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TOWARD A RELIABILITY FRAMEWORK FOR THE OBSERVATIONAL METHOD

Johan Spross

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Observationsmetoden från ett sannolikhetsbaserat perspektiv

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PREFACE

The observational method in geotechnical engineering is often emphasised as a suitable method for verifying structural safety, when large uncertainties are present. However, its use has been limited, at least in accordance to its formal definition in Eurocode 7. The present study aims to identify, highlight, and solve the aspects of the observational method that limit its wider application.

The research was carried out during 2012–2016 at the Division of Soil and Rock Mechanics at KTH Royal Institute of Technology in Stockholm, Sweden. The research was the author's Ph.D. project. The support from the supervisors, Prof Stefan Larsson, Dr Fredrik Johansson, and Dr Rasmus Müller, is gratefully acknowledged, as well as the support from reference group: Prof Em Håkan Stille/KTH, Dr Mats Holmberg/Tunnel Engineering, Dr Marie Westberg Wilde/KTH, Beatrice Lindström/Hard Rock Engineering, Isabelle Staub/Swedish Geotechnical Institute, Lars Rosén/Chalmers and Per Tengborg/BeFo. Other acknowledged contributors to the project are the co-authors of the produced research papers: William Bjureland, Alexandra Krounis, Anders Prästings, Dr Jalalledin Rafi, and Lauri Uotinen.

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[1] SVC has been established by the Swedish Energy Agency, Elforsk and Svenska Kraftnät together with Luleå University of Technology, KTH Royal Institute of Technology, Chalmers University of Technology and Uppsala University. www.svc.nu.

FÖRORD

Observationsmetoden framhålls ofta som en lämplig metod att verifiera gränstillstånd inom geoteknik och bergbyggande. Metoden används dock sällan – särskilt sällan i enlighet med dess strikta definition i Eurokod 7. I detta projekt undersöks tillämpbarheten av observationsmetoden när man bygger i och på berg. Målet är att belysa de aspekter som begränsar dess användning och i dessa fall föreslå förbättringar som ökar tillämpbarheten.

Forskningen utfördes som ett doktorandprojekt på Avd. för jord- och bergmekanik på KTH, Stockholm, under 2012-2016. Ett särskilt tack riktas till dels till handledarna Prof Stefan Larsson/KTH, Dr Fredrik Johansson/KTH, och Dr Rasmus Müller/Tyréns; dels referensgruppen som bestod av Prof Em Håkan Stille/KTH, Dr Mats Holmberg /Tunnel Engineering, Dr Marie Westberg Wilde/KTH, Beatrice Lindström/Hard Rock Engineering, Isabelle Staub/Statens Geotekniska Institut, Lars Rosén/Chalmers och Per Tengborg/BeFo,; dels medförfattarna till de publikationer som ingår i doktorsavhandlingen: William Bjureland, Alexandra Krounis, Anders Prästings, Dr Jalalledin Rafi, and Lauri Uotinen.

Projektet stöttades finansiellt av Svenskt vattenkraftcentrum (SVC)[2], Stiftelsen Bergteknisk forskning och Formas. Utöver dessa huvudfinansiärers bidrag har även Philips stiftelse, Stiftelsen vattenbyggnadslaboratoriets fond, KTH V:s resefond, samt Åke och Greta Lissheds stiftelse bistått med resebidrag.

Stockholm

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[2] SVC har etablerats av Energimyndigheten, Elforsk och Svenska Kraftnät tillsammans med Luleå tekniska universitet, Kungliga Tekniska Högskolan, Chalmers tekniska högskola och Uppsala universitet. www.svc.nu

SUMMARY

Constructing sustainable structures in rock that satisfy all predefined technical specifications requires rational and effective construction methods. When the geotechnical behaviour is hard to predict, the European design code, Eurocode 7, suggests application of the observational method to verify that the performance is acceptable. The basic principle of the method is to accept predefined changes in the design during construction to comply with the actual ground conditions, if the current design is found unsuitable. Even though this in theory should ensure an effective design solution, formal application of the observational method is rare.

