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VALUE OF INFORMATION ANALYSIS IN ROCK ENGINEERING INVESTIGATIONS

Miriam S. Zetterlund

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Datavärdesanalys vid bergtekniska undersökningar

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PREFACE

Rock construction is an activity that always needs to handle uncertainty. This is amongst other due to the variation of the rock material properties, and due to the site investigations which are only carried out for limited parts of the rock mass at the actual site, and due to that some investigations, mainly those with geophysics examine the properties of rock in an indirect way. It is therefore difficult to assess rock material properties throughout a project before design and construction.

Site investigations are important and this research project develops and adapts a method, VOIA (Value of Information Analysis) to judge the value of additional site investigations. The method can be utilised to structure site investigations aiming to reduce uncertainty and cost within geology, rock mechanics and hydrogeology.

In the project, structured expert elicitation was used for judgements of uncertainty when the VOIA methodology was tested in a case study at Äspö Hard Rock Laboratory, Oskarshamn.

The PhD research was performed by Miriam Zetterlund (Chalmers University of technology) as PhD student and Lars O Ericsson (Chalmers University of technology) as principal supervisor. The reference group that supported the project consisted of Mats Holmberg from Tunnel Engineering, Rolf Christiansson from SKB, Jonny Sjöberg from Itasca Consulting Group, Anders Fredriksson previous from Golder Associates now independent consultant, Olle Olofsson and from Swedish Transport Administration, Jimmy Töyrä previously from Swedish Transport Administration now LKAB, Mehdi Bagheri previously from KTH now URS Nordic, Erling Nordlund and Kelvis Pérez from LTU, and Tomas Franzén and Mikael Hellsten from BeFo.

Stockholm in October 2014

Per Tengborg

FÖRORD

Bergbyggande är en verksamhet som alltid måste hantera osäkerhet. Anledningen till det är bland annat att bergets egenskaper varierar, att de förundersökningar som utförs endast beskriver en liten del av bergmassan och att vissa undersökningar, främst med geofysik är indirekta metoder för att ta fram bergets egenskaper. Det är alltså svårt att bedöma berget inför projektering och byggande.

Förundersökningar är viktiga och detta forskningsprojekt utvecklar och anpassar en metod, VOIA (Value of Information Analysis) för att bedöma värdet av tillkommande undersökningar. Metoden kan användas som stöd för att strukturera förundersökningar som syftar till att minska osäkerheter och kostnader inom geologi, bergmekanik och hydrogeologi.

I projektet utnyttjades strukturerade expertbedömningar för osäkerhetsuppskattning då VOIA metodiken testades i en fallstudie i Äspölaboratoriet, Oskarshamn.

Doktorandarbetet genomfördes av Miriam Zetterlund (Chalmers tekniska högskola) som doktorand och Lars O Ericsson (Chalmers tekniska högskola) som huvudhandledare. Den referensgrupp som bistått projektet har bestått av, Mats Holmberg från Tunnel Engineering, Rolf Christiansson från SKB, Jonny Sjöberg från Itasca Consulting Group, Anders Fredriksson f d från Golder Associates nu egen konsult, Olle Olofsson och från Trafikverket, Jimmy Töyrä f d från Trafikverket nu LKAB, Mehdi Bagheri f d från KTH nu URS Nordic, Erling Nordlund och Kelvis Pérez from LTU samt Tomas Franzén och Mikael Hellsten från BeFo.

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Per Tengborg

ABSTRACT

A challenge in rock engineering is to strike a balance between a reasonable level of investigation and uncertainty in the geological conditions. Value of Information Analysis (VOIA) provides support for decisions about investigation strategies. The purpose of the method is to assess the economic value of an investigation before it has actually taken place.

The overall aim of this study was to use VOIA to assess the value of prior investigations for underground construction projects. The study has focused on tunnelling projects in crystalline rock where the main rock engineering uncertainties are related to the anisotropy, heterogeneity and scale-dependent properties of the rock mass. The specific aims of the study were to develop and adopt VOIA as a basis for decisions regarding investigations in underground construction and to test the method under realistic conditions with real project costs. A further aim was to investigate how expert judgement can be incorporated transparently into VOIA.

Three studies of VOIA with different levels of complexity have been conducted. The input probabilities were assessed by means of stochastic modelling of the rock mass or through expert knowledge. The method was tested in a case study of a tunnel at the Äspö Hard Rock Laboratory, Oskarshamn, where the probabilities were assessed by experts as part of a structured elicitation procedure.

VOIA models quickly become large and complex although the method provides useful input for uncertainty assessments and risk analysis of limited decision problems. One of the strengths of the method is that expert judgement can be incorporated stringently into the calculations. A recommended simplification of VOIA is to limit the analysis to calculation of the expected value of perfect information, which produces an upper boundary of the maximum value that can be obtained by any investigation. This value can be practically used as a benchmark when determining whether it is worth carrying out investigations or not.

Keywords: Rock mass characterisation, Observational Method, Value of Information Analysis, Decision Analysis, Expert elicitation, Expert knowledge.

SAMMANFATTNING

En av utmaningarna inom bergbyggande är att hitta balansen mellan en rimlig mängd förundersökningar och osäkerheterna i de geologiska förutsättningarna. Som ett stöd för beslut om undersökningsstrategi kan Datavärdesanalys (VOIA) användas. Syftet med metoden är att bedöma det ekonomiska värdet av en undersökning innan den faktiskt har genomförts.

Det övergripande syftet med denna studie var att använda VOIA för att bedöma värdet av förundersökningar vid undermarksbyggande. Studien fokuserar på tunnelprojekt i kristallint berg där de huvudsakliga ingenjörsgeologiska osäkerheterna är relaterade till anisotropi, heterogenitet och skalberoende egenskaper i bergmassan. Studiens specifika mål var att utveckla och anpassa VOIA som en grund för beslut om undersökningar i undermarksbyggande, samt att testa metoden under realistiska förhållanden med verkliga projektkostnader. Ett ytterligare mål var att undersöka hur expertbedömningar kan utnyttjas på ett transparent sätt i en VOIA.

Tre studier med olika komplexitet har genomförts. De ingående sannolikheterna uppskattades genom stokastisk modellering eller expertkunskap. Metoden testades i en fallstudie av en tunnel i Äspölaboratoriet, Oskarshamn, där sannolikheterna skattades av experter genom en strukturerad process.

Modeller för VOIA växer snabbt sig stora och komplexa, men trots detta ger metoden värdefull indata för osäkerhetsbedömningar och riskanalys av begränsade beslutsproblem. En av metodens styrkor är att expertbedömningar kan infogas på ett stringent sätt till beräkningarna. En rekommenderad förenkling av VOIA är att begränsa analysen till beräkning av det förväntade värdet av perfekt information, vilket ger en övre gräns av det maximala värdet som någon undersökning kan ge. I praktiken kan detta värde användas som en måttstock för när undersökningar är värdefulla.

Nyckelord: Bergkarakterisering, Observationsmetoden, Datavärdesanalys, Beslutsanalys, Expertelicitering, Expertkunskap.

NOTES TO THE READER

This report is a representation of a doctoral thesis with the title *Value of information analysis in rock engineering investigations*. The text has been slightly edited for this report and some sections of academic formalities have been excluded. The doctoral thesis includes the following papers, referred to by Roman numerals:

I. Zetterlund, M., Rosén, L., Norberg T., and Ericsson, L.O. (2008). Characterisation of Hard Rock According to the Observational Method and Value of Information Analysis. *Proceedings of the World Tunnel Congress*, Agra, India. 164-171.

II. Zetterlund, M., Norberg, T., Ericsson, L. O. and Rosén, L. (2011). A Framework for Value of Information Analysis in Rock Mass Characterisation for Grouting Purposes. *Journal of Construction Engineering and Management* 137(7): 486-497.

III. Zetterlund, M. (2009). Geological Characterisation and the Observational Method. Application of Value of Information Analysis. Licentiate thesis. Department of Civil and Environmental Engineering, Chalmers University of technology. Göteborg, Sweden.

IV. Zetterlund, M., Ericsson, L.O., Stigsson, M., (2012). Fracture mapping for geological prognoses. Comparison of fractures from boreholes, tunnel and 3-D blocks. *Proceedings of Eurock 2012*, Stockholm, Sweden.

V. Zetterlund, M.S., Norberg, T., Ericsson, L.O., Norrman, J., Rosén, L. (2014). Value of Information Analysis in rock engineering: A Case Study of a tunnel project in Äspö HRL. Submitted to *Georisk*.

VI. Zetterlund, M.S., Norrman, J., Ericsson, L.O., Norberg, T., Rosén, L. (2014). Elicitation of expert knowledge for use in Value of information analysis of rock engineering investigations. Submitted to *Tunnelling and Underground Space Technology*.

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1. INTRODUCTION

The Precambrian bedrock in Sweden was formed more than 545 million years ago and has since then been subjected to several tectonic regimes with the formation of new fractures resulting from extension and shearing as well as reactivation of old fractures. The changes in stress fields that have affected the rock mass over geological time and an understanding of the geological history have led to major uncertainties in geoengineering prognoses. Most of the bedrock covering Sweden today is hard and crystalline and is traversed by fractures that transmit the groundwater. As a construction material, the bedrock is heterogeneous and anisotropic and some of the properties are scale-dependent (Fredén 2002, Palmström and Stille 2010, Gustafson 2012).

When constructing underground, it is intrinsically difficult to know the geological conditions in advance although geotechnical investigations are performed as a basis for geological predictions of the rock mass. The number of investigations is project-specific although they need to capture the characteristics sufficiently in order to design reinforcement and grouting correctly. According to the European standards (SIS, 2005), geotechnical design can be based on four alternative methods:

- Calculations
- Prescriptive measures
- Load tests and tests on experimental models
- Observational Method (review of design during construction)

The Observational Method is suggested for situations where the geotechnical conditions are difficult to predict and when the design can be altered during construction. The method was first introduced by Terzaghi and Peck (1948) for situations where the uncertainties in prior investigations were high. The method was later defined and described in more detail by Peck (1969) where eight conditions were stated for the method to be full filled:

a) Exploration sufficient to establish at least the general nature, pattern and properties of the deposits (geological media, *author's comment*), but not necessarily in detail.

b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major role.

c) Establishment of the design based on a working hypothesis of behaviour anticipated under the most probable conditions.

d) Selection of quantities to be observed as construction proceeds and calculation of their anticipated values on the basis of the working hypothesis.

e) Calculation of values of the same quantities under the most unfavourable conditions compatible with the available data concerning the subsurface conditions.

f) Selection in advance of a course of action or modification of design for every foreseeable significant deviation of the observational findings from those predicted on the basis of the working hypothesis.

g) Measurement of quantities to be observed and evaluation of actual conditions.

h) Modification of design to suit actual conditions.

