as the product of probability and consequence according to the following:

$$R = Pf * Cf \quad (10)$$

where Pf = probability of the unwanted event, and Cf = cost consequence of the event.

By using a rough analysis and fault trees, it is possible to structure causes, probabilities and consequences of unwanted events. The probability of disturbance could also be obtained by using experience values from earlier events. According to the definition of constructability states, a simplified probability assessment can be performed (See table 4).

Table 4 Assessment of probabilities and consequences of unwanted events for different constructability states. This is valid for all zones and methods.

Constructability state	Pf	Consequence class
I	0.9	2-3 (4)
II	0.1	2
III	0.05	1

The cost consequences due to damage when excavating the tunnel can be calculated as the sum of the costs of down time and extra measures taken e.g. support, according to the formula below.

$$Cf = \sum C_{time} * t + Ext \quad (11)$$

where $\sum C_{time}$ = the sum of time-dependent costs,
 t = down time and Ext = extra costs for support, for example.

The cost consequences can be divided into different consequence classes according to table 5.

Table 5. Definition of cost consequences

Consequence class	Consequence description	Cost [% of tender sum]	Example
4	Extensive damage	>100	Method failed
3	Considerable damage	50-100	Face collapse
2	Limited damage	10-50	Machine failure
1	Minor damage	<10	Segment fault

Table 6. Unwanted events in the case of shield excavation. Cause statistics based on 15 projects (The consequence class is based upon a subjective assessment).

Type of problem	Description	Class of consequence	No.
Geology			33
Problems at the face	Face collapse	2-3	9
	Collapse to the surface	3	2
	Collapse and water inflow	3	2
	Jamming	3	6
	Vertical deviation	2	3
	No contact cutter head- rock	2	2
Other	Methane gas leakage	3	1
Function failure (TBM)	Transport syst not suitable for geology	2-3	1
	Cutters not suitable for geology	2-3	2
	Grippers not suitable for geology	4	4
Problems at the perimeter	Jamming of segments	1	1
Problems at surface	Sink hole	1	2
	Settlements	1-3	2
Mechanics			7
Cutter head	Main bearing failed	1	2
	Screw conveyor failed	1	2
Shield break	Head / tail	1	1
	Main component out of order	2	2
Miscellaneous			2
Material failure	Hydraulics	1	1
	Ventilation fans	1	1

To gain a picture of possible unwanted events and their related cost consequences in the case of shield excavation, table 6 has been compiled, based on literature data.

The events that occurred can be divided into geological, mechanical and other events. The geological events are often caused by a combination of unpredicted geology and human error in the form of shortcomings in information flow or in the decision-making process. Mechanical failure are often a result of faulty component, and other events may be due to erroneous dimensioning or manufacturing faults.

3 CASE STUDY

The developed theory for choice of method has been applied to the Grauholz Tunnel in Bern, Switzerland. The double-track railway tunnel has a diameter of 11.6 m and a length of 5550 m. Construction began in 1990 and was completed in 1993.

The geology of the area can be roughly divided into three zones (Rohrer 1994). Zone 1 was composed of moraines with a relatively high clay content and occasional boulders. The water pressure rose in this zone to 0.37 MPa. Zone 2 consisted of sandstone with a maximum overburden of 120 m. The last zone was made up of moraines and boulders above groundwater level.

The following three types of shield machines were considered for the construction of the tunnel (Rohrer 1994):

- Mixshield with the option of rebuilding from hydroshield to TBM.
- EPB shield in which the soil mixture ahead of the cutter head absorbs soil and water pressure. The excavated material is transported by a screw conveyor.
- Open shield which does not have the possibility to support groundwater pressure at the face. This means, that the shield can be operated in groundwater if the soil is not impermeable, or reinforced with grouting or ground freezing.

The advantages and disadvantages of different types of machine have been summarised in table 7.

Table 7. Advantages and disadvantages of different types of machine

Machine type	Advantage	Disadvantage
Mix shield	• Little influence on groundwater	• Overpressure at face necessary for change of cutters • Bentonite and separation expensive
EPB shield	• No separation necessary • Different layering can be overcome	• Difficult to plan in inhomogenous soil
Open shield	• Low investment costs • Possible to operate in different soil/rock hardness	• No occurrence of water acceptable in non-cohesive soil • Clay content <6% requires face support • No system for supporting face

Source: (Barbendererde 1991), (Maidl 1994)

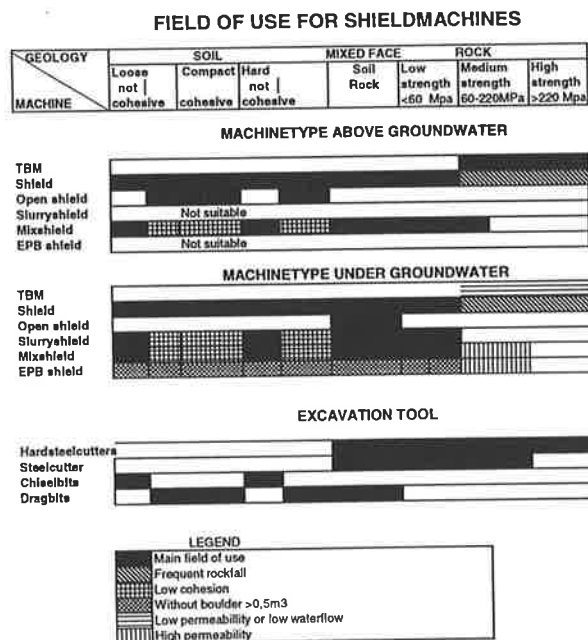


Figure 4. Geological field of use for different shield machines

As can be seen in figure 4, only a relatively small number of geological and hydrogeological parameters are required to make a preliminary choice of machine type. The large overlapping areas, however, show that the final choice of machine type is a complex process, encompassing both technical parameters and economic, environmental and safety factors.

The decision is further influenced by local negotiation strategies and claims management.

4 RESULT

The probability-based decision model (described in the Section 2) for assessing expected costs for excavation with different shield methods has been applied in the Grauholz Tunnel. In figure 8, a probable cost for excavating the tunnel has been calculated for the three types of machine. In order to judge the distribution of the total implementation costs for the different machine types and thereby facilitate a decision, the tree has been evaluated using a Monte Carlo simulation.

Figures 5 till 7 show the results of a Monte Carlo simulation of the total costs of the whole tunnel, i.e. the sum of all three zones. In the figures, the costs with and without measures and the standard costs have been marked. It is clear from the figures that the standard costs can vary considerably, which renders them less efficient as the basis of a decision. The figures also show that the method can be made more robust for different geological factors with the help of additional measures.

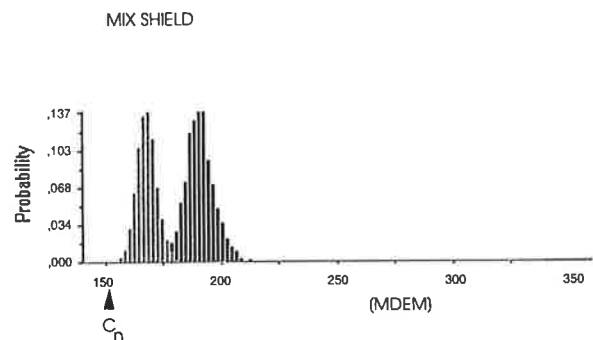


Figure 5. Mix shield with and without centrifuges for separation

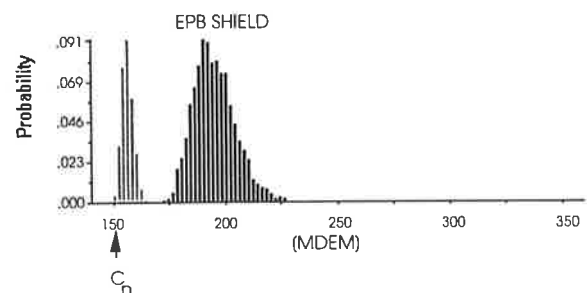


Figure 6. EPB shield with and without capability to crush boulder (technique not possible today)

The result of the simulation shows that:

- 1 The mixshield technique is suitable for excavation both in soil under water pressure and in dry sandstone, which was present in the Grauholz Tunnel project. In very clayey soils, however, considerable separation of fines is necessary.
- 2 The EPB shield is sensitive to rocks. The cost of this type would likely be less than for mix

shield if it were able to crush rocks. However, this is not possible with present-day technology. This method involves no separation

- 3 The open shield requires major drainage and support measures for excavation of large-diameter tunnels in soil under high water pressure. Thus using this method entails very high costs.

5 CONCLUSIONS

The developed model can be used in the choice of shield machine. It is important to have clearly formulated decision criteria, i.e., not only to choose the method with the lowest standard cost estimate, but to select the one that gives the lowest expected total costs depending on the cost increases that may occur as a result of incorrect geological assumptions. By assessing the probability of the method succeeding or failing because of variations in the geology, the robustness of the method can be studied.