Investigating the applicability of the observational method in rock engineering, the aim of this project is to identify, highlight, and solve the aspects of the method that limit its wider application. Furthermore, the project aims to improve the conceptual understanding of how design decisions should be made when large uncertainties are present.

The main research contribution is a probabilistic framework for the observational method. The suggested methodology allows comparison of the merits of the observational method with that of conventional design. Among other things, the report also discusses (1) the apparent contradiction between the preference for advanced probabilistic calculation methods and sound, qualitative engineering judgement, (2) how the establishment of limit states and alarm limits must be carefully considered to ensure structural safety, and (3) the applicability of the Eurocode definition of the observational method and the implications of deviations from its principles.

Keywords

Rock engineering, observational method, Eurocode 7, structural safety, reliability analysis, dam safety.

SAMMANFATTNING

För att kunna konstruera en anläggning i berg, som uppfyller satta tekniska krav, krävs det en rationell och effektiv konstruktionsmetod. När konstruktionens beteende är svårt att förutsäga, erbjuder den europeiska standarden Eurokod 7 den så kallade observationsmetoden. Denna metod tillåter i förväg förberedda förändringar i designen under konstruktionstiden, om observationer av konstruktionens beteende indikerar att så behövs. På så vis anpassas konstruktionen till de faktiska förhållandena i marken. Trots att detta tillvägagångssätt i teorin ger en rationell design, används metoden sällan i enlighet med Eurokod 7.

Denna doktorsavhandling undersöker tillämpbarheten av observationsmetoden när man bygger i och på berg. Målet är att belysa de aspekter som begränsar dess användning och i dessa fall föreslå förbättringar som ökar tillämpbarheten. I ett vidare perspektiv syftar avhandlingen även till att förbättra den konceptuella förståelsen för hur beslut bör fattas i designprocessen när det finns stora osäkerheter.

Avhandlingen visar hur observationsmetoden kan användas i ett sannolikhetsbaserat ramverk. Metodiken ger användaren möjlighet att jämföra för- och nackdelarna med observationsmetoden och konventionell dimensionering. Avhandlingen diskuterar bland annat även (1) den skenbara motsatsen mellan användandet av sannolikhetsbaserade beräkningsmetoder för att lösa komplexa dimensioneringsfrågor och kvalitativa ingenjörsmässiga bedömningar, (2) hur larmgränser och brottgränstillstånd bör definieras för att ge tillräcklig säkerhetsmarginal, samt (3) hur Eurokod 7:s strikta definition av observationsmetoden påverkar dess användbarhet.

Nyckelord

Bergmekanik, observationsmetoden, Eurokod 7, sannolikhetsbaserad dimensionering, dammsäkerhet.

LIST OF PRODUCED RESEARCH PAPERS

As a part of this research project, the following scientific articles were produced:

Paper A

Spross, J. & Larsson, S. 2014. On the observational method for groundwater control in the Northern Link tunnel project, Stockholm, Sweden. *Bulletin of Engineering Geology and the Environment, 73*(2), 401–408.

Paper B

Spross, J., Johansson, F. & Larsson, S. 2014. On the use of pore pressure measurements in safety reassessments of concrete dams founded on rock. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 8*(2), 117–128.

Paper C

Spross, J., Johansson, F., Uotinen, L. K. T. & Rafi, J. Y. 2016. Using observational method to manage safety aspects of remedial grouting of concrete dam foundations. *Geotechnical and Geological Engineering*, *34*(5), 1613–1630.

Paper D

Spross, J., Johansson, F., Stille, H. & Larsson, S. 2014. Towards an improved observational method. In: L. R. Alejano, A. Perucho, C. Olalla & R. Jiménez (eds.), *EUROCK 2014: Rock Engineering and Rock Mechanics – Structures in and on Rock Masses, Vigo, Spain, 26–29 May 2014.* London: Taylor & Francis group, 1435–1440.