Consequently, the method is only suitable in projects where the design can be altered as the construction proceeds, and the Observational Method should preferably not be used in cases where the probability of failure is low, or where the cost of a conservative design is lower than the cost of applying the Observational Method (Stille et al. 2005). It is very important for the implementation of the method that actions for all possible outcomes are planned in advance. If not, it cannot be said that the method has been used completely (Peck 1969).

The initial design should be based on the most probable conditions (Peck 1969), and a key requirement for application of the Observational Method is that an acceptable level of risk must be identified and controlled (Powderham 1994). It must be possible to measure the whole range between the most probable and unfavourable conditions with the monitoring system, and the formulation of contingency plans needs to be explicit and include clear instructions on how to proceed if stated trigger values are exceeded (Nicholson 1994). The benefits of this method include a stronger link between the design and construction as well as improved understanding of the interaction between geology and structure (Powderham 1994).

Value of Information Analysis (VOIA) can be used as an aid for structuring investigations aimed at reducing uncertainties and costs regarding geological, rock mechanical and hydrogeological issues. The method combines cost-benefit analysis with Bayesian probability theory for updating of probabilities as new information becomes available, and subjective judgements can be incorporated into the calculations. The underlying idea of VOIA corresponds well with the Observational Method, since VOIA focuses on reduction of uncertainty and contributes to decision-making between different plans of action.

1.1 Aim and objectives

The overall aim of the study is to use VOIA to assess the value of prior investigations in underground construction projects.

The specific objectives of the doctoral thesis are as follows:

- To develop and adapt the method of VOIA for decisions regarding geological investigation programmes for underground constructions.
- To test VOIA in realistic circumstances for underground constructions with real project costs.
- To investigate how subjective expert judgement can be incorporated transparently into VOIA.

1.2 Scope of work

The overall aim of the study is achieved through theoretical studies, method development and application of the method in a case study. The work is presented in the following six publications (short titles in parenthesis):

Publication I (*VOIA for rock mass characterisation*)	VOIA for investigations in a tunnel project.
Publication II (*Framework of VOIA*)	Development of VOIA for grouting purposes using stochastic modelling.
Publication III (*Characterisation and the Observational Method*)	Licentiate thesis discussing rock mass characterisation, the Observational Method and VOIA.
Publication IV (*Fracture mapping for geological prognoses*)	Study of different types of fracture mapping. Discussion of uncertainty in investigations.
Publication V (*Case study Äspö HRL*)	Application of VOIA in a tunnelling project for two decisions.
Publication VI (*Use of expert judgement*)	Incorporation of expert judgements for probability assessment.

The report includes a theoretical background to the area, which is presented in Chapters 2-6. An overview of the publications and the main findings are presented in Chapter 7. Chapter 8 comprises a discussion of the results and Chapter 9 includes conclusions and recommendations.

1.3 Limitations

The thesis focuses on interdisciplinary method development of VOIA in rock engineering and simplifications in the decisions and geological models are needed for the purpose of exemplification. Even though a clear link to management and contractual issues is seen, the thesis does not include anything that deals with this subject in great depth. A distinction is made between the concept of characterisation and classification. Moreover, since the focus is on characterisation and not classification, classification systems will not be dealt with specifically.

2. ROCK MASS CHARACTERISATION AND INVESTIGATIONS

To characterise means to describe the condition of a material or a substance and to define or attach value to the various features it displays. Rock mass characterisation involves description and quantification of parameters governing or influencing rock mass behaviour. The parameters include the intact rock characteristics, the characteristics of the individual fractures and the fracture network see e.g. Stille and Palmström (2003). The aim of the process is to describe the properties of the rock mass in such way that it is possible to make a conceptual model of a certain investigation area. In addition, the conceptual model should not only describe the properties of the site but also the identified uncertainties (Andersson et al. 1998).

The fracture network in the rock mass provides clues about the formation of the rock and the tectonic movements that have occurred since the rock was formed. The brittle structures are induced mechanically by faults and overthrusts, whereas the plastic structures are induced at great depth by high pressures and high temperatures. The pattern of the brittle structures may in some regions be controlled by the previously formed plastic structures (Andersson et al. 1998). The brittle structures are often of direct importance to the hydrogeological and rock mechanical properties of the rock mass, and may therefore cause many rock mechanical problems as well as groundwater-related problems during construction of a tunnel. However, the largest quantities of water in a tunnel are generally caused by just a few of the fractures in a fracture zone (Gustafson 2012). The mechanical stability of the rock is also affected by the mineralogical composition of the rock types and by the alteration and weathering of the minerals (Andersson et al. 1998). In addition, grain size, grain geometry and texture are all geological factors affecting fracture propagation in a rock (Jern 2004). The primary geometrical properties of the discontinuities are shown schematically in Figure 2-1.

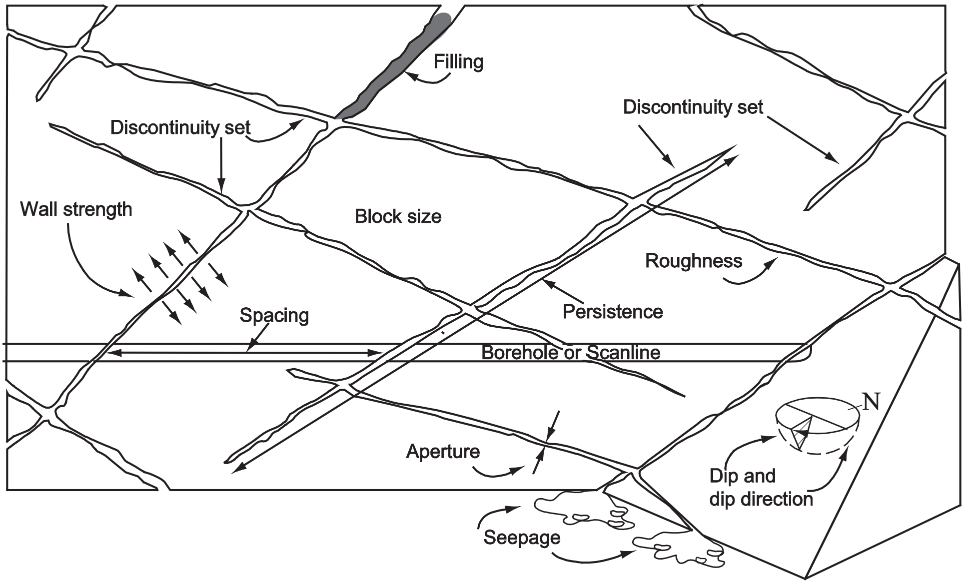

Figure 2-1. Primary properties of discontinuities in a rock mass (modified from Hudson 1989).

To simplify the geoengineering information, the rock mass is commonly arranged into different classes for different purposes. In classification, the likely reaction of the rock mass to the engineering process in which it is to be performed is determined (Price 2009). The result of the classification is a numerical value that can be used for the engineering design of, for example, rock support (Sturk 1998). Several rock mass classification systems are used today. For a presentation of some of these systems, see (Bieniawski 1989, Price, 2009, Palmström and Stille 2010, and others).

The characterisation is based on investigations and measurements in the area and it is not possible to investigate the rock mass as a whole. There will always be parts in between the investigations where interpolation or estimation of the conditions needs to be made. Nevertheless, a good prediction of the rock mass, close to the real conditions, leads to efficient use of resources, which is obviously good from the point of view of all the parties involved in the project. The reasons behind a poor geological prognosis could be that the pre-investigation was not based on realistic expectations or that the investigation was not focused on project-specific questions and problems (Bergman and Carlsson 1986).

From a geoengineering point of view, the purpose of ground investigations is to determine and describe the rock mass behaviour in response to the underground construction. It is not necessarily the case that the same investigations are needed to solve problems related to water as are needed to solve stability-related problems, and the characterisation process should start by establishing the purpose of the characterisation in relation to a decision that needs to be made. The amount of data required depends on the level of detail in the decision and the geological conditions on site. More investigations are naturally needed to describe complex geological conditions. However, when it comes to risk assessment, the question when characterising is not only how to find the more difficult geological conditions but also how important it is to find them, i.e. what are the consequences if the geology turns out to be more unfavourable than expected? Key questions in a strategy for rock mass characterisation are thus related to how to describe the rock mass properly for the decision in question and how to collect a reasonable amount of data (Sturk 1998, Price 2009).

Rock mass characterisation is an evolving process that is often divided into separate stages, starting at a general level in a reconnaissance stage with a review of the local and regional geology based on available data and published documents of the area. Investigations are then conducted to collect data for quantitative estimations of the required rock mass properties, and for formulation and confirmation of quantitative hypotheses (Baecher and Christian 2003). In order to collect the correct data and to avoid missing important input data for numerical modelling tools, a clear and comprehensive picture of the whole design process is needed in the initial stages. This presupposes good communication between geologists and engineers, but is often obstructed by personnel changes between the different project stages (Hadjigeorgiou 2012).

3. UNCERTAINTIES IN INVESTIGATIONS

Geological and geotechnical investigations of a site are point estimations of the total area, involving many uncertainties and, irrespective of the number of measurements, the geological conditions will never be known completely before construction. The conclusions drawn from the investigation results are therefore sometimes more like working hypotheses than fixed statements, a fact that may give rise to numerous problems during construction. There is not only uncertainty about the geology but also about the construction process as the advance rates and costs depend on the reliability and performance of the equipment and the skills and morale of the staff Haas and Einstein (2002)

The uncertainties that cannot be reduced through investigation are sometimes referred to as being aleatoric and are related to natural variability. The uncertainties that are related to lack of knowledge are called epistemic. These can be reduced by more tests, measurements and investigations but, as will be shown later, there is a point where it is not economically justified to continue investigating. The motivation for a subdivision of uncertainties into aleatory and epistemic may initially seem unnecessary but in order to reduce the total uncertainty in a project, the uncertainties must be identified and understood. The categorisation will contribute to a deeper understanding of the degree to which the uncertainties can be reduced through learning and measurements, and it thus serves as a basis for quantification and modelling choices (Bedford and Cooke 2001). Nevertheless, the boundaries of the two categories of uncertainties are sometimes indistinct. For instance, the uncertainty about an input parameter for a model is epistemic in the sense that there is a lack of sufficient knowledge about the parameter but the parameter may include an aleatory component that cannot be reduced (O'Hagan and Oakley 2004). Although the natural variability in geology is sometimes referred to as random, Baecher and Christian (2003) compare the geological setting to a deck of cards to be played. Once the cards have been played, their order is not random although it is unknown to the player. This is the same for geology in the sense that the geology is a product of the rock-forming processes and geological history. These processes are not random and nor are the results. Even if the spatial distribution is unknown to the geologist, it is not random. The division of uncertainties into different groups is dealt with in more detail in Morgan and Henrion (1990), Bedford and Cooke (2001), Baecher and Christian (2003), Zetterlund (2009), Hadjigeorgiou and Harrison (2012), and others.