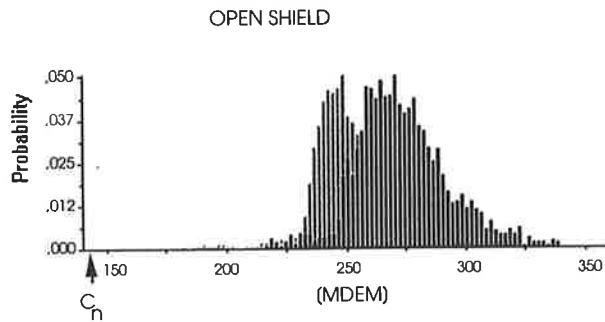


Figure 7. Open shield with and without comprehensive drainage measures

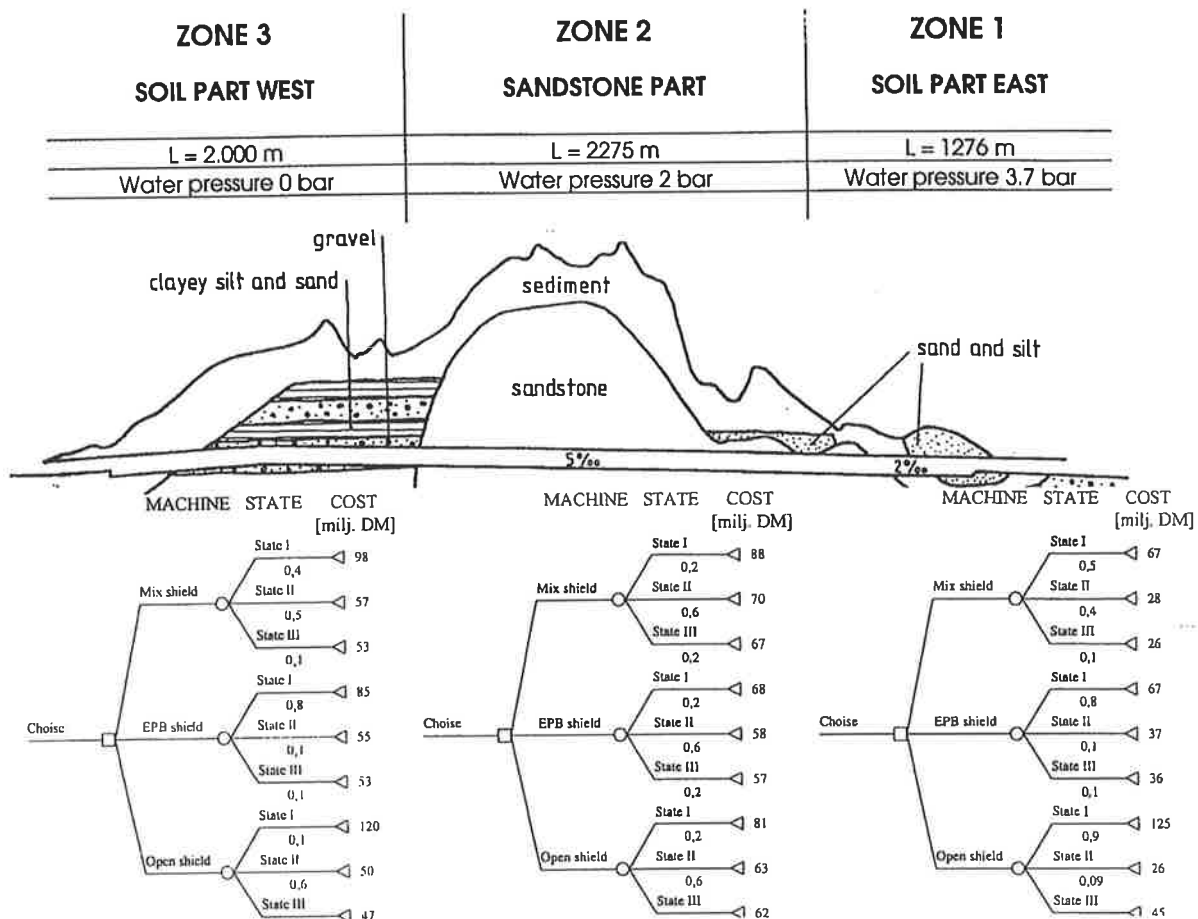


Figure 8. Decision tree without measures

A further refinement of the methodology for calculating the robustness of an excavation method is planned, since a robust method is less sensitive to different disturbances. The manufacturing industry has been carrying out different forms of robustness calculation for many years (the Taguchi method).

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Quality systems and risk analysis – New philosophies in underground construction industry

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ABSTRACT: In order to fulfil the increasing demands seen lately in the underground industry it is necessary for both clients and contractors to implement advanced quality systems. Quality systems, primarily based on ISO 9001, have been developed during the last decades. Experience from large underground projects has, however, revealed shortcomings in the application of these systems. In order to overcome these shortcomings the concept of quality should be given a broader sense and be linked to the use of formal risk and system analysis. The combined use of quality systems and risk analysis, is aiming not only to "do things right" but also to "do the right things". A procedure for quality work is proposed, focused upon finding important factors and demands and concentrate quality assurance on them. The proposed procedure is based on the use of tools such as a precise project model, risk analysis, system analysis, team qualification and audits.

1 INTRODUCTION

Large 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 projects are characterised by; difficult conditions, high technical level, uncertainty associated with the soil and rock mass, complex contracts, long project time and political and environmental focus. In addition to this the organisations are often complex and several actors (client and consultant, contractor and engineer) are involved. These actors shall all co-operate for the benefit of the project, yet defend their own interests. Society also becomes more involved in large construction projects as demands on environment and quality continuously increases. Nylén (1996) found in an investigation on quality failures, that a few complex failures cause the majority of failure cost in large civil engineering projects.

In the light of the above it is obvious that the need for quality systems is large and also continuously increasing. 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 organizations but to a large extent based on the European Standard EN ISO 9001:1994 (referred to as ISO 9001).

This paper discusses quality work within the underground construction industry and focuses upon a broader definition of the concept of quality including a risk management approach. First, some examples of underground projects, in some way or another, exhibiting insufficient quality are given. Secondly, 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.

2 EXPERIENCE FROM UNDERGROUND PROJECTS CONCERNING INSUFFICIENT 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.

The following sections presents a survey of experiences from some major underground projects where insufficient quality has led to damage. These examples are principally described considering different types of accidents common within underground construction. Furthermore, initiating events and hazards are identified for the described types of accidents.

2.1 Environmental accidents

During the 60s and 70s the metro system of Stockholm was enlarged. Most of the tunnels were constructed as unlined, partially pregrouted tunnels in hard, jointed granitic rock. The tunnels were normally situated well below the ground water level. The rock surface is in the Stockholm area to a large extent covered by layers of soft compressible clay. The hazard in this type of geological formations is connected to the ground water situation. Lowering of the ground water table will give damages related to deterioration of wooden piles or consolidation settlements of the clay (Morfeldt 1967). The initiating event is the ingress of water to the tunnels. Due to lack of knowledge of the theory of ground water flow in soil and rock and of grouting techniques at that time, severe damage occurred at several locations (Bruce et al. 1980). Though engineering knowledge constantly is increasing this problem still exists when underground construction is carried out in urban areas.

Another example of environmental accidents is related to the railway tunnels through Hallandsås. Even with advanced grouting techniques both with cement based grouts and chemical grouts it has been impossible to prevent a lowering of the ground water level in the area. The surface water and the ground water has in addition to this locally been

polluted by the chemical grout. The hazards were in this case related to the water bearing, jointed rock and the poisonousness of the chemical grout. The initiating events were the ingress of water as well as the lack of capability to fully recognize the mechanisms of chemical grouting.

2.2 Tunnel failure after completion

In Scandinavia several tunnel failures have occurred after completion due to swelling clay (Selmer-Olsen & Palmstrøm 1989, Heiner & Stille 1990). The tunnels which have failed are normally water tunnels excavated in hard competent igneous or metamorphic rock. The hazards in this type of geology is the presence of clay seams with swelling minerals. When the seams are exposed and get in contact with water the swelling process starts and may cause tunnel failure years after completion. The damage is normally connected to loss of revenue and cost for reparation. Both the lack of knowledge of the true behaviour of swelling clay and the possibility of identifying clay seams during the tunnelling work have caused the accidents.

2.3 Tunnel failure during excavation

During excavation minor failure will normally take place as outfall of blocks creating so called chimneys. However, sometimes major outfall can occur, normally associated with water or flowing ground. Such failures will occur rapidly, without warning and may more or less fill the tunnel with mud. Flowing ground might cause failure progressing up to the ground surface and cause severe damage both for the tunnel work and the environment. The hazards are the pressure of soil, unconsolidated rock material or pockets of water. The initiating event is normally the blasting or excavation procedure giving a possibility for the failure to be developed. Problems of this kind may be avoided if probe drilling and geological follow up are carried out.

The Great Belt Project is a TBM project carried out under difficult conditions, (Wallis 1993). The tunnel was flooded during the excavation and caused delays and damage on the equipment. The geological hazards were pockets of water and flowing ground in the rock mass. The initiating event was the excavation and the ignorance or lack of knowledge of the type of hazards involved. A strict obedience of a correct safety procedure could have substantially reduced the damage.

2.4 Well handled hazards

Most underground projects are constructed without any damage, even if the hazards have been substan-

tial. 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 is railway tunnels and stations excavated under 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 Hvalfjörður Tunnel which is a subsea road tunnel in a thermal active area on Island (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.

3 IMPORTANT FACTORS INFLUENCING QUALITY

3.1 *Obstacles to achieving quality*

As mentioned earlier, quality work should be focused upon important factors and problems. Insufficient quality of greatest concern is related to loss of money, time or goodwill. The first two aspects are obvious. However, the third aspect, loss of goodwill, has increased in concern specially 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 fulfilled 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 getting initiating events.