Paper E

Bjureland, W., **Spross, J.**, Johansson, F. & Stille, H. 2015. Some aspects of reliability-based design for tunnels using observational method (EC7). In: W. Schubert & A. Kluckner (eds.), *Proceedings of the workshop "Design practices for the 21st Century" at EUROCK 2015 & 64th Geomechanics Colloquium, Salzburg, 7 October 2015.* Österreichische Gesellschaft für Geomechanik, 23–29.

Paper F

Spross, J. & Johansson, F. 2016. When is the observational method in geotechnical engineering favourable? Submitted to *Structural Safety*.

CONTENTS

1. INTRODUCTION

> *"Engineering is indeed a noble sport, and the legacy of good engineers is a better physical world for those who follow them."*
>
> – Ralph B. Peck (NGI 2000).

1.1. Background

The performance of a structure built in soil or rock may be evaluated based on many types of criteria stated by the owner, by the designer, or in laws and regulations. Anything from aesthetic design to technical requirements on stability, strength, durability, and serviceability can be considered. In addition, a planned structure must generally satisfy requirements regarding economical, societal, and environmental sustain-ability to be approved by the society. This implies using rational and effective construction methods that minimise the life cycle cost without inflicting unnecessary harm to humans or the environment during the lifetime of the structure.

An important aspect is the choice of verification method to ensure that the performance of the structure is acceptable, because the verification method influences the choice of construction method. Choosing the right verification method can therefore have a major influence on the outcome, in terms of both total cost and environmental impact.

According to the European design code for geotechnical structures, Eurocode 7 (CEN 2004), acceptable performance of the structure is assured by verifying that no limit state is violated; i.e., all specified technical requirements on the structure are fulfilled. The Eurocode states four acceptable verification methods for geotechnical structures:

- calculating with analytic, semi-empiric, or numeric models,
- adopting prescriptive measures,
- using experimental models or load tests,
- applying the observational method.

The first includes calculation models that either are accurate or err on the safe side. If not, another method must be chosen. Prescriptive measures include, for example, strictly empirical – and often very conservative – design rules. They may be appropriate when calculation models are unavailable or unnecessary.

The observational method is pointed out as more suitable when the geotechnical behaviour is hard to predict. The basic principle of the method is to accept changes in the design during construction to comply with the actual ground conditions, if the current design is found unsuitable. When put like this, it seems simple enough and certainly rational: adjusting the design to the conditions at the site should be an effective way to achieve the optimal solution. Still, the method is seldom used when constructing in soil or rock, and application in accordance with its formal definition in Eurocode 7 is even rarer. Some reasons for this may be the lack of guidance in design codes and the lack of well-documented case studies that discuss the applicability of the method. Previously, there have also been concerns regarding uncomfortably low safety margins in cases where the observational method has been used, as reported by Powderham (2002).

1.2. Aim of project

Investigating the applicability of the observational method in rock engineering, the aim of this thesis is to identify, highlight, and solve the aspects of the method that limit its wider application. As a basis, I study the observational method from a reliability-based perspective, attempting to improve the conceptual understanding of how design decisions should be made when large uncertainties are present, as this is when the observational method is believed to be favourable.

1.3. Outline of the report

The report is a summarising essay that should be read in conjunction with the six research papers (A–F) that are listed on page VII (the research papers are not appended because of copyright reasons). This report puts the research papers into a wider context.

The essay includes three main chapters (2–4) that cover the development of the observational method, some background to the reliability-based methods that were used to assess structural safety in the some of the produced research papers, and some background to Bayesian statistical decision theory, which was applied in Paper F. This is followed by chapter 5, which is a summary of the six research papers:

- Paper A is a published, peer-reviewed journal paper. The paper discusses the applicability of the observational method for groundwater control in a rock tunnel projects, based on a case study of a tunnel project in Stockholm.