The process of uncertainty identification requires understanding of separate parameters as well as the total system in which they are involved. Uncertainty management involves identification of the sources of uncertainty, expression of the uncertainties in the form of probability distributions, a choice of appropriate computational methods for uncertainty analysis, and a system of ways to communicate the results (Morgan and

Henrion 1990). Parameters such as anisotropy, heterogeneity and scale-dependence give rise to uncertainties that ought to be considered throughout the whole process of investigation, modelling and design. Moreover, considering that one of the main sources of uncertainty within rock mass characterisation is the fact that our conclusions are drawn from a limited number of single-point samples, the understanding of the total system is vital for interpretation and analysis of the geological conditions. By having an understanding of the geological mechanisms and processes it is possible to draw conclusions from even a limited amount of information (Sturk 1998).

Within rock engineering, the definition of uncertain variables and identification of their interactions is a complex task involving both geological aspects as well as mechanical aspects. Examples of state variables are rock stress, rock mass deformation properties, water pressure and tunnel geometry (Stille et al. 2003). As an illustration of the relationship between *in situ* stress, rock structure and water flow, Hudson and Harrison (1997) developed an interaction matrix for the interactions between the parameters, see Figure 3-1.

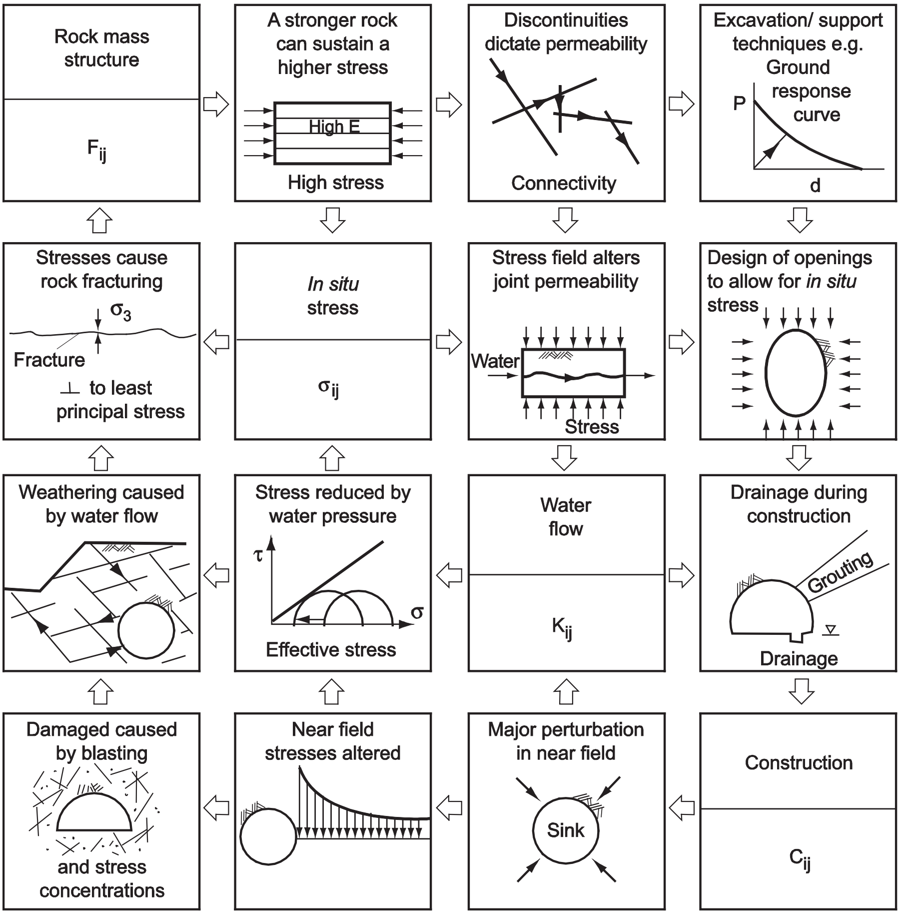

Figure 3-1.Interaction matrix for rock engineering (modified from Hudson and Harrison 1997).

In site investigations it is common to use data from investigation boreholes to characterise the rock mass and these boreholes are usually drilled more or less vertically from the ground surface. The drillings are the basis for prognoses for the horizontal tunnel even though they only represent a small part of the rock mass and may be directionally biased in terms of anisotropy in the rock mass (Hudson and Harrison 1997, Zetterlund et al. 2012).

A way of describing uncertainty is to use probability distributions. There are different views of probability and in this study the subjectivist view is adopted. Morgan and Henrion (1990) define this view of probability as “the probability of an event is the degree of belief that a person has that it will occur, given all the relevant information currently known to that person”. The reasoning behind this standpoint is that the problems in geoengineering are generally unique and not repeatable. As opposed to the subjectivist view of probability, there is the 'frequentist' view, in which probability is defined as the “frequency with which a certain event occurs in a long sequence of similar trials” (Morgan and Henrion 1990).

In Bayesian decision analysis and VOIA, which will be described in more detail in Chapter 4-5, subjective probability assessments of different events are used to calculate risk costs of different decision alternatives. However, these assessments are associated with uncertainty which can be described with a beta distribution. This is described in more detail in Zetterlund et al. (2011) and Zetterlund et al. (2014a).

Generally a beta distribution is appropriate to use for engineering problems where there are upper and lower bounds on the values, that is whose range of the variables belongs to the interval [a, b]. When modelling of uncertainties in probabilities, the beta distribution is continuous in the interval [0, 1] and a beta distribution for *X* with the parameters α and β has the density function (Bedford and Cooke 2001, Olofsson 2005):

$$\theta(\mathrm{x}) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{\mathrm{B}(\alpha,\beta)}; \quad \alpha,\beta > 0, 0 \le x \le 1 \tag{3.1}$$

where the beta function $B(\alpha,\beta)$ is:

$$B(\alpha,\beta) = \int_0^1 x^{\alpha-1}(1-x)^{\beta-1}\,dx \tag{3.2}$$

The expected value of the beta distribution is:

$$E[X] = \frac{\alpha}{\alpha+\beta} \tag{3.3}$$

with the variance:

$$Var[X] = \frac{\alpha,\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} \tag{3.4}$$

When modelling uncertainties in probabilities, the parameters of the beta distribution can be defined as:

$$\alpha = N^+ + 1 \tag{3.5}$$

$$\beta = N^- + 1 \tag{3.6}$$

$$\min = 0 \tag{3.7}$$

$$\max = 1 \tag{3.8}$$

where N^- represents the support, e.g. number of observations, that indicate that an event is going to happen, and N^+ represents support, e.g. the number of observations indicating that an even is *not* going to happen(Harr 1987).

The most likely probability is then calculated as:

$$P = \frac{N^+}{N^+ + N^-} \tag{3.9}$$

Within the prescribed interval, the distribution can have both symmetric and skewed shapes depending on the values of α and β, see

Figure 3-2. When $\alpha < 1$ and $\beta < 1$ the distribution is U-shaped, J-shaped when $(\alpha - 1)(\beta - 1) < 0$ $(\alpha - 1)(\beta - 1) < 0$, and unimodal for other values of α and β. When α and β are large, the cumulative probabilities of the distribution may be approximated by a normal distribution (Krishnamoorthy, 2006).

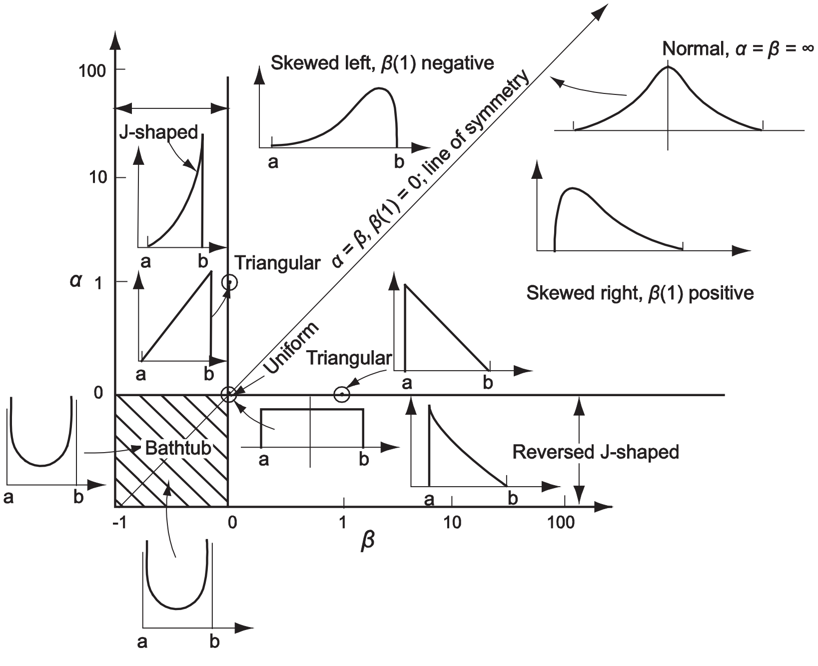

Figure 3-2. The shapes of the beta distribution with varying values of α and β (modified from Harr, 1987).

4. DECISION ANALYSIS IN ROCK ENGINEERING

Generally, problems related to engineering geology cannot be regarded as repeatable experiments since the geological conditions are new for each new construction site. Uncertainty is therefore a natural element in rock mass characterisation and rock engineering, and rock investigations are performed to reduce the uncertainties. The extent of the investigation is often determined by the economic constraints in the project, and it could be difficult to strike a balance between knowledge requirements and investigation costs.

Decision analysis can be used as a decision-making aid under such uncertain circumstances. Within decision analysis there are a number of techniques for the formalisation of complex problems and the primary aim of the methods is to assess the merits of different decision alternatives, usually expressed in terms of expected utility, in order to understand the consequences of choosing one alternative rather than another (Keeney 1982, Morgan and Henrion 1990). The analysis includes prediction of observable events and consequences associated with the decision alternatives as well as a description of the uncertainties related to lack of knowledge of the events. This turns the focus to the background knowledge on which the analysis is based and on how available knowledge can be used to predict future consequences. The process is normative in the sense that it describes how people should structure their decision in an optimal setting, although it is known that people tend not to be rational in a real case scenario (Aven 2012). Since there are constant feedback loops and managerial reviews, there is no strict procedure for performing a decision analysis although a basic decision-making structure is shown in Figure 4-1.

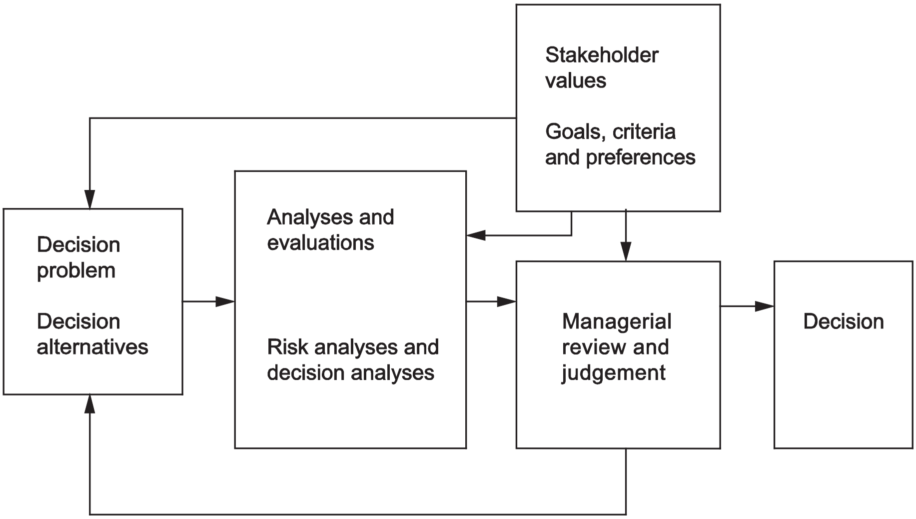

Figure 4-1. Basic decision-making structure (according to Aven, 2012).