If damage is unacceptable or it is impossible to eliminate or reduce the probability of getting initiating events it is important to reduce the consequence of possible accidents and still achieve an acceptable quality in broad sense.

Insufficient quality due to failure of meeting the above aims within a project work may depend on several different obstacles. The obstacles may be divided into the following groups:

- General obstacles
 - lack of knowledge
 - contractual blocking
 - wrongly defined demands or prerequisites

- Organisation obstacles
 - indistinct organisations
 - indistinct responsibilities
 - indistinct working procedures
- Person obstacles
 - lack of competence
 - lack of insight
 - prestige
 - human errors

The general obstacles are obvious in connection to underground projects, as they include a high degree of uncertainty. Many aspects, for example of the rock mass behaviour and the complex interaction between rock excavation and rock support, are only partially known. There is in real sense a lack of knowledge. The contractual blocking and wrongly defined demands or prerequisites have in many cases given projects that are correctly carried out but from an overall point of view completely wrong and thus with a poor quality.

Most of the quality systems used today, certified according to ISO 9001, have an intention of reducing organisation and personal 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, which has been shown by the examples of insufficient quality described and discussed in the previous chapter.

3.2 *Definition of the project*

The very definition of the project with its aims and demands is closely related to quality. Demands are set in order to achieve a certain level of acceptance of probability for malfunction. Given the definition of quality, presented above, it is obvious that the demands must reflect both stated and implied needs. Today, demands such as technical specifications, which may be referred to as stated needs, are discussed in detail whereas demands associated with implied needs, for example demands on public relation, environmental needs, good relations, creativity and clear communication easily are forgotten.

Consequently, an important element within a broader quality work is to define distinct demands not only on technical issues but also on how the project work is carried out, how it is kept together and how it is secured that requirements are fulfilled. Critical activities are, in this respect, the identi-

fication and assessment of hazards and potential damage events, contractual agreements and start-up of different project stages.

A very important necessary but not sufficient prerequisite for achieving good quality within a project will therefore be the use of a clear and structured project work procedure (project model).

When discussing the importance of increased focus upon implied needs, contractual aspects on quality and project demands arise. It is not obvious that a client will pay for implied needs, just as the contractor is unwilling to give them away for free. In a Build Operate Transfer (BOT) concept the contractor has to identify implied needs in order to be successful. The client only specifies simple functional demands, putting large stress on the contractors quality work but also giving him a high degree of freedom. Within a general contract, on the other hand, the task of identifying implied needs stays with the client and his consultant and the quality work for a contractor becomes more related to stated demands and technical specifications.

4 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.

4.1 *Doing the right thing*

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

- function,
- aesthetics and

- economy, for instance initial investment or better still 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 function 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 demands 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 demands 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 summarize 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 emphasized that these tools, further described in Section 5, could and should be used within all project phases.

4.2 *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

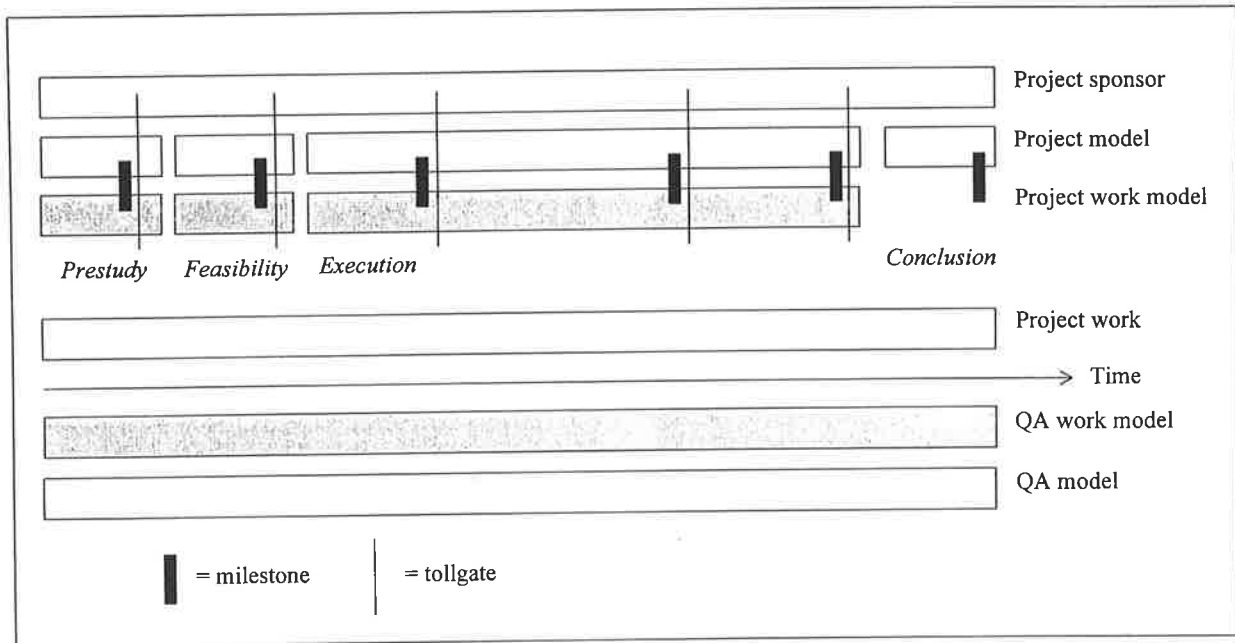


Figure 1. Project model, based on PROPS, and QA-model (after Stille & Stille 1997).

good relations and clear communication the possibility of doing the things right will be further increased.

5 QUALITY TOOLS

5.1 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, Figure 1. The use of a project model contribute 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 1. The quality work is then connected to the activities within the project.

5.2 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 1996). 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 et al. 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 clients 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 1998).

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

5.4 Technical audits

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

5.5 Team qualification

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

6 CONCLUSIONS

In this paper it is shown that based on experience from underground projects, often characterized 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.

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System analysis of the Hvalfjörður tunnel

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ABSTRACT: A road tunnel is being constructed underneath Hvalfjörður, a fjord north of Reykjavik. The project is purchased as a turn-key contract and is the first subsea tunnel in Iceland.

As a part of the project quality assurance, a system analysis (risk analysis) was carried out during the introductory phase of the construction work. The objectives with the analysis was to identify geological and organisational hazards that could inhibit the construction works.

The system analysis carried out for the Hvalfjörður project resulted in several concrete and useful results for the contractor and has been accepted at the work site as support when forming the work procedures. This has led to a reduction of risks and therefore improved the quality of the whole project. Hvalfjörður can also serve as a general example on how methods for system and risk analyses can be utilised to minimise risks in underground construction.

1 INTRODUCTION

In 1987, the Icelandic Public Road Administration published the results of a preliminary study indicating that a subsea tunnel crossing the fjord Hvalfjörður, would be both beneficial to the national economy and technically feasible. After studies and site investigations the work commenced in 1996. The tunnel is now, in the beginning of 1998, excavated and installation work is presently being executed.

The construction of the tunnel underneath the Hvalfjörður involves tunnel excavation under special conditions and is a good example of how system analysis can be applied to rock construction projects.

Chapter 2, which is the project description, briefly describes the system analysis, the tunnel project, the type of contract applied and the existing geology. Chapter 3 describes the system analysis, from the identification to the remedying of technical hazards, and finally organisational hazards. The results of the analysis and concluding comments are presented in Chapter 4.

2 PROJECT DESCRIPTION

2.1 System analysis

The task of the independent System Analysis Group was to study existing documentation and to take into

account verbal information concerning the project, in order to identify and describe the hazards (geological and/or organisational) which may jeopardise the construction of the tunnel. The group was also charged with studying and proposing methods which could be used, and with defining the scope of the geological exploration programme. This was to result in guidelines for the handling of information and decisions by the organisation.

In projects such as this, chains of events and causal connections are often complex since geological and organisational hazards are closely related.

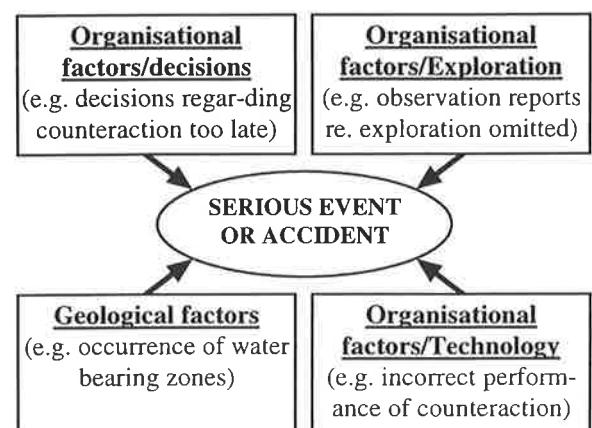


Figure 1. Illustration of interaction between different categories of hazard.