- Paper B is a published, peer-reviewed journal paper. The paper studies the merit of using pore pressure measurements in safety reassessments of concrete dams, considering the probability of pore pressure increase caused by clogged drains.
- Paper C is a published, peer-reviewed journal paper. The paper discusses the applicability of the observational method for remedial grouting of concrete dam foundations, based on a case study of a grouting project at a Swedish dam site.
- Paper D is a published, peer-reviewed conference paper. The paper outlines a probabilistic framework for how measurements of a rock pillar can be used to assess the safety margin of the completed structure, when the observational method is applied.
- Paper E is a published, peer-reviewed conference paper. The paper develops the framework of Paper D for tunnel applications and describes how the concept satisfies the requirements in Eurocode 7 on observational method applications.
- Paper F is currently under review in a scientific journal. The paper presents a probabilistic optimisation methodology that aids the decision-making engineer in choosing between the observational method and conventional design. The methodology allows alarm limits of observed parameters to be established based on the target reliability of the structure.

In chapter 6, the major findings of the aforementioned papers are discussed in the context of the observational method set in a probabilistic framework. The main discussion topics concern (1) the apparent contradiction between the preference for advanced probabilistic calculation methods and sound, qualitative engineering judgement; (2) how the establishment of limit states and alarm limits relates to the structural safety; and (3) the applicability of the definition of the observational method in Eurocode 7. Conclusions are presented in chapter 7 together with suggestions for future research.

1.4. Limitations

The report focuses on the application of the observational method in rock engineering. As a major part of the work has been on case studies, the content and conclusions are naturally coloured by the specific features of the studied cases.

In addition to being a design method, the observational method can be applied to manage risks in geotechnical projects with large uncertainties. Though this aspect of the method is indirectly discussed, as reduced uncertainty by observation implies reduced risk, formal risk management procedures are not within the scope of the report. However, as a part of this research project, I have studied how the observational method can be applied based on thorough risk management in a geotechnical project; see Spross et al. (2015).

Although contractual constraints are recognised as an important aspect that may limit the applicability of the observational method, they are only briefly addressed in the literature study (section 2.4.4).

2. THE OBSERVATIONAL METHOD

> *"Unhappily, there are far too many instances in which poor design is disguised as the state of the art merely by characterizing it as an application of the observational method."*
>
> – Ralph B. Peck (NGI 2000).

2.1. Early development

The origin of the observational method in geotechnical engineering is often credited to Peck (1969). Peck himself, however, acknowledged Terzaghi as the originator of this systematic procedure for geotechnical design. The formulation of the observational method was the result of Peck's attempt to generalise Terzaghi's way of attacking practical geotechnical problems that Peck often found leading to significant – and sometimes even spectacular – successes. Terzaghi referred to the procedure as the learn-as-you-go method.

Even though Peck (1969) promoted the observational method as an attractive new alternative in geotechnical engineering, the general philosophy of the observational method can be traced back through history. The Greek historian Herodotus (c. 430 B.C.) provides an antique example[3] about how the Phoenicians improved the design of a canal after observing that its sides were prone to failure when cut too steeply (Figure 2.1).

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[3] "/.../ This Athos is a mountain great and famous, running out into the sea; it is inhabited by men. At the mountain's landward end, it is in the form of a peninsula, and there is an isthmus of about twelve furlongs' width; here is a place of level ground or little hills, from the sea by Acanthus to the sea which is over against Torone. On this isthmus, which is at the end of Athos, there stands a Greek town, Sane; there are others too seeward of Sane and landward of Athos, which it was now the Persians' intent to make into island and not mainland towns; to wit, Dion, Olophyxus, Acrothoum, Thyssus, Cleonae. These are the towns situate on Athos; and the foreigners dug as I shall show, dividing up the ground among their several nations. They drew a straight line near the town of Sane; and when the channel had been digged to some depth, some stood at the bottom of it and dug, others took the stuff as it was digged out and delivered it to yet others that stood higher on stages, and they again to others as they received it, till they came to those that were highest; these carried it out and cast it away. With all save only the Phoenicians the steep sides of the canal break and fell, doubling the labour thereby; for inasmuch as they made the span of the same breadth at its highest and its lowest, this could not but happen. But the Phoenicians showed therein the same skill as in all else that they do; having taken in hand the portion that fell to them, they so dug as to make the topmost span of the canal as wide again as the canal was to be, and narrowed it ever as they wrought lower, till at the bottom their work was of the same span as what the rest had wrought. There is a meadow hard by, where they made a place for buying and marketing; and ever and anon much ground grain was brought to them from Asia."