Probabilistic decision analysis is typically based on Bayesian statistical theory. According to Bayes' theorem, equation 4.1, the prior and the posterior are probabilities of the unknown parameter(s), and the posterior is proportional to the prior times the likelihood. The likelihood represents the information in the data, and for any given value of the unknown parameter the likelihood plots the probability of observing the data that was actually observed. In Bayes' theorem, each source of information is weighted according to its strength. Weak information is downweighted, e.g. if the prior information is very weak relative to the data information, the prior value is weighted so low in Bayes' theorem, that the posterior distribution is effectively equal to the likelihood (O'Hagan and Luce 2003, Olofsson 2005):

$$P(X|I)=\frac{P(I|X)P(X)}{P(I|X)P(X)+P(I|X')P(X')} \tag{4.1}$$

where $P(X)$ is the prior probability, $P(X|I)$ the posterior probability, and the terms $P(I|X)$ form the likelihood (Olofsson 2005). Expert opinions can be regarded as data and can be used for assessment of prior and preposterior probabilities. A Bayesian decision-maker may use the assessments to update his/her opinion and to form a posterior distribution based on the experts' judgements (Morgan and Henrion 1990).

In the initial stage of a rock engineering project, probabilities of different events are assigned and used as prior probabilities. The prior information is a compilation of the best possible knowledge at that time and could be scarce and mostly based on general expert knowledge at the beginning of the project. As the project moves forward it is important to update the generally assessed probabilities and replace them with site-specific information. Updating with new information and new data takes place on several occasions and should be done in a documented and stringent way (Einstein 1997, Sturk 1998). The iterative updating process is important not only to understand the geology on site but largely to understand the consequences of the geology in the design of support and excavation methods and in the allocation of resources in the remaining part of the construction (Haas and Einstein 2002). Bayes' formula not only allows the use of investigation data in the analysis but also the use of subjective expert knowledge, such as judgements from geologists and experienced staff for formal mathematical processing. Bayesian statistics is particularly suitable for problems where there is a limited number of observations and where experience and expert knowledge play an important role (Bedford and Cooke 2001), which in reality is the case in many underground construction projects.

The principles of the Observational Method are closely related to the thoughts behind Bayesian statistics. The updating process is central in the Observational Method and is a way to validate the design of an underground construction to new data (Holmberg and Stille 2007). One of the aims of the updating process is to reduce the uncertainty and to improve a prediction. Properly done, this is not just the replacement of one model by another but a learning process that can improve the precision of the predictions (Haas and Einstein 2002).

Decision analysis in engineering geology and rock engineering has been dealt with, for example, by Einstein (1996) who provides a comprehensive presentation of risk and risk analysis in rock engineering. A decision framework for risk analysis in tunnelling that uses Bayesian networks to represent uncertainties is presented in Sousa and Einstein (2012). Lacasse and Nadim (2011) link risk analysis theory to practical work on geotechnical risks and hazards. In Karam et al. (2007a and 2007b) a method for the practical application of decision analysis in tunnel exploration is presented, where the value of collecting new information is assessed through "virtual" exploration before any investigations are performed. Sturk et al. (1996) present a case study of risk and decision analysis in tunnelling, where different design alternatives were analysed using decision trees. Isaksson and Stille (2005) propose a probabilistic model for estimation of tunnelling costs in the planning and procurement phases of the project. Hernqvist et al. (2013) present a decision method for grouting at the tunnel construction stage, which uses results from water pressure tests to make decisions regarding grouting of specific tunnel sections. The International Tunnelling Association (ITA) has also presented general guidelines for risk management in tunnelling, including risk management in early design stages, in tendering and contract negotiation and in construction (Eskesen et al. 2004).

5. VALUE OF INFORMATION ANALYSIS

Value of Information Analysis (VOIA), sometimes also referred to as Data Worth Analysis, is a central element in decision-making for complex problems and can help to create a rational design strategy for investigation programmes (Bedford and Cooke 2001, Freeze et al. 1992, Back 2006). VOIA methodology is based on Bayesian decision theory and cost-benefit analysis and it is a source of support for making decisions regarding the extent of investigation programmes. The method is suitable when different decision alternatives are evaluated, e.g. when deciding how many investigations should be performed as a basis for a geoengineering prognosis. Using this method it is possible to assess the economic value of an investigation before it is carried out. The value of new information, derived from geological investigations for example, is assessed by making a comparison of the uncertainties in the existing information and the reduced total uncertainty that could result from additional investigations. The cost and the time for carrying out the investigations are compared with the amount of money that is expected to be saved at a later stage by modifying the investigation programme.

An outline of how VOIA can be used in rock mass characterisation for tunnelling, or for other geoengineering problems, is shown in Figure 5-1. A VOIA is generally performed in two steps, the prior analysis and the preposterior analysis, and it is completed before making any potential investigations. The result of a VOIA is an *expected value of the information* (EVI) of a planned investigation, sometimes also called *data value*.

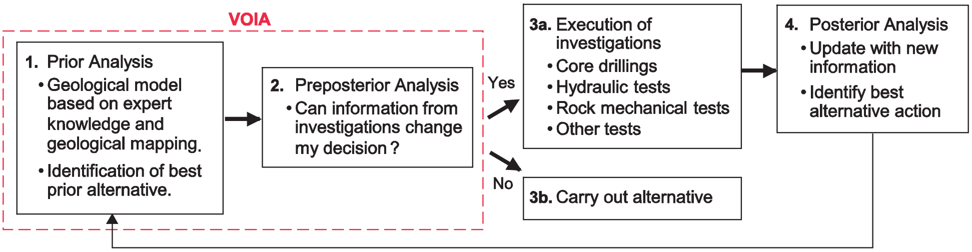

Figure 5-1. Framework for Value of information analysis in rock mass characterisation.

5.1 Prior analysis

In the prior analysis, the different decision alternatives are compared based on available information, which in an early pre-investigation could be rather sparse. One alternative emerges from the prior analysis as the most suitable according to available geological information. In principle, for a case in which two alternatives are compared, one null alternative and one action alternative, the calculations could be performed using the following procedure, see Zetterlund et al (2008) for additional details).

If $P(F)$ is the probability of failure, C_F the cost if failure occurs, and C_I the cost of preventing failure, the value of the prior analysis can be calculated as the maximum of the null alternative (e.g. to construct tunnel without grouting) and the other alternative (e.g.to construct tunnel with grouting), where the risk cost, $C_F \cdot P(F)$, can be reduced completely by measuring using the cost C_I. Failure is defined as an undesired state of nature or event. If one null alternative and one action alternative are compared, the value of the prior analysis is given as:

$$\Phi_{prior} = \max_i \Phi_i = \max(0, C_F \cdot P(F) - C_I) \tag{5.1}$$

5.2 Preposterior analysis

The purpose of the preposterior analysis is to find out if information from additional investigations is of value to the decision. The question is whether the decision-maker is so certain about the choice that no further investigations are needed or whether information from new investigations could change his/her mind.

The expected value of the preposterior analysis is calculated as:

$$\Phi_{prepost} = \max(0, C_F \cdot P(F|D') - C_I) \cdot P(D') + \max(0, C_F \cdot P(F|D) - C_I) \cdot P(D) \tag{5.2}$$

where $P(F|D)$ is the conditional probability of failure given that failure has been detected with investigations, and correspondingly, $P(F|D')$ is the probability of failure given that failure has not been detected through investigations.

Finally, the expected value of information (EVI) is calculated as:

$$EVI = \Phi_{prepost} - \Phi_{prior} \tag{5.3}$$

In the VOIA concept, new information is only of interest and value to the decision-maker if it can change the outcome of the decision. Moreover, the value of new information should be greater than the investigation cost. Consequently, investigations should not only reduce uncertainty, they should also add significant value (Bedford and Cooke 2001) and others. Generally, the result from this preposterior analysis is an assessment in monetary terms of the value of investigations compared with the investigation cost. However, the value of an investigation can also be expressed as a reduction in total uncertainty because of the acquired knowledge (Back 2006).

The lower bound of EVI is zero, i.e. EVI can never be negative, since there is always the choice not to perform the investigations and to continue the process based solely on the prior information. The expected value of perfect information (EVPI) is the upper bound of the maximum value that can be obtained through any investigation. EVPI is based on an ideal investigation with no adherent errors, and even though a totally flawless investigation is hardly realistic in a real project, EVPI can be used as a benchmark to determine whether it is worth carrying out investigations or not. If the alternative investigations for collection of additional information cost more than the EVPI, then the investigations are never worth performing since no source of information can be better than perfect information (Bedford and Cooke 2001), and others.

The VOIA is completed before the investigation is carried out and the analysis is therefore a source of support for well-informed decisions. The difference between VOIA and an ordinary cost-benefit analysis is the use of probabilities of different events related to the decision alternatives, i.e. that the risk costs for the alternatives are calculated.

VOIA has been used in several geoscientific fields. Freeze et al. (1992) presented the concept for hydrogeological purposes and the methodology has been used in remediation projects (Norberg and Rosén 2006, Back et al., 2007), and in the oil and gas industry (Bratvold et al. 2009). An example of VOIA for geophysical methods was presented by Danielsen (2010). Within the scope of this report, the method has been developed and adopted for engineering geology and tunnelling in three studies (Zetterlund et al. 2008, Zetterlund et al. 2011, Zetterlund et al. 2014a).

6. USE OF SUBJECTIVE JUDGEMENTS

Because the geological conditions are never known exactly prior to construction, decisions in underground construction projects must often be based, wholly or in part, on expert knowledge. In Bayesian decision theory it is possible to incorporate the professional judgement of experts into the analysis in a formal way, but there are pitfalls that must be avoided during the process. Most of these are related to psychology and the way people tend to think when expressing their thoughts about uncertainty and probability. Tversky and Kahneman (1974) identified a set of heuristics that people employ when they try to assess probabilities and predict values:

1. Representativeness
2. Availability
3. Adjustment and anchoring

Heuristics describes how the complex task of assessing the probabilities is reduced to simpler judgmental operations, and they may lead to both severe and systematic errors if they are not controlled in the process (Tversky and Kahneman 1974). Heuristics not only explains how people think when they quantify probabilities but also how well the probabilities are quantified (Baecher and Christian 2003).