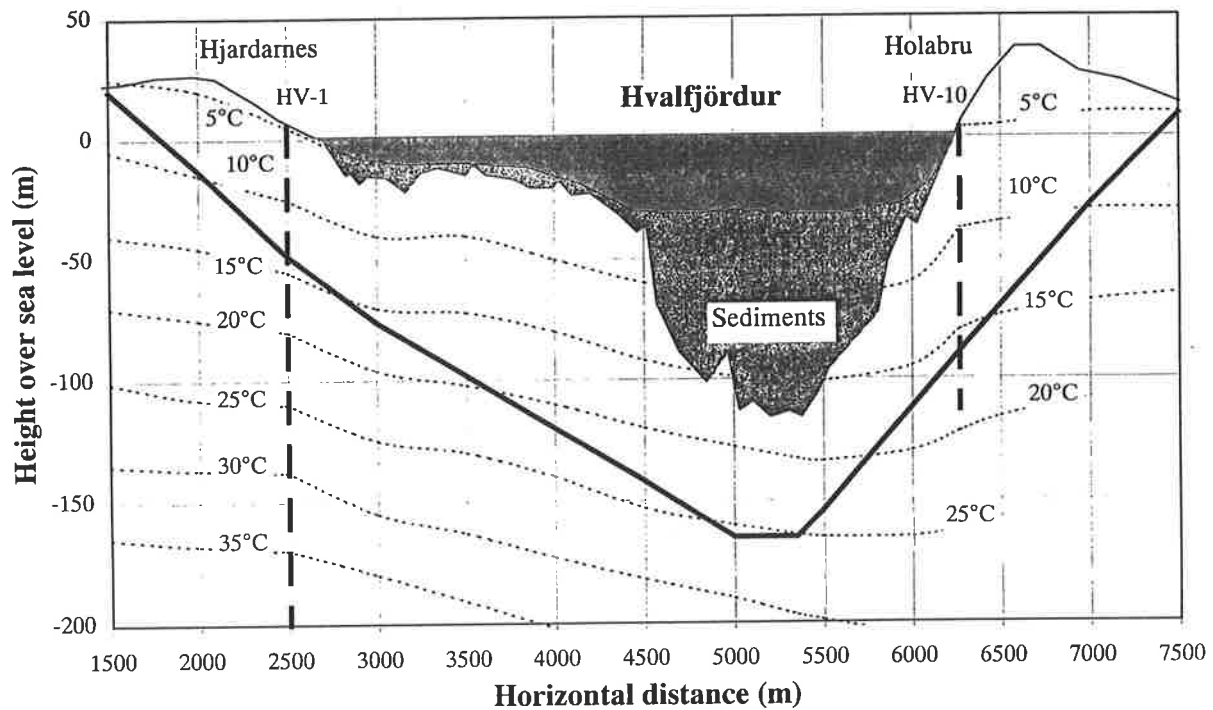


Figure 2. Schematic longitudinal section of the tunnel underneath Hvalfjörður showing expected temperature conditions.

2.2 The Hvalfjörður tunnel

Hvalfjörður is a 30 km long and 3-4 km wide fjord, located approximately 30 km north of Reykjavik on the south-west coast of Iceland. By constructing a 6 km tunnel underneath the fjord the distance by road between Reykjavik and western/northern Iceland would be reduced by 50 km. Figure 2 above shows a schematic longitudinal section of the tunnel.

The private company Spölur Ltd., has been granted the concession by the Icelandic authorities to build, own and operate the tunnel as a pay-tunnel for a limited time period. Spölur has engaged the contractor Fossvirki to execute the tunnel construction. Fossvirki is a consortium consisting of the Swedish company Skanska, the Icelandic company Ístac and the Danish company Pihl & Søn. Fossvirki has entered into a turn-key contract with Spölur Ltd which means that they are responsible for the design, construction and commissioning of the tunnel. In order to ensure that rock excavation is executed in a satisfactory effective way, a decision was made by Fossvirki to carry out a system analysis which would take into consideration the risks during the project.

2.3 Geology

Iceland is located in the middle of the so-called Mid Atlantic ridge, which is the borderline between the North American and the European continents.

In Iceland, the magma is of low viscosity and the slopes of the volcanoes are thus rather shallow. Volcanic eruptions occur intermittently, and sometimes several hundreds of years can pass between eruptions. As a new eruption approaches, the magma can find new pathways and cut through the already formed rock mass. This will result in basalt dikes which will cut through the general layer sequence. The contact zone between the basalt dike and the parent rock may have a high water conductivity, while the dike itself is often impermeable.

The layered geology consists of layers of stiffened magma. These have a relatively impermeable central layer of "basalt" while the layers above and below are more porous and are described as "scoria". Since long periods may pass between eruptions, layers of sediment can sometimes be formed between two basalt layers, see Figure 3 below. The basalt is normally of good quality but with dominating vertical fractures from the cooling phase. The scoria often has low permeability and low strength.

Due to tectonic movement, the rock mass is crossed by faults. These faults may be of rather good quality rock and more or less impermeable, or they may be associated with extensive crushed zones which are permeable. In both cases, the faults will change the normally regular and similar geology very suddenly.

The Hvalfjörður tunnel is located in an area

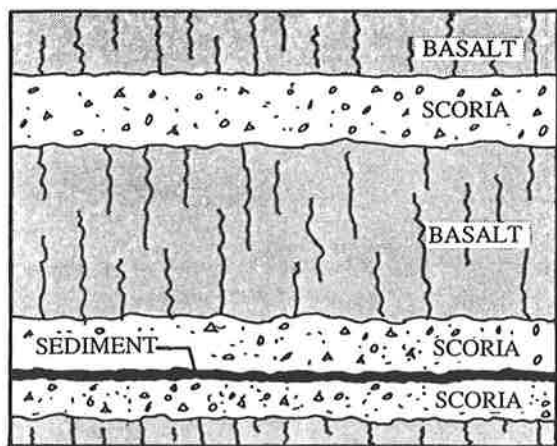


Figure 3. Typical geological layer sequence.

which is approximately 3 million years old, and no active volcanoes or geothermal fields are to be found nearby. A study of the area has shown that the temperatures in the tunnel will rise as it goes deeper. The temperature at breakthrough was based on field investigations, and was estimated to be approximately 25°C, see Figure 1 above. However, during the actual tunnel construction the temperature was substantially higher.

The level of the rock surface and the thickness of the bottom sediments were defined by seismic methods. At the deepest part of the tunnel the rock cover is approximately 40 m, and the bottom sediments are approximately 80 m thick.

3 SYSTEM ANALYSIS

3.1 Methodology

The analysis was carried out in three phases. Since the System Analysis Group does not have its own experience of tunnel construction on Iceland, the strategy for Phase 1 was to gather as much information as possible regarding the geological conditions and related problems for the construction work. The result of Phase 1 was a preliminary model of the present geology and a list of possible geological hazards.

In Phase 2, the preliminary geological model and the possible hazards identified were discussed, revised and evaluated. Icelandic experts made important contributions and also served as a sounding board by reviewing proposals put forward by the System Analysis Group. Phase 2 resulted in a revised geological model and a reviewed list of probable (and serious) geological hazards.

During Phase 3, work was carried out along two parallel tracks. One was to identify measurable indications of geological hazards and to find methods of exploration and analyses suitable for

practical use, and thereby be able to measure and evaluate the indications. The second track was concerned with the organisational demands on decision making and information paths; i.e. how information gained from exploration and tunnel excavation should be handled so as to make correct decisions regarding the execution of the construction work while there is still time to influence the work.

The system analysis resulted in a proposal and recommendations to the contractor Fossvirki regarding suitable methods of exploration as well as a suitable organisation for the handling of information.

3.2 Phase 1 - Determination of possible geological hazards

An initial fault tree analysis was carried out to identify all chains of events which may lead to technical failure of the Hvalfjörður tunnel construction. All available written information as well as verbal communication with experts within and outside of the project was utilised. In this initial phase, no estimation of probabilities were associated with the events identified. The criterion was rather to include too many events than run the risk of overlooking something important. Therefore, only obviously preposterous events were excluded. The result of the initial fault tree analysis was that six primary possible events were identified as crucial for the technical success of the project. These events are:

- Large waterflow cannot be handled. Such large volumes of water enter the tunnel that continued tunnelling is impossible or delayed, making the project prohibitively expensive.
- Stability problems, no water. Rock fall in the tunnel, primarily due to weak rock formations and not water pressure.
- Heat problems. The work is made more difficult or is hindered by an inflow of hot water or by high temperatures in the rock formation.
- Harmful gases in tunnel. Suffocating or poisonous gases flow into the tunnel and prevent or make tunnelling operations more difficult.
- Seismic damage. Damage to the tunnel as a result of seismic activity in the form of an earthquake and associated faulting etc.
- Tunnel durability unacceptable. The tunnel is completed but quickly starts to deteriorate due to unfavourable and unexpected environmental influences leading to unreasonably high maintenance costs.