Representativeness mostly occurs when people need to judge the probability that one object or event belongs to one class or another (Tversky and Kahneman 1974). Then people tend to base their judgements on the similarities in the particular event and the conditions in the classes (Baecher and Christian 2003). Generally, representativeness leads to too much focus on specific details and too little focus on background information (Morgan and Henrion 1990). More specifically, it leads to people neglecting to take account of the prior probabilities when estimating the outcomes, and it also leads to that people are insensitive to the sample size. In research, this can lead to far too much reliance on small sample sizes and overinterpretation of the results. In some cases, there is prior information about an object or an event that is very favourable but not relevant to the parameter that needs to be assessed. In theory, the predictions should be the same for all objects, but people nevertheless tend to be affected by the positive information and consequently the accuracy of the predictions is affected too (Tversky and Kahneman 1974).

Availability mostly occurs when the frequency of a class or the plausibility of a particular development should be predicted. It is related to the fact that it is easier to recall salient, large classes better than smaller, less familiar classes, as well as how easy the events can be imagined (Tversky and Kahneman 1974). In addition, availability could also affect predictions of how often two events occur at the same time. If there is a strong association between the events, the events are frequently predicted to be correlated even though contradictory evidence is presented (Tversky and Kahneman 1974). If imagination is enhanced during assessment, by links to recent experience and dramatic events for example, the estimated value is probably overestimated, and analogously the value is probably underestimated if it is difficult to recall or imagine a similar event (Morgan and Henrion 1990).

Anchoring generally occurs when a numerical value should be predicted by first estimating an initial value that should then be altered to a final answer (Tversky and Kahneman 1974). People usually start with a best estimate of the value and then adjust upwards and downwards. The final estimates of the value are then biased towards the initially estimated values in the sense that the uncertainty is not reflected sufficiently (Baecher and Christian 2003). It is also suggested that anchoring and adjustment explain why people tend to overestimate the probability of conjunctive events and conditional probabilities and underestimate the probability of disjunctive events.

Anchoring is also a possible explanation for overconfidence in assessing subjective probability distributions. It means that the expert or assessor makes judgements that are too extreme or reflect a certainty that does not correspond to the background information (Tversky and Kahneman 1974). A general conclusion from studies of probability assessment is that most assessors are overconfident although a way to reduce overconfidence is to ask the assessors to provide reasons and arguments for their judgements. It is also indicated in the studies that the more background knowledge people have about the quantity to be assessed, the less likely they are to be overconfident. As stated before, however, subjective judgements will be affected by bias regardless of the elicitation method (Morgan and Henrion 1990).

6.1 Elicitation practice

The process of transforming a person’s knowledge and beliefs about an uncertain quantity into an expressed probability distribution for the quantity is called elicitation (Garthwaite et al. 2005). The aim is to represent the person’s knowledge and beliefs as representative as accurately as possible and the elicitation process must be designed wisely to avoid heuristics and biases in the assessments of the experts (O'Hagan et al. 2006). Within the process, the person who will make the assessments needs to be guided to reflect on uncertainties and how they can be quantified. A key to success is to help the expert avoid common errors and check for consistency in the assessed probabilities (Baecher and Christian 2003). Although it is not possible to eliminate the effects of heuristics or the effects of overconfidence, it is possible to reduce the problems by means of a systematic elicitation process (Morgan and Mellon 2011).

There are many studies that present suggestions for structuring elicitation, see e.g. Cooke (1991), Garthwaite et al. (2005), O'Hagan et al. (2006), Low Choy et al. (2009), Gosling et al. (2012), and others. Kuhnert et al. (2010) provide a compilation of different elicitation approaches used in ecological studies, which is also useful in in geoengineering. There are differences in detail in the suggested structures but the general outline does not differ significantly. Clemen and Winkler (1999) state that the most important thing is that a clear structure is followed and that the process should be well documented and adapted to the specific case and available economical resources. Since the aim behind the elicitation process is to use expert judgement to express uncertainty, the methodology also needs to involve consideration of how the uncertainty in the elicited values is represented (Cooke 1991).

According to O'Hagan et al. (2006) the stages in an elicitation process are:

1. Background and preparation
2. Identify and recruit expert(s)
3. Motivating and training the expert(s)
4. Structuring and decomposition
5. The elicitation

It should be noted that specific elicitation is the final stage after four preceding preparatory stages, which are as important as the elicitation itself to the accuracy of the final result. In practice, it is an iterative process since some stages can only be completed if the entire process and calculations have been planned. To lead the elicitation it is preferable to have interdisciplinary teams, including persons with knowledge of elicitation, as well as knowledge of statistics and the psychology of heuristics and biases. The first stage includes identification of the parameters that are the subject of the elicitation. This is a difficult task that balances between the needs of the decision-maker and the statistician. The first stage also includes detailed planning of the elicitation session and preparing documents for the experts (O'Hagan et al. 2006).

The second stage includes identification and recruitment of experts. In this context it is important to define what really makes an expert. According to Garthwaite et al. (2005) an expert is someone who has specific knowledge of the subject and the parameters being elicited. When recruiting experts, it is not only the expertise that needs to be evaluated. There are also practical issues to consider, such as the person’s willingness to participate and the person’s neutrality. If there are any doubts that the experts could have personal gain from any of the elicitation findings, this conflict of interests must be well documented (O'Hagan et al. 2006).

Part of motivating the experts is to explain why their estimations are needed and how they will be used. Most people’s intuition regarding numerical probabilities is poor and experts with no former experience in assessment of probabilities should receive training in the subject before the actual elicitation. Information about common heuristics and biases will enhance the results of the elicitation (Cooke 1991, O'Hagan et al. 2006, and others).

The structure of the elicitation, including formulation of questions, can reduce the influence of heuristics and biases in the elicited values. A heuristic such as anchoring can, for example, be affected by the order of the questions (O'Hagan et al. 2006) in the sense that there will be differences in the assessed values if the experts are first asked to state the higher and the lower values of a parameter, and thereafter the most probable parameter, compared to if the experts assess the most probable value before giving the possible interval (Baecher and Christian 2003).

The questions should be written clearly and the quantities should be defined precisely to avoid misunderstanding and false interpretations (Cooke 1991). It has been found that most experts, regardless of the level of statistical knowledge, have great difficulty assessing mutually exclusive events and conditional probabilities. Consequently, when eliciting these kinds of parameters, the coherence of the assessed estimations needs to be checked. In practice, this means that some of the assessments will be based on and limited by answers to earlier questions (O'Hagan et al. 2006). The preparation of the questions not only serves to prepare a good result in the elicitation, it also serves to provide a good and serious impression to the participating experts. Prior to the actual elicitation session, it is recommended that the questions be tested on a smaller group of experts (Cooke 1991).

During the elicitation session, the main purpose is to elicit values or statistical distributions that represent the experts' current knowledge (Garthwaite et al. 2005). The facilitator should avoid excessive coaching of the experts and instead focus on understanding the experts' opinion and judgement (Cooke 1991). Since there is a difference in eliciting a person's knowledge of a certain event and reality, good elicitation is where the finally derived distribution reflects the expert's current knowledge sufficiently, irrespective of how well that knowledge corresponds to the real conditions (Garthwaite et al. 2005). Feedback and interactive computing is necessary to find a distribution that reflects the expert's opinion accurately (O'Hagan et al. 2006).

6.2 Methods for elicitation

The literature on expert elicitation provides no unanimous advice on the use of group elicitation or individual assessment. The procedure used must be designed for the specific case with regard to elicitation (Clemen and Winkler 1999, and others). However, methods based on interaction between experts do not necessarily need to involve face-to-face communication but can involve an exchange of information through the facilitator without direct contact between the experts (Clemen and Winkler 1999).

Group elicitations make great demands on the facilitator's ability to guide the experts through the questions without giving people with strong personalities too much influence on the discussion, or without allowing overlapping judgements from different experts to have too much weight in the total result (Garthwaite et al. 2005). Nevertheless, group elicitation has an advantage in the potential for synthesis and analysis of knowledge that is possible through the interaction between the experts (O'Hagan et al. 2006). In addition, interaction enhances the possibility of clarification of definitions and assumptions among the experts. However, the facilitator needs to handle the risks of overconfidence and group polarisation strategically, i.e. the risk that the group adopts a more extreme position than any of the group members would do. Studies have shown that even though groups tend to perform better than the average for the individuals, there is often an individual who is better than the group as a whole. The general conclusion, however, is that it is still advisable to consult several experts for probability assessments (Clemen and Winkler 1999).

Individual assessments have the advantage that it is possible to analyse each expert's judgements and by doing so increase the understanding of their specific implications for the outcome of the result (Morgan and Henrion 1990). In that way, expert elicitation can be used both to discover and to illustrate the different opinions of a problem (Morgan and Mellon 2011). Nevertheless, before drawing any conclusions about the differences it is advisable to analyse how significant the differences are between the different experts compared to their individual uncertainty. The effect of the difference on the final result can then be analysed properly (Morgan and Henrion 1990).

6.3 Aggregation of different judgements

In most elicitations based on individual assessments, the experts make differing judgements and probability assessments which should be summed up and merged into decision support. This could also be the case in a group discussion when experts have different opinions. There are several mathematical methods to perform mathematical aggregation of the expert judgements. Clemen and Winkler (1999) present an extensive review of different aggregation methods and state that simpler aggregation methods are usually better than more complex methods. However, after a well-structured elicitation process with competent experts, a complex mathematical aggregation method could have the potential to perform better. O'Hagan et al. (2006) agree that the more complex methods should be used only in situations of extensive elicitation, and concludes that more simple methods, such as averages of distributions from different experts, are robust methods for aggregation in general.

One of the simplest methods is the linear opinion pool (O'Hagan et al. 2006) which is a weighted average of the individual distributions with a weight w_i assigned to each expert, and where all weights total one. The aggregation aims at obtaining a consensus distribution $f(\theta)$ from the individual expert distributions $\{f_1(\theta),,,f_n(\theta)\}$.

$$f(\theta) = \sum_{i=1}^{n} w_i f_i(\theta) \qquad (6.1)$$

When the expert distributions are updated, either each expert’s opinion can be updated individually and the distributions are then pooled or initial distributions can first be pooled and the pooled prior distribution is then updated. A major drawback of this method is that the two choices produce different results and it is impossible to know which of the distributions best represents the experts’ opinions.

Another aggregation method is the logarithmic opinion pool, through which the aggregated distribution is obtained by the weighted geometrical mean of the individual expert distributions *n*:

$$f(\theta) = k\prod_{i=1}^{n} f_i(\theta)^{w_i} \tag{6.2}$$

where *k* is a normalising constant that ensures that $f(\theta)$ integrates to 1 (O'Hagan et al. 2006).

When new data is to be included in the analysis with logarithmic aggregation, it does not matter if the expert’s probability distributions are first updated and then combined, or if the probability distributions are first combined and then updated with new information. Either way, the result will be the same (Clemen and Winkler 1999, O'Hagan et al. 2006, and others).