3.3 Phase 2 - Identification of probable geological hazards

On a visit to Iceland, discussions with geological experts and the contractor were carried out regarding

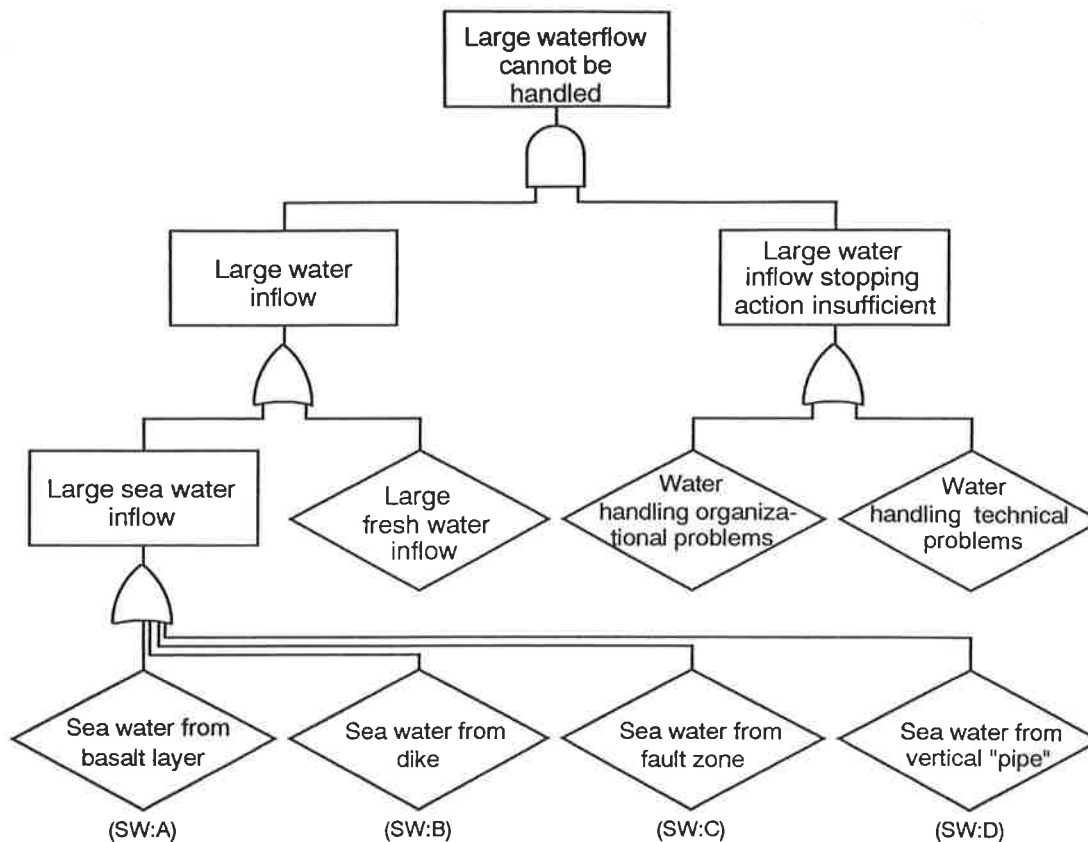


Figure 4. Sub-tree for the top event "Large waterflow cannot be handled".

the expected geology, geohydrology and geothermal conditions on site, as well as planned methods for investigations and driving during rock excavation. Additional documentation was also handed over by the contractor as basis for the continuous analysis.

Of the scenarios outlined in the previous section, the event "Large waterflow cannot be handled" was found to be the most serious threat to the tunnel construction, especially since the tunnel is to be excavated with a small rock coverage below the ocean. The access of water close to the tunnel is therefore unlimited. The following analysis dealt mainly with this threat since the other hazards identified in the main fault tree were not expected to constitute threats of the same magnitude as the inflow of water.

The event "Large waterflow cannot be handled" was further analysed and resulted in the identification of eight partial events. See Figure 4 below where 4 of these are shown.

Each of these events was then further developed. Figure 5 below shows an example of this detailed development for one of the eight sub-events, namely "Large sea-water inflow from dike".

3.4 Phase 3 - Measures to minimise the probability of large water inflow

In order to ensure the safe management of events occurring during rock excavation, the contractor must be forewarned of hazards of importance in the rock mass in the vicinity of the tunnel. Firstly, it must be made clear which indications are characteristic of the different geological hazards. Useful exploration and analysis methods must then be developed.

During this phase, the demands which will be placed on the project organisation were dealt with, as well as the decision making and information flow within the organisation. This was done to facilitate the correct handling of information for exploration and tunnel excavation, allowing the correct decisions to be taken in time to facilitate the safe excavation of the tunnel.

3.4.1 Indications of geological hazards

The presence of potentially strong water-bearing geological structures in the vicinity of the tunnel is characterised by the following indications:

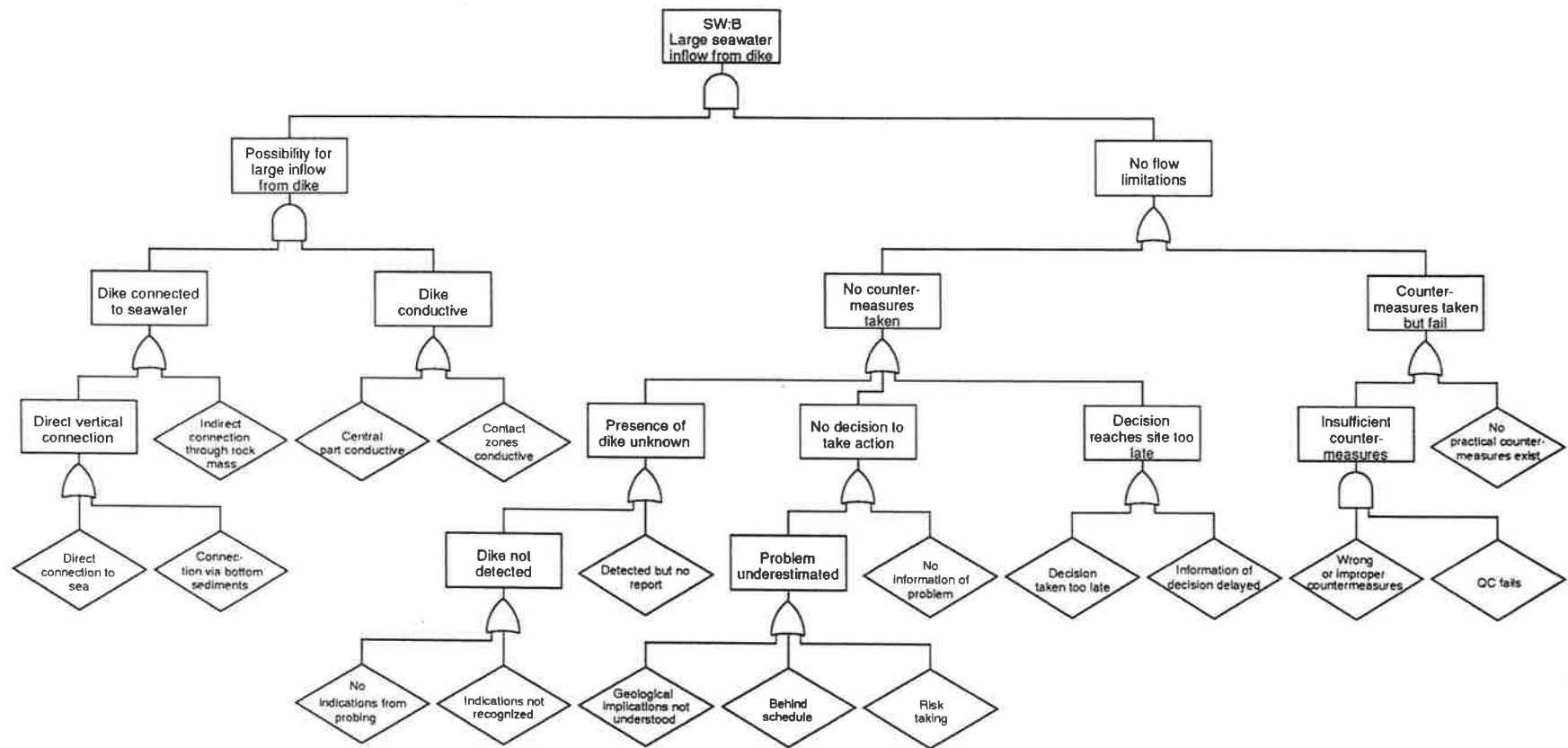


Figure 5. Detailed tree for the event "SW:B Large sea-water inflow from dike".

- Vertical or sub-vertical geological structures: Intersections between zones are especially important.
- Temperature: The thermal gradient interpreted from site investigations shows an expected temperature of 25°C in the lowest part of the tunnel. A major deviation from the expected temperature gradient may mean connection with the deeper (warmer water) or with more shallow layers (cooler water).
- Salinity: Increased salinity may indicate sea-water or thermal water from deeper levels.
- pH value: The pH of groundwater is expected to increase with depth. Low pH values are an indication of water from shallow levels, while high pH values indicate the presence of water from deep levels.
- Colour of drill water and drill cuttings: A certain colour may indicate the presence of sediments or breccia. The presence of these materials may lead to stability problems.
- Drill penetration: In combination with the colour of the drill water, changes in the rock mass geology may be indicated.

3.4.2 Methods for exploration

With knowledge on the probable hazards and indications of these, different methods of investigating the rock mass were studied. In the selection of methods for exploration it is important that they give clear indications which are simple to interpret.

The System Analysis Group did not present a complete programme for exploration methods, but instead gave recommendations to be used as a checklist by the contractor while developing their working routines for this task.

Exploration can be divided into a routine part and a part adapted to contingency requirements. Routine exploration should be performed on the complete length of the tunnel and is intended to identify warning signals of impending danger in the

vicinity of the tunnel with a high degree of reliability.

Specific recommendations were made regarding the exploration programme and probe drilling, including measurements in the probe-hole, Measurement While Drilling (MWD) and georadar measurements, or other geophysical methods.

If warning signals are detected during routine exploration, further information on the suspected hazard must be obtained (if the indication is not so definite that the hazard can be identified directly). This information is obtained by extending the exploration and supplementing it with a contingency exploration. The intention is to improve the decision-making data and to enable the implementation of appropriate countermeasures. The sequence of events is described in the illustration in Figure 6.

3.5 Organisational hazards

Apart from the technical hazards previously mentioned, an inadequate organisation can considerably affect the results.

In this section, the flow of information during tunnel excavation and factors that might disturb this flow are described. The distribution of responsibility is then discussed.

Hazards related to faults in the technical equipment (pumps, electrical systems, etc.) which are crucial in handling the inflow of water have not been investigated.

3.5.1 Flow of information

Measurements and observations may generate a considerable amount of information which is to be collected, documented, interpreted and distributed within an organisation. This is then used as basis for making decisions and implementing

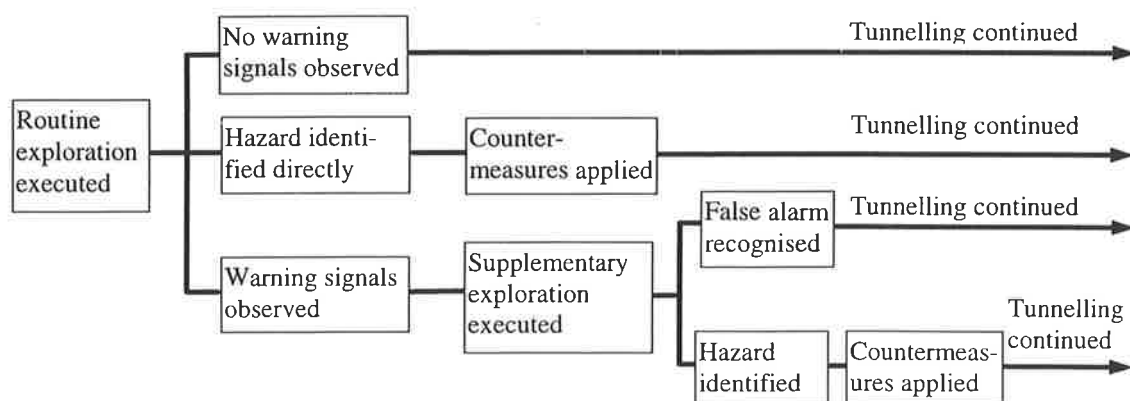


Figure 6. Illustration of the sequence of events in routine exploration.

countermeasures. Figure 7 shows a general a chain of events beginning at an indication of danger, and ending when corrective measures have been taken. Two alternative situations can develop at each branching point in the chain of events, a negative (downward) or a positive (upward) situation from which the chain continues.

Possible reasons and relations leading to unwanted events have been further developed by fault tree analysis. These fault trees can be used to study the strengths and weaknesses of the organisation in the different situations described in the event tree.

Some of the more important factors which have been identified regarding the information flow are presented below, together with proposed countermeasures.

- Rate of information flow: The time elapsed from the indication of large waterflow via decision making to implementation of countermeasures must be as short as possible to avoid serious consequences. Several different countermeasures should be planned and practised for emergency situations together with the personnel involved. These measures shall be operated by the crew on site without waiting for decisions from others.
- Control system: Measuring and recording routines should be introduced in order to ensure that probing is carried out far enough into the rock mass in relation to the rock excavation works.
- Amount of information: Too large an amount of information may lead to important information not being identified. Reduce the amount of information as much as possible.
- Feedback: The learning procedure within the project is important so that methods can be adapted and developed to the site-specific conditions. Information regarding observations and prognoses should therefore be sent to relevant personnel.

3.5.2 Distribution of responsibility

As the time which elapses from indications of a hazard during exploration, e.g. probe drilling, to the decision to implement countermeasures should be as short as possible a person qualified to take such decisions must be appointed at a suitable level in the organisation. In this kind of project, involving hazards which may lead to extreme consequences, the responsibility for decision making should be given to employees who are connected with the tunnelling work close to the front.

The study of organisational hazards resulted in the following demands which should be pointed out to the organisation:

- Short paths for information dissemination within the operative parts of the project.
- The operative decision makers within the project should be constantly updated.
- Personnel responsible for decision making or their replacement must be present on site.

4 RESULTS OF THE ANALYSIS AND CONCLUSIONS

The system analysis resulted in a number of recommendations to the contractor regarding the exploration programme and organisation. The recommendations were formulated as a checklist to improve the existing tunnelling work. The contractor decided to consider the system analysis as part of his quality assurance and has implemented the majority of the recommendations in his working procedures.

The methodology applied, i.e. the systematic study and the formulation of the documentation have, in this case, differed from that which is normal for a contractor or consultant. This was possible

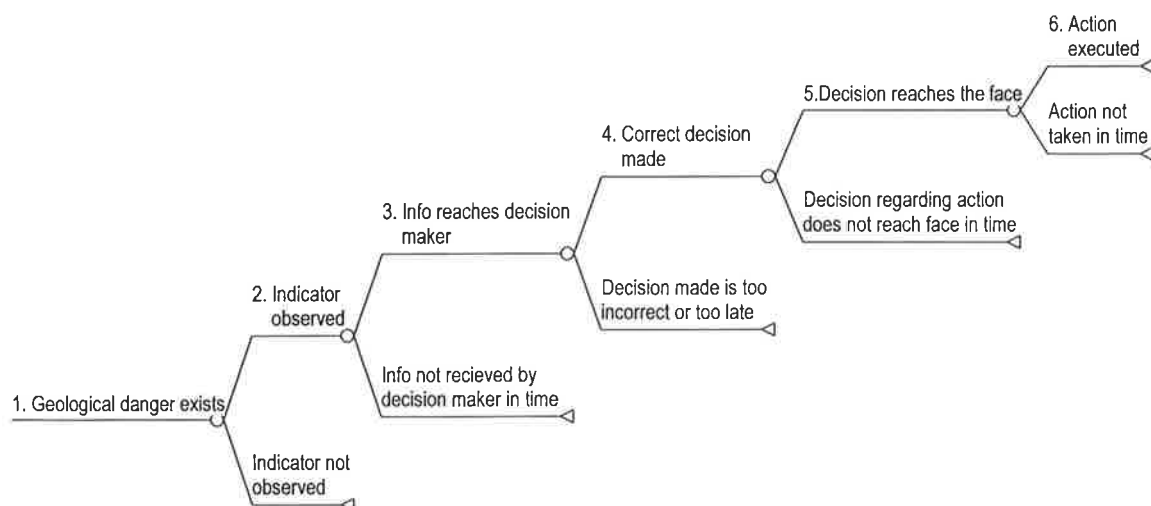


Figure 7. General event tree for the chain of events indication–decision–action.

primarily as the System Analysis Group was independent, the work was executed with "new eyes" and also because methods for risk analyses were utilised. The analysis therefore constituted a systematic check of factors which may lead to very serious consequences for the project, and is a complement to the judgement made by the contractor before commencing the tunnelling work.

Work on the report has involved impartial discussions between the System Analysis Group, geological/geothermal experts and the contractor. This resulted in an increased awareness by the parties of the geological and organisational hazards which should be taken into consideration.

According to both the contractors and the System Analysis Group the methodology applied was suitable for underground projects. We expect system and risk analysis to be more widely applied as alternative forms of contract become more common and as projects tend to increase in size and become more complicated.

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Engineering geological prognoses – Their value and impact on tunnelling

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ABSTRACT: Engineering geological prognoses, as one part of a risk analysis approach, are an important tool for planning and executing underground projects. The purpose of the prognoses varies depending on what scale and project stage are considered, however the overall objective should be to serve as basis for decisions. The paper discusses prognoses based on statistical modelling as a tool of improving the handling of uncertainty and thereby facilitating difficult decisions. Different statistical models may be used and the choice of model depend on a number of factors, such as geological regimes and homogeneity, scale, project stage and type of decisions. Guidelines concerning the choice of model are given and a statistical model based on a bayesian approach with main application in the construction stage is presented. Results from application indicate that uncertainty may be treated in a stringent matter and the relevance of additional information may be evaluated.

RESUME: Les prévisions de l'ingénierie géologique, un des facteurs de l'analyse des risques, constituent un outil important pour l'organisation et l'exécution des travaux souterrains. Les prévisions varient selon l'importance et l'avance du projet, cependant leur objectif majeur est d'établir une base correcte pour les mesures à entreprendre. Le présent exposé traite les prévisions basées sur le modèle statistique, celui-ci permettant de mieux gérer les incertitudes et facilitant les décisions délicates. Différents modèles statistique peuvent-être envisagés. Le choix du modèle dépend d'un certain nombre de facteurs comme l'entité géologique, l'homogénéité, l'importance et l'avancement du projet et la nature des décisions à prendre. Les recommandations concernant le modèle à choisir ainsi qu'une méthode statistique basée sur l'approche Bayésienne, applicable principalement durant la construction, sont présentées. Cette méthode indique une maîtrise rigoureuse des incertitudes et la pertinence des informations apportées permet l'analyse des résultats.

1 INTRODUCTION

The fundamental objective for most owners, clients and contractors involved in an underground project is to execute and complete the work, fulfilling customer demands, within the scheduled time and cost frames without loss of goodwill. The opposite is to be considered as severe damage (often expressed as economic loss). Damage is an outcome of a process caused by an accident. The accident is initiated by an event that triggers a hazard contained in a risk object. Within an underground project several types of hazards may usually be identified. Geological, contractual and organisational hazards and hazards associated with construction methods are the ones considered most important.