7. INCLUDED PUBLICATIONS

This chapter summarises the six publications that are part of the doctoral thesis. The aims and main findings of the studies are presented here and the outcomes are discussed further in Chapter 8.

7.1 VOIA for rock mass characterisation

The aim of the paper (Zetterlund et al 2008) was to present the first steps towards a methodology for rock mass characterisation in accordance with the Observational Method and decision theory. The focus of the generic study was on how to obtain the necessary information in a pre-investigation of a tunnel by means of VOIA. The tunnel in question, approximately 90 metres in length, was to be constructed in Precambrian diorite. In order to reduce the inflow of water into the tunnel, pre-excavation grouting was planned for the whole length of the tunnel. Initially, a basic grouting design was planned although there was a possibility that the design would not be sufficient in certain sections of the tunnel. These sections would then be grouted a second time prior to excavation. The second round of grouting was seen as a project risk, i.e. if the time for the grouting activities is not included in the project budget and time schedule, it would entail delays and unforeseen costs.

The main findings of the paper were:

Although VOIA is a useful tool for structuring thoughts and formalising a decision process, the conditions and requirements that affect the decision-maker's priorities and attitude to risk vary between projects.

VOIA in rock mass characterisation is site-specific and although the key questions are the same the answers may vary.

VOIA focuses the decision process in rock mass characterisation on the most essential parameters.

By focusing on the parameters that are crucial to the purpose of the characterisation, VOIA contributes to a more transparent process where each step is openly evaluated and the value of further investigations is compared with the present level of knowledge about the underground construction site. This leads to an investigation programme that is well adapted to the statutes of the Observational Method.

7.2 Framework of VOIA

A further development of the VOIA methodology is presented in Zetterlund et al (2011). The aim of the study was to develop a framework for VOIA in rock mass characterisation for grouting purposes in tunnels in hard rock. The method was illustrated in a generic case involving a feasibility study of a tunnel constructed in crystalline rock in the Fennoscandian Shield. Two alternative grouting design choices were available; one conventional design with cement grout and one extensive design with cement in combination with silica sol. Two questions were asked: Which of the alternatives is best suited to the geological conditions on site? Is information from investigations of value in making the decision? The value of new information from a core-drilled borehole was compared with the cost of drilling and measurement.

The uncertainty of the grouting efficiency was represented using beta distributions for each scenario. More specifically, it was the probability of the grouting design meeting the requirements that was modelled using the Beta distribution.

A stochastic model was set up of the geology, based on transition probability and Markov chains, see Figure 7-1. The model was the basis for probabilistic judgements of the geological conditions, such as the probability of detection given the geological conditions.

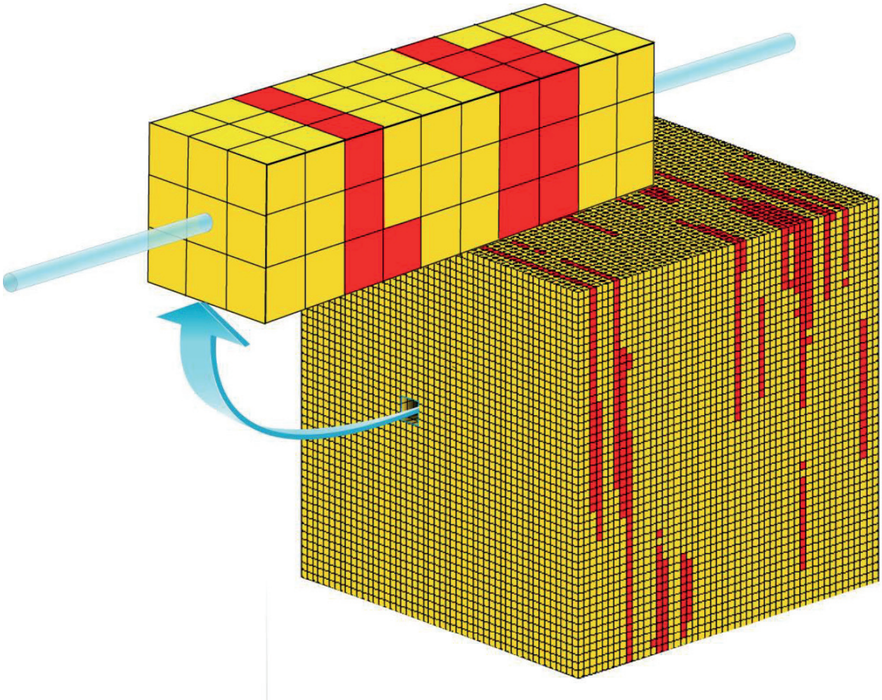

Figure 7-1. Example of one realisation of the stochastic model of the geology. Each section of the planned tunnel was represented by 3 cells along the y- and z-axes, and 10 cells along the x-axis. The virtual drilling was performed in the central cell of the planned tunnel section. Deformation zones are represented by red colour, rock matrix is represented by yellow colour (Zetterlund et al. 2011).

The main findings of the paper were:

VOIA can contribute to a good structure in geological surveys when the geology is difficult to predict and when repeated updating is necessary during the course of a project.

The prescribed method provides a tool to design well-motivated investigation programmes where geotechnical value is weighed up against execution costs.

The prescribed method also serves as a good basis for updating problems by quantifying the reduction in uncertainty in monetary terms. By doing so, the method facilitates the use of the Observational Method in underground construction projects.

The suggested method for application of VOIA in rock mass characterisation is:

1. Formulate the purpose of characterisation. Identify key questions.
2. Preliminary study of all available geological information for the area, such as maps, earlier investigations, etc.
3. Create an initial conceptual model of the geological and hydrogeological conditions.
4. Perform field mapping.
5. Update the conceptual model.
6. Perform a prior analysis.
7. Make a stochastic model of the geology in, for example, T-PROGS.
8. Preposterior analysis.
9. Compare the expected value of information with investigation costs.
10. Make a decision regarding further investigations.

7.3 Characterisation and the Observational Method

This chapter summarises the author's licentiate thesis. The aim of the thesis is to create a platform for rock mass characterisation according to the Observational Method. The objectives of the thesis are as follows:

- To describe how Bayesian statistical methods can be useful in rock mass characterisation according to the Observational Method.

- To show how Value of Information Analysis can be used as a tool when working according to the Observational Method.

The thesis presents how a decision-maker can prepare for a continuous updating process at the exploration phase of a project and the main findings of the thesis were:

‘Characterisation’ should not be confused with ‘classification’. In rock mass characterisation the condition of the undisturbed rock mass is described and parameters governing or influencing rock mass behaviour are described and quantified. Classification is performed for direct application to an underground construction. It is a way of simplifying the geological information and can be of help in organising and obtaining a better overview of the data. If classification has been carried out properly, it could simplify the process and ease communication.

Communication and transfer of knowledge between different persons and project participants is one of the difficulties when the Observational Method is applied. However, this knowledge transfer is essential for an efficient updating procedure.

A rock mass characterisation process needs to focus on the problem to be solved and the parameters required for that specific problem. The question of whether or not further investigations or measurements are beneficial is not only governed by the value of the latest measurement but also by the uncertainties in the process itself. In some cases the uncertainties can be of such magnitude that they override the value of making further investigations.

With VOIA the decision process in rock mass characterisation is focused more on the most essential parameters. By focusing on the parameters crucial to the purpose of the characterisation, VOIA contributes to a more transparent process, where every step is evaluated and the value of further investigations is compared with the present level of knowledge regarding the underground site.

The structure of a VOIA and the mathematics it involves are quite straightforward and yet the statistical notations may be unfamiliar. Development of computer aids for VOIA calculations would simplify use of the method in project planning and construction and in doing so facilitate implementation of the method.

The costs included in the cost-benefit analysis are presumably already known by the decision-maker but, as stated previously, the difficult part is to assign values to the probabilities involved. In one example in this study, the probabilities were based solely on expert knowledge. In a second example, it was shown that a stochastic model of the rock mass can be a basis for the probabilities. In the latter example, the uncertainty in the grouting result was represented by a beta distribution.

Purpose-driven rock mass characterisation will, using VOIA, contribute to a transparent decision procedure and to an investigation programme that is well adapted to the statutes of the Observational Method.

The theory of decision analysis is already well developed, although the link to rock mass characterisation is not as developed. Very few examples have been found where decision analysis has been used to its full extent in rock engineering projects. A test of the method in real, ongoing projects is necessary.

7.4 Fracture mapping for geological prognoses

Fracture mapping is generally used to make predictions about the properties of the fracture network in the rock mass and these mappings form the basis for different models and decisions of vital importance are often based on the compiled fracture pattern. One of the aims of the study by Zetterlund et al (2012) was to illustrate how uncertainties in anisotropy, heterogeneity and sampling scale affect conclusions regarding rock mass conditions. A qualitative comparison of fracture orientations from fracture mappings from different sources was made based on a unique data set from the TASS tunnel at Äspö HRL. At one location in the rock mass fracture mappings were available from three core-drilled boreholes in the same direction as the planned tunnel – mappings from the tunnel roof and walls, as well as mappings from eight blocks sawn out of one of the tunnel walls. The initial hypothesis was that the blocks would serve as a key to the three-dimensional properties of the rock mass.

The three boreholes analysed in the study at Äspö were all approximately 100 m long and drilled horizontally in the planned tunnel direction at a depth of 450 m. Using wire saws, the blocks were excavated from the tunnel wall from an eight-metre section. The blocks were 1 m wide, 1.5 m high and approximately 0.7 m deep. Each block was then sawn into nine or ten slabs, which resulted in a total of 75 slabs. Each slab has been cleaned and surveyed (by means of an impregnated dye) and in total 2,509 fracture traces in the slabs were mapped and documented.

The focus of the study was on qualitative orientation analysis of fractures using stereographic projection. Comparison of the different data sets showed how input data for geological models vary depending on the type of investigation the fracture mapping is based on, as well as the scale on which the fractures were mapped.

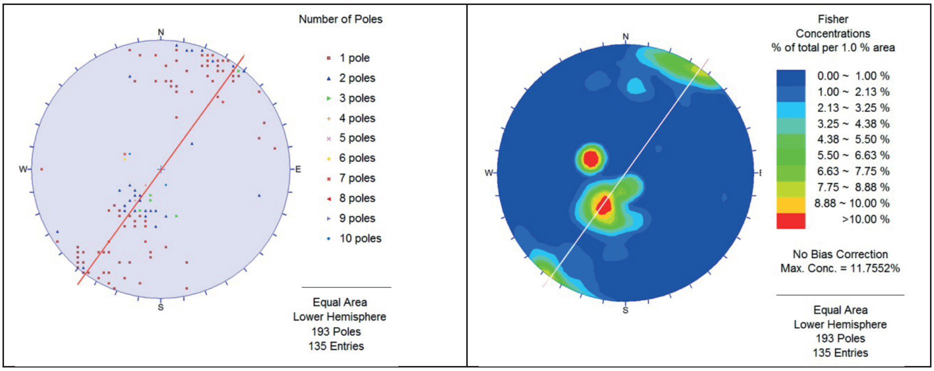

Figure 7-2. Pole and contour plots (Schmidt nets) of open and partly open fractures mapped in selected sections of the boreholes KI0010B01, KI0014B01 and KI0016B01 in Äspö HRL. Terzaghi corrected data (Zetterlund et al. 2012).