History has shown that large civil engineering projects tend to take longer time and cost more than initially predicted. This is understandable given the fact that such projects are characterised by a high degree of complexity, not only because of the

uncertainty associated with the soil and rock mass but also as they include major risks, difficult political and environmental aspects, complicated contracts and large organisations. By applying risk analysis, including for example tools of handling and describing uncertainty, the fundamental objective of avoiding damage may easier be fulfilled. Risk analysis work should focus upon (i) identifying and eliminating/reducing hazards, (ii) reducing the probability of getting initiating events and (iii) reducing the consequences of possible accidents. The methodology may for example be used to:

- give better input for estimating project time and cost,
- facilitate preparation of strategies for design, tendering, production, environmental impact, quality and maintenance,
- give better input for decisions on production methods,
- create a basis for implementing quality systems and executing quality work,

presents main interests from an engineering geological point of view during the construction stage. The decisions also become more specific in this stage and are mainly related to final design, project organisations, equipment, material and working procedures.

Table 3. Some important engineering geological parameters and how they should be described during a construction stage.

Rock type	Location of difficult rock types. Location of geological boundaries. Stand-up time.
Weathering/rock cover (sub-horizontal boundaries)	Exact location of areas with weathering and low rock cover. Exact mapping of interesting boundaries.
Rock stress	Location of areas with stress problems. Rock stress properties in these areas. Magnitude of problem
Water	Location of water bearing structures. Pressures and permeability. Groutability. Warning bells in current geology.
Major fault zones	Location of zones. Quality of zones. Width of zones. Warning bells in current geology.

3.2 Statistical models for engineering geological prognoses

When introducing a probability based methodology for describing the uncertainty in geological information it is desirable to have a statistical model for making prognoses that is stringent, consistent and applicable in all projects stages and scales. The model should also be suitable for decisions, i.e. give a result that could be used within the decision process. Further demands are related to the possibility of assessing and computing data. The model also has to be geologically logical, i.e. it should properly describe the prevailing geological regime, see Figure 1.

Looking at these geological regimes it is possible to speculate in some principles concerning statistical modelling of geological parameters. The problem of modelling geological parameters for example along a tunnel is analogous to time-series. Consequently, statistical models using a time-series approach is applicable. Four major modelling principles and examples of corresponding regimes may be identified:

1. Independent models without memory (regime b).
2. Models with memory
 - a) Short memory. Markov processes (regime e, matrix in regimes c and d)
 - b) Longer memory. E.g. (higher order) auto-regressive models (regime a and e).

3. Layered models with a more or less homogeneous matrix with different geological features such as joints and faults stochastically put on top of the matrix (regime c and d).
4. Compound models describing different geological interpretations each given a probability of being the right one.

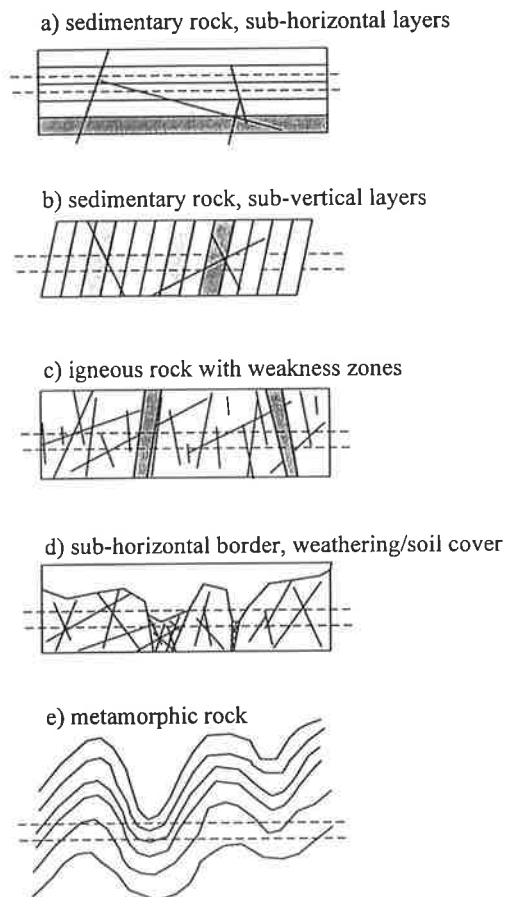


Figure 1. Some geological regimes. A tunnel is illustrated by dotted lines.

In order to summarize the preceding sections we may conclude that engineering geological prognoses play an important role in decision-making throughout an underground project. They also have somewhat different purposes in different project stages. Furthermore there are several ways of statistically modelling geological conditions and there are a lot of parameters influencing the choice of an appropriate model. In the next section some general principles for choosing a statistical model are discussed based on the above given background.

3.3 Statistical modelling philosophy for engineering geological prognoses

The main purpose of an engineering geological prognosis is, as earlier mentioned, to describe the

geological conditions in such way that it may be used as a base for important decisions. This is important and also implies that it is not always necessary to seek full statistical inference, i.e. a perfect description of nature.

However, a lot of decisions become more difficult due to uncertainties and it is consequently important to understand and describe these. It is also important to understand how uncertainties are handled by different statistical models and the correlation between uncertainty and the relevant problem. Recalling the different categories of uncertainty we may for example see that there is a connection between the inherent variability and choice of both statistical model for prognoses as well as tunnelling method. In areas with high spatial variability, modelled with an independent model or a model with short memory, it might be better to choose a flexible tunnelling method. In order to treat statistical uncertainty, decisions are mainly connected to how much investigations should be carried out in order to increase the amount of information. Professional uncertainty are related to many decisions throughout an underground project. When choosing a rock classification system or an investigation method we must understand the limitations and handle this in the statistical model. This may for example be reflected in prior models and likelihood functions. Generally the concept of updating is a good tool for handling both professional and statistical uncertainty.

Another important factor influencing the choice of statistical model is the scale considered. As we have seen above, there is a correlation between scale, main geological interests and project stage. Consequently, in early stages of a project (feasibility) a larger scale is considered and the most important thing is to describe proportions of different rock types, stop signs and major zones and persistence of poor rock. In this case different types of models, both independent models and models with long memory, may be considered mainly based on the degree of geological homogeneity. If observations are available these might help in determining whether the geological conditions at a specific site give a process with or without memory (Davies 1986). For a construction feasibility analysis, carried out in an early project stage at the Äspö Hard Rock Laboratory for nuclear waste (Sturk et al. 1996), a layered statistical model was used in order to simulate geological conditions. In this case the geological regime consisted of a good quality matrix of granitic rock with discrete weakness zones stochastically occurring within the rock mass, c.f. regime c in Figure 1.

In later project stages questions and decision become more detailed and the scale considered much smaller. During the construction stage the main interest is the location of different geological fea-

res and description of geology in the next excavation rounds. Even in this case different statistical models may be considered. However, for many geological sequences a markov model (Cressie 1993) is appropriate as it is a reasonable compromise between an independent process and a process with memory. It is also very straight forward when working with sequences of different units, such as excavation rounds. Statistical models and decision systems based on markov processes have previously been presented in the literature see for example (Einstein et al. 1992, Rosén 1995).

During the construction stage additional information concerning the geological conditions will within most underground projects be available. This stresses the need for a statistical model that could be updated, for example a bayesian model. Given all the demands discussed above it is reasonable to create a model based on a markov process combined with a bayesian approach for applications at least during the construction stage.

4 A BAYESIAN MODEL FOR ENGINEERING GEOLOGICAL PROGNOSSES DURING THE CONSTRUCTION STAGE

The dependence between scale, project stage and necessary data as basis for relevant decisions implies that it is not possible, even not desirable, to investigate for complete knowledge in the earlier project stages. This will lead to a situation where geological investigations and the making of engineering geological prognoses will be necessary also during the construction stage especially within complex underground projects.

The statistical model presented in this paper has therefore been developed as a tool to predict the geological conditions, in this case described as engineering geological states (EGS), ahead of the tunnel face in a five metre scale. The EGS constitutes a set of parameters describing both geological conditions, such as classification values (Q, RMR), degree of weathering and water content, as well as actions taken during tunnelling, for example careful excavation and increased rock support measures. The EGS is site and method specific and describes the tunnelling conditions along the proposed tunnel alignment.

The bayesian model combines prior geological knowledge, gathered during pre-investigations in an early project stage, with observations made during tunnelling in order to create a posterior (updated) prognosis. The bayesian calculation has two important inputs. The prior statistical model describes the degree of knowledge before additional information is available and the likelihood describes how probable it is to get a certain (observed) sample given a specific state. The posterior distribution of

EGSs is calculated using a numerical computational technique for bayesian inference called MCMC. The major principles of the model is briefly presented below, a detailed description of the model is given by (Sturk in prep.).

It should be noted that the model in this case simulates the EGS, i.e. a combination of both geological and construction related parameters. However, using the same statistical principles it would be possible also to simulate geological parameters directly.

4.1 Description of the statistical model (prior)

The tunnel is modelled as a string of 5 m long segments (sections). Each of these can belong to one of four states (EGS). However, the state of each individual segment is not known beforehand and the prior knowledge of the geology must be described using statistical principles, i.e. by giving probabilities for each state and each segment.