The main findings of the study were:

After Terzaghi correction of data, the fracture mapping of tunnel faces identified almost the same fracture sets as the boreholes, even though the scanlines along the boreholes are perpendicular to the tunnel faces.

Plots of fractures mapped on the blocks appear to be slightly different from the plots of the fractures mapped from the boreholes or in the tunnel. One fracture set, clearly identified in data from the boreholes and the tunnel, is barely indicated in plots of fractures mapped in the blocks.

The fracture data from the analysed blocks was initially considered to give the most comprehensive and general picture of the fracture system orientations in the rock mass. However, it was indicated in the results that there are obvious differences between the plots according to sampling scale and dimensionality.

Large epistemic directional uncertainties in the data itself were related to the understanding of the sequence of the geological stress field that have affected the rock mass over geological time. Hence, the study indicated that there is a need to improve the detailed conceptual understanding at the tunnel site of the generation and intensity of fracture sets in order to make a reliable interpretation of fracture intensities and orientations.

7.5 Case Study Äspö HRL

The previous studies of VOIA in rock engineering (Zetterlund et al. 2008; Zetterlund et al. 2011) focused on grouting-related issues for just two decision alternatives in only one position. Since decisions in tunnelling projects are generally more complex, and include several possible alternatives, the aim of this study was to develop a methodology for VOIA that takes into account two decision alternatives in two alternative positions. Experience from previous work with VOIA in rock engineering has also shown that there is the potential to facilitate the use of VOIA by developing methods where expert judgements can be used to generate input data instead of complex models.

An application of the methodology in a case study at Äspö Hard Rock Laboratory (Äspö HRL) in south-east Sweden is presented in Zetterlund et al. (2014a). An overview of the site is shown in Figure 7-3. The purpose of the VOIA was to find out if it is justified in economic terms to invest in a core-drilled borehole (KA2051A01) to provide information for decisions on the location of a niche (TAS04) in a tunnel (TASP), and whether or not to plan for grouting. The VOIA calculations were based on expert knowledge which was acquired through a structured elicitation process.

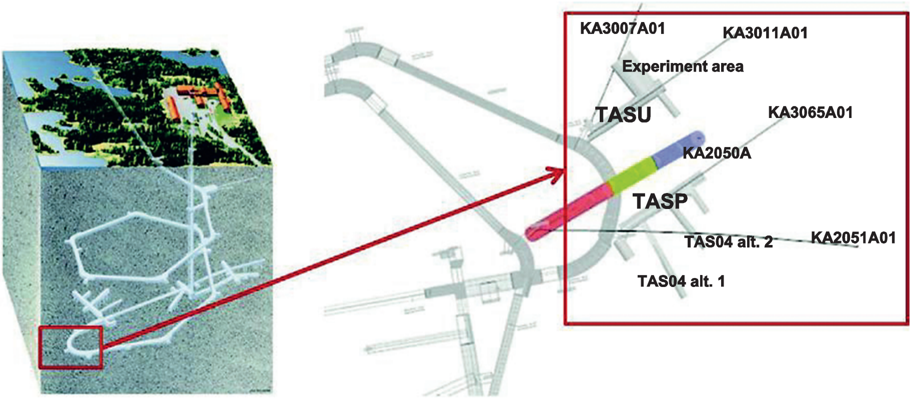

Figure 7-3. Overview of the investigation boreholes and the new tunnels TASP and TASU at Äspö HRL. There were two alternative positions for the analysed niche TAS04.The observational borehole KA2050A was drilled earlier in the area between the new tunnels. The colours (blue, green and red) represent the different sections for monitoring of groundwater pressure in the borehole. (Figure modified from SKB).

Prior- and preposterior probabilities were assessed by expert judgement based on a geological and hydrogeological description of the conditions around the planned tunnel. The description was a compilation of data from real project data, and the costs included in the VOIA calculations were also the real project costs. The uncertainty in the expert's assessments was described with a beta distribution.

The main findings of the study were:

The analysis showed that the expected value of perfect information (EVPI) was less than SEK 50,000 for any of the separate positions, with an aggregated value of SEK 35,000 for either position 1 or position 2. Considering both positions, the EVPI varies between SEK 35,000 and SEK 185,000, with an aggregated value of SEK 106,000. The realisation costs for investigation borehole KA3065A01 were estimated at SEK 1.6 million, which is considerably more than both the expected value of information and the value of perfect information.

Since neither the expected value (EVI) nor EVPI exceeds the investigation costs the investigations are not economically justified. However the project at Äspö HRL had a complex structure with many research groups involved from different geoscientific fields, and the results from the investigation borehole were intended to serve different purposes other than grouting and groundwater pressure issues. The investigation costs could therefore also be distributed between different purposes, with the result that the borehole may be justified any way. A comprehensive view of the project is thus needed in decision-making based on VOIA as there may be additional fields of applications for an investigation, which has not been considered in these VOIA calculations.

The models for VOIA become quickly complex for decision problems in underground construction projects and they become even more complex if quantitative simulation models are used as input data. The extended use of expert knowledge is therefore important as a simplification and to make it easier to use the model in practice.

The study shows that another useful simplification is to calculate EVPI to acquire important information about the boundaries for reasonable realisation costs for investigations.

7.6 Use of expert knowledge

The chapter summarises the findings of the expert elicitation part of the case study at Äspö HRL (Zetterlund et al 2014b).

The work with stochastic modelling as a basis for probability assessment is time-consuming and difficult if data is sparse. Hence, the aim of this study was to develop a method for VOIA based on expert judgements and to investigate whether expert judgements from several experts can be incorporated stringently in order to make the method more operational from a practitioner's point of view in the early phases of projects. The paper focused on 1) development of a protocol for expert elicitation within the VOIA methodology, and 2) testing and evaluation of the elicitation process in a case study.

The protocol was tested in an elicitation process in a case study in a tunnel at Äspö HRL. Using VOIA, the value of a core-drilled borehole was estimated in order to decide on the position of the niche and grouting preparation. The probabilities needed for the calculations were acquired from a structured elicitation process with six participating experts. An elicitation procedure was organised following the main stages of O'Hagan et al. (2006) but adjusted to suit this case:

1. Background and preparation
2. Identification and recruitment of experts
3. Structuring and decomposition
4. The elicitation session
5. Follow-up session

During the first three stages, the practical work was performed iteratively between the stages. Motivation of the experts took place within the other stages.

The elicitation was carried out as a web-based workshop, and the purpose of the session was to achieve estimates of probabilities related to different scenarios in a tunnel project. The process involves several uncertainties and the questions in this study were formulated in such a way that the influence of heuristics and bias was reduced. The experts made their probability assessments as intervals between the lowest reasonable value and the highest reasonable value and the uncertainties in the estimates were described using beta probability distributions.

Main findings of the study were:

A well-structured elicitation process within rock engineering projects not only needs experts in geology, rock mechanics and hydrogeology but also a facilitator with general knowledge in both psychology and geoengineering as well as a statistician to set up a project-specific model. Consequently, although a proper expert elicitation was found not to be less time-consuming or easier to perform than stochastic modelling, it was experienced the expert elicitation provided valuable synergy effects that would not have been achieved otherwise. Examples of experiences from this study are that the preparation of the elicitation process may contribute to decision-oriented planning of investigations and that the subsequent discussions could be a basis for a structured discussion about uncertainties in the background information which could be a part of a project’s risk management.

The elicitation process gave valuable experience not only in how to structure an elicitation, but also on the practical use of VOIA in rock engineering. In addition, expert knowledge was found to be useful for probability assessments within VOIA of rock engineering investigations.

8. DISCUSSION

8.1 Fracture mapping as an investigation method

The study of the results of fracture mapping based on different geological information (Zetterlund et al 2012) showed that if fracture mapping data is to be traceable throughout the different project stages, the mapped fracture parameters must also be consistent throughout the process. Consistency in nomenclature is vitally important if prognoses are to be followed up and updated during the construction process and if data from different geological investigations is to be compared.

The initial hypothesis that data from the blocks could be used as a key for the three-dimensional fracture pattern proved to be false due to scale effects in sampling. Nevertheless, after Terzaghi correction of data, the same fracture sets were found in the plots of both fractures from core samples and fractures from tunnel faces, despite perpendicular scanlines. This implies that fracture mapping of core samples is a reliable investigation for predictions of fracture patterns on the tunnel scale. The result is consistent with the findings of Alm et al. (2013) that core drillings and other ‘direct’, in situ investigation methods are considered valuable and reliable by experienced staff in the underground construction industry.

The investigation results from core drillings were used as input for prior and preposterior analyses of the VOIA and the reliability of the investigation methods were assessed in the conditional probabilities $P(F_i \mid D_i)$, $P(F_i \mid D_i^c)$, and, $P(F_i^c \mid D_i)$. In the expert elicitation study (Zetterlund et al. 2014b), the experts assessed the reliability of core drilling as an investigation method by assessing one of the error probabilities for each position of the planned niche, $P(F_1 \mid D_1^c)$ and $P(F_2 \mid D_2^c)$. They described the probability of failure due to tunnelling in Position 1 or Position 2 respectively, given that no conductive feature is detected by the investigation borehole. The mean values of the experts’ assessed probabilities varied between 0.0 – 0.55, and two experts' assessed maximum values were higher than 0.5. Assessments higher than 0.5 indicate very low method reliability, which means that the probability that investigation results will be misinterpreted is greater than the chances of drawing correct conclusions. Accordingly, the assessed reliability of core drilling in this study is not consistent with the other studies. A possible explanation for the inconsistency could be unclear formulations of questions or insufficient feedback in the elicitation questionnaire, in the sense that the experts could not fully understand the implications of their assessments.

8.2 Expert elicitation

A major strength of VOIA as decision support is the possibility to incorporate expert knowledge in a structured manner. In all three studies of VOIA within the scope of this report, expert knowledge has been used in some way, although it was only in one study where several experts were asked for assessments. The elicitation process is demanding and includes several uncertainties in the formulation of questions to avoid heuristics and bias in the analysis and interpretation of the resulting probability distributions.

In the elicitation process in the case study of Äspö HRL (Zetterlund et al. 2014b) it was shown how expert knowledge can be used for probability assessments although the discussion about the background information, the conditions in the project and the goals of the project are even more important than the results of the VOIA. The elicitation process served as a framework for more structured and documented discussions about uncertainties than what is generally the case in tunnelling projects today. Decisions are made in projects but the motives behind them are seldom well documented or traceable.