It is not likely that the states of the segments varies randomly when we move along the tunnel. It is more probable that some stochastic law governs the relationship between states of neighbouring segments. As stated above this relationship may be described using a markov chain in many geological sequences. The basic principle of a markov chain is that the probability that the next segment ($i+1$) is state x_{i+1} depend only on what state the present segment i has and not on what states prior segments have had, i.e. the process has a short memory and depends only on its nearest neighbour.

$$\begin{aligned} P(X_{i+1} = x_{i+1} | X_1 = x_1, X_2 = x_2, \dots, X_i = x_i) \\ = P(X_{i+1} = x_{i+1} | X_i = x_i) \end{aligned} \quad (1)$$

The stochastic law that describes the relationship between the segments is given in the form of a transition matrix, Figure 2, in which each matrix element gives the probability of the different possible transitions from one segment to the next. A markov chain has a unique equilibrium distribution q which is defined by the transition matrix. In this distribution all segments have the same statistical distribution of the probability θ_i of the different states. This distribution describes the level of knowledge prior to getting sample data or observations of the real state of the segment during excavation, Figure 2.

The equilibrium distribution gives the expected proportions of the different states along the tunnel. This is a quantity that the engineering geologist is more used to assessing compared to probabilities in the transition matrix. However, it is not possible to determine the transition matrix from the equilibrium distribution so there are some difficulties with assessing the transition matrix. Some suggestions on

methods of facilitating these difficulties have been described by Ashley et al. (1981).

From EGS	To EGS				
	1	2	3	4	
1	0.35	0.55	0.08	0.02	1.00
2	0.20	0.65	0.13	0.02	1.00
3	0.10	0.50	0.32	0.08	1.00
4	0.20	0.50	0.20	0.10	1.00

$$q = \begin{aligned} P(\theta_i = 1) &= 0.218 \\ P(\theta_i = 2) &= 0.600 \\ P(\theta_i = 3) &= 0.150 \\ P(\theta_i = 4) &= 0.032 \\ &\hline &1.000 \end{aligned}$$

Figure 2. Example of transition matrix for four EGSs and corresponding equilibrium distribution.

4.2 Principles for treatment of additional data

A bayesian approach to the problem is proposed. The prior knowledge is updated using data from geological investigations. Bayes theorem, Equation 2, implies that the posterior knowledge is defined as the prior knowledge multiplied by the likelihood divided by the normalising constant (Benjamin & Cornell 1970). The updating process results in the posterior distribution of states in each segment. The posterior distribution is in this way related to the prior knowledge.

$$P[B_j | A] = \frac{P[A | B_j] P[B_j]}{\sum_{i=1}^n P[A | B_i] P[B_i]} \quad (2)$$

where,

$$\begin{aligned} P[B_j | A] &= \text{à posteriori probability of } B_j \text{ given} \\ &\quad \text{information } A \\ P[A | B_j] &= \text{probability of getting information } A, \\ &\quad \text{given the outcome } B_j \text{ (likelihood)} \\ P[B_j] &= \text{à priori probability of } B_j \end{aligned}$$

The relationship between the true state and the specific type of data is described by a likelihood function. For each relevant type of data the relationship between those data and the true state vector θ need to be modelled. In this case models for three types of data derived from three common geological investigation methods are proposed, i.e. core drill data, probe drill data and resistivity data. The likelihood function for a specific type of data may quite easily be expressed mathematically with different levels of simplifications, However, the major task connected to the likelihoods are the

assessment of the input data, i.e. the actual relation between measured data and the modelled parameter, in this case the EGS. The likelihood is often given as a matrix, Figure 3.

		Actual EGS in tunnel			
		1	2	3	4
EGS indicated by investigation method	1	0.75	0.60	0.10	0.03
	2	0.20	0.30	0.20	0.17
	3	0.04	0.07	0.50	0.30
	4	0.01	0.03	0.20	0.50
		1.00	1.00	1.00	1.00

Figure 3. Example of likelihood matrix.

This assessment may both be made based on observations as well as subjective knowledge. There are risk analysis and statistical tools that may be helpful in assessing likelihoods and analyse what biases are likely with different investigation methods. One such method is fault tree analysis where events such as "core drilling indicates wrong state" may be analysed (Sturk in prep.). Another method is analysis of spatial variability using variogram analysis.

4.3 Principle for calculation of the product of the prior distribution and various likelihood functions

The product of the prior distribution and the various likelihood functions for the different types of data is proportional to the posterior distribution of the parameters. This will be a complex expression, which will not be amenable to analytical derivation of relevant statistical inferences. Instead a computational approach known generically as MCMC (Markov chain Monte Carlo - note that the use of markov chains in this method is not in any way connected to the assumption of a markov chain prior distribution). The specific MCMC algorithm used is known as the Gibbs sampler which is a general procedure of computing posterior inferences in a bayesian analysis (O'Hagan 1996).

5 CASE STUDY AT THE HALLANDSÅS TUNNEL PROJECT IN SWEDEN

The above presented statistical model is being tested within the frames of a complex tunnelling case presently undertaken in Sweden, the Hallandsås Railway Tunnel Project. The geological conditions at the site is difficult and some major fault zones strongly affected by pronounced jointing, crushing and deep-weathering are encountered. The excavation method is based on an conventional drilling/blasting approach with successive adaptation

to decreasing rock quality by stepwise excavation and increasing rock reinforcement by using spiling, rock bolting and shotcrete. An active design approach has been used in which the engineering geological prognoses is an important part.

The statistical model has been used as a support in preparing the engineering geological prognoses. Statistical modelling is based on combined information from subjective assessments (prior distribution of states) and observations during tunnelling including surface investigations (resistivity measurements) and investigations from the tunnel face (core drilling and probe drilling). The four EGSs (engineering geological states) has been defined as the total sample space of geological conditions allowing a certain excavation method.

- EGS 1: Good and Fair rock, no tunnelling problems ($Q > 0.1$, weathering = W1-W2).
- EGS 2: Poor rock, limited tunnelling problems ($Q < 0.1$, weathering = W3-W4). The rock mass requires spiling and gallery/bench excavation or extensive grouting.
- EGS 3: Extremely poor rock, tunnelling problems ($0.005 < Q < 0.1$, weathering = W4-W5). Multiple drift and extensive rock support or extreme inflow of water in fresh rock necessitating extreme and time consuming grouting measures.
- EGS 4: Geological hazards, extensive tunnelling problems ($Q < 0.005$, weathering = W5). Soil like conditions, extensive ravelling ground, running ground or flowing ground.

By using the statistical model a prognosis of the updated distributions of states ahead of the tunnel face can be done. An example of simulation of four 5 m segments ahead of the face is shown in Table 4. In the table the prior and posterior probability of the most likely state for the four segments are shown together with the states indicated by probe, core and resistivity data. These values may also be compared with the actual state observed during tunnelling. The probe drilling is made only for the next segment and data is only available for Segment 1. The posterior probability of the most likely state have been used in order to plan the excavation of the forthcoming segments.

Table 4. Results from statistical simulation of EGS in four tunnel segments ahead of the face.

Segment	1	2	3	4
Predicted prior EGS (probability)	2 (0.6)	2 (0.6)	2 (0.6)	2 (0.6)
Probe	1	-	-	-
Core	1	1	1	2
Resistivity	2	2	2	2
Predicted posterior EGS (probability)	1 (0.8)	2 (0.55)	2 (0.55)	2 (0.8)
Actual state	1	2	1	2

Given the results in Table 4 it is concluded that we might be quite confident in getting EGS 1 in Segment 1 and EGS 2 in Segment 4, but the uncertainty is greater for Segments 2 and 3. When planning the detailed excavation of these sections these results must be taken into consideration. A comparison with the actual states mapped after excavation further accentuates the uncertainty in Segments 2 and 3 as one turns out to be EGS 1 and the other EGS 2. The predictions for Segments 1 and 4 are correct.

Even though the results from the Hallandsås project so far are preliminary it may be concluded that a stringent handling of uncertainty may be done using a statistical approach and the proposed statistical model is a good tool for practical use within tunnelling as a basis for engineering geological prognoses.

6 CONCLUSIONS

In this paper engineering geological prognoses and their value for and impact on tunnelling have been discussed. It is concluded that engineering geological prognoses, as one part of a risk analysis approach, are important in several stages of an underground project. The purpose of the prognoses varies, depending on what scale and project stage are considered, however the overall objective should be to serve as basis for decisions.

Some aspects concerning the possibilities of improving the handling of uncertainty by applying statistical models have also been given. The choice of statistical models depend on a number of factors, such as geological regimes and homogeneity, scale, project stage and type of decisions that should be taken. Some guidelines concerning the choice of model is given and a statistical model based on a bayesian approach with main application during the construction stage is presented.

The proposed statistical model is presently tested at a tunnelling site in Sweden, the Hallandsås project, where it has been used as a base for geological predictions ahead of the tunnel face. The engineering geological prognoses have continuously been used as an integrated part of the excavation and active design processes. Results indicate that uncertainty may be treated in a stringent matter and the relevance of additional data may be evaluated.

Based on the application at Hallandsås it may be concluded that it is very important that the results from the engineering geological prognosis are understood both by geologists, tunnel engineers and project managers. This is essential as the results should be used in the daily decision process. From a statistical viewpoint it is also important that the assessment of input data, both subjective assessments and assessments based on observations, is not made too complicated in the statistical model.

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