The explicit use of subjective probabilities in VOIA in particular, and in Bayesian decision theory in general, may be an obstacle for the use of the methods in rock engineering, since rock engineers and engineering geologists are usually unaccustomed to specifying their uncertainty in this manner. In addition, the fact that it is not possible to check the probabilities in relation to the reality may be a further obstacle to introducing these methods to engineers who are only educated in the frequentist view of probability. Nevertheless, probability assessment is difficult and it is important to realise that there is uncertainty in the assessments and that this uncertainty also needs to be acknowledged. In the case study at Äspö HRL (Zetterlund et al. 2014a, 2014b), the uncertainty in the experts' estimates was described using a Beta distribution.

In some fields it is possible to use methods to calibrate experts in order to perform better assessments (O'Hagan et al. 2006, and others), but this is not possible in rock engineering. Even though there are similarities between different projects, the geological and hydrogeological conditions are site-specific. This means that it is not repeatable events that are elicited but events that happen only once. However, this does not mean that experts with training cannot improve their ability to express their uncertainty in probabilistic terms, and consequently improve their ability to identify the implications of their assessments.

As regards expert elicitation, it is important to bear in mind that the expert assesses the probability of the required event. If the question is not correctly phrased, or if it can be misinterpreted in any way, the assessment will not describe reality correctly. In this context, it should also be borne in mind that the elicited probability is the expert's opinion based on the knowledge he or she has at present stage. An optimal elicitation is when the chosen probability distribution describes the expert's opinion correctly, at the same time that the assessment describes the reality adequately.

8.3 VOIA

Since the properties of the rock mass are spatially dependent, the EVI from an investigation is very much dependent on where in the rock mass the investigation is performed. A site investigation with limited resources will most probably be targeted at describing the weaknesses in the rock mass. The data value of these investigations not only depends on the investigations and the cost of failure, it is also affected by where the investigations are located in the rock mass. For example, the EVI from investigations at a spot with very uncertain geological conditions will most probably be significantly higher than in a spot with more certain geological conditions. However, the EVI is also dependent on the consequence costs if failure occurs. In the case study of Äspö HRL (Zetterlund et al. 2014a, 2014b), the value of the investigation borehole was almost practically non-existent, which indicates that data from a borehole in that direction and position is not what the experts need to reduce their uncertainty.

Estimating the EVI of an investigation in a project includes assessments of conditional probabilities that may not be intuitive and therefore difficult to assess. Calculation of the EVPI is somewhat easier and may provide an initial estimate. However, it still provides very important information. It provides in many cases a rough but useful estimate of the potential maximum value of the investigation for decisions regarding investigation programmes. Hence, a complete VOIA is not always needed as decision support.

The difference between the EVPI and the EVI is related to the reliability of the investigation method. Low assessed reliability in the investigation method will most probably result in a low data value. It could also be the case that if the data value of one investigation is low, indicating that one investigation alone cannot reduce the uncertainty, then the value of two or more investigations can be greater since together they have the power to reduce the uncertainty sufficiently.

Within this project, VOIA has been developed further and adopted for rock engineering purposes, but not without difficulty. The method has proved to quickly lead to complex models when used in the real world even if the rock engineering problems are relatively simple. Due to the time and effort it takes to set up the model, VOIA methodology is not suited to all rock engineering problems.

For instance, it is often difficult to set up the model for a chain of decisions in a real tunnelling project since investigations are seldom carried out for the purpose of making just one decision. In practice, the investigations are the basis for decisions in different project stages and with different levels of detail. Defining the failure criteria and identifying the real alternatives of the decision and their consequences is not as straightforward as it may seem initially. In order to avoid a model that is too complex, limitations and simplifications are often necessary.

There is an obvious problem of working with VOIA in the early phases of large infrastructural projects in Sweden and it relates to the economic and contractual situation in the projects. In general, the greatest possibility of influencing a project is in the early phases and if more money is spent on investigations in these early phases it is assumed that this will lead to reduced costs later on because a better design is developed from the outset. This may be true in some cases, but there are practical issues to be resolved when working in this way. Firstly, a fact, which is only indirectly related to VOIA, is that in some cases it is less expensive to hold back with an investigation until a later stage when a project organisation, staff and equipment have been established on site (Andersson et al. 2000). Secondly, and more importantly, there must be an economic incentive for people working in the early stages to carry out measures that will reduce risks in later stages, since additional investigations increase the costs at the present stage. If VOIA is to be viable for use in a project, a comprehensive view of the whole project in economic terms is needed and not just a focus on a budget for a certain assignment. In current underground construction projects, this is obstructed by the long-term perspectives and horizons for the entire project.

8.4 Link between VOIA and the Observational Method

There are no clear parallels between the results of a VOIA and the conclusions about when to use the Observational Method in tunnelling. VOIA is a source of support for making decisions regarding different plans of action when there is a possibility of further investigation to reduce uncertainty. The results of a VOIA (prior costs, EVI and EVPI) are affected by uncertainty in prior information and by project-specific costs and the consequences of failure, which can vary between projects even though the geological, hydrogeological and rock mechanical conditions are similar. However, probabilistic risk analysis may be useful for establishing the acceptance limits and the range of the possible behaviour required according to the European standard (SIS 2005, Spross 2014). Moreover, Bayesian decision analysis puts a focus on decisions and adds structure to the identification of possible scenarios and contingency plans.

The extent of an investigation programme in a project where the Observational Method is prescribed must be determined by the required level of the prognoses of the geological, hydrogeological and rock mechanical conditions. If the design is to be based on the ‘most probable condition’, there must be sufficient background information available to establish that condition with reasonable uncertainty. Additionally, there must be sufficient background information for the design of the contingency plans. Obviously, the magnitude of the parameters that need to be observed during the construction phase must be known in order to define the monitoring programme and the acceptable limits.

9. CONCLUSIONS AND RECOMMENDATIONS

The overall aim of this study was to use VOIA to assess the value of prior investigations for underground construction projects. The study has focused on tunnelling projects in crystalline rock types where the main rock engineering uncertainties are related to the anisotropy, heterogeneity and scale-dependent properties of the rock mass. The specific aims of the doctoral thesis were to develop and adopt VOIA for decisions regarding investigations in underground construction and to test the method under realistic conditions with real project costs. A further objective was to investigate how expert judgement can be incorporated transparently into decision-making.

The aims of this study were achieved through three studies of VOIA on different levels of complexity. It was shown that a strength of VOIA is that it provides a structure for discussing uncertainties and it focuses on decision-oriented investigations that are also well justified from an economic perspective. It was also shown that VOIA can be used as an aid for grouting-related decisions and for decisions regarding tunnel positioning, although not without limitations.

Based on experience from this study, a decision-oriented way of working is promoted, see Figure 9-1. The economic value of prior investigations can be assessed using VOIA although the specific value of prior investigations is project- and site-specific since it depends on the purpose of the investigation and the decision that needs to be taken.

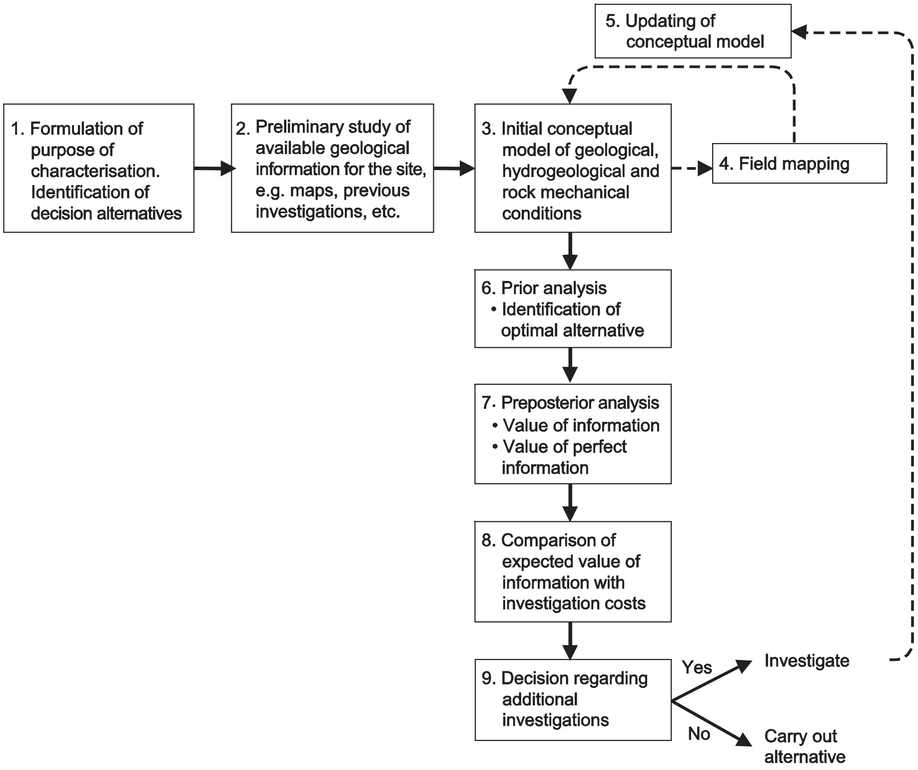

Figure 9-1. General flowchart of value of information analysis in rock engineering. This is an iterative process that starts with the purpose of the characterisation activities and the appropriate investigations for the decision.

The greatest benefit of VOIA is in situations where there is a genuine possibility of choosing between different alternatives, and when the choice is related to major consequences and risks. However, there is no clear relationship between the results of a VOIA and when to use of the Observational Method, although it can be beneficial to use Bayesian decision analysis in the Observational Method.

Probabilistic decision theory in general, and VOIA in particular, have an approach but in practice there are limitations to their use. Even though the VOIA models quickly become large and complex, the method provides useful input for uncertainty assessments and risk analysis of limited decision problems. One way to simplify the model is to begin by only calculating the value of perfect information, i.e. the value of results from an optimal investigation with no adherent errors. This value can be used as an indicator of the potential benefits of a planned investigation.

Structured expert elicitation has been shown to be a useful method for uncertainty assessments, not only for the strict numerical probability assessments but also as an organised method for uncertainty identification, which in itself could be valuable for project organisations.

There is a gap between the simplistic introductory examples of Bayesian methods and real-world scenarios that this study has attempted to fill. The study has provided theory and academic studies of VOIA in rock engineering as well as a simplified case based on real project data. However, this work is a further step towards more widespread use of Bayesian decision theory in the underground construction industry. If the probabilistic methods are to attract more attention in the industry, more documented practical experience of work according to Bayesian risk and decision analysis is needed. Furthermore, documented practical examples are needed of possible applications and simplifications and in particular the benefits of the methodology.

Practical experience is of great importance for further evaluation and adaptation of the model to decision problems in rock engineering. An interesting test of the method would be to use VOIA in a small number of underground construction projects but to limit the analysis to calculations of the EVPI. The analysis would then only provide an upper boundary of the value of the investigations and the calculations and the probability assessments would be simplified considerably. The aim of the study would be to evaluate how the use of the method would affect investigation costs and the related decision process.

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