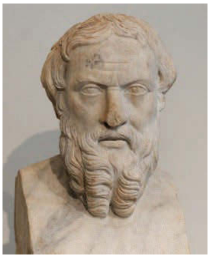

Figure 2.1. The Greek historian Herodotus may have given the first description of an applied observational approach in geotechnical engineering around 430 B.C. (Photo: © Marie-Lan Nguyen, 2011)

The importance of making observations when there are geotechnical uncertainties was also recorded by pioneering Swedish engineers in the early 20th century. In the final report[4] by the Geotechnical Committee of the Swedish State Railways (1922), observation of ground movements combined with ample warning systems was suggested to avoid accidents, because absolutely safe embankments were not deemed financially defensible. Still, the common practice of geotechnical engineers at the time was normally not as sophisticated; Peck's and Terzaghi's motivation for promoting the observational method was both to eliminate the risk-taking they often noticed in geotechnical projects and, at the same time, to reduce the use of excessive – and therefore costly – safety factors that more cautious engineers applied. Concluding that the current practice needed improvement, Terzaghi and Peck laid the basis for the first structured definition of the observational method.

2.2. Peck's definition of the observational method

Peck (1969) summarised Terzaghi's approach in eight steps to follow when applying the observational method:

a) "Exploration sufficient to establish at least the general nature, pattern and properties of the deposits, but not necessarily in detail.

From Herodotus (c. 430 B.C.), *The histories*, Book VII, verses 22-23.

[4] Incidentally, this milestone report also introduced the first known record of the word "geotechnical" (Massarsch & Fellenius 2012).

b) Assessment of the most probable conditions and the most unfavourable conceivable deviations from these conditions. In this assessment geology often plays a major rôle.
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) Calculations of values of the same quantities under the most unfavourable conditions 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."

Peck adds that these principles may not be possible to completely fulfil, depending on the nature and complexity of the problem at hand.

2.3. The Géotechnique special issue in 1994

During the following decades, the observational method was applied in various types of geotechnical construction, although very few cases were documented in detail and published. In Sweden, a similar approach known as "active design" was used during the 1980s; Stille (1986) presented a number of successful cases. Later, Muir Wood (1990) briefly summarised some application examples of the observational method, trying to draw attention to it.

To celebrate the 25th anniversary of Peck's 1969 paper, Géotechnique called for papers on the observational method for a special issue that was published in December 1994. An accompanying symposium was held in January 1995, discussing the method and its future development with the authors of the special issue. The symposium discussions were published together with the special issue in a book edited by Nicholson (1996).

Although the symposium was mainly positive to application of the observational method, there was a notable disagreement regarding its status and definition. Hence, further clarification of how and when to apply the method and ensure safety was found to be needed. In fact, not even Peck himself was fully content with his own definition of the method (Peck 1991). The possibility to extend the observational method into long-term monitoring during the operational phase was acknowledged great potential, even though the documented case studies were few. Other key issues identified as in need of attention were the current contractual constraints, the measurement techniques, and interpretation of data. In addition, the symposium addressed the need for more research projects and documented case studies on the observational method (Powderham & Nicholson 1996).

2.4. Requirements for applying the observational method

2.4.1. When to choose the observational method

Although there is an ongoing discussion on how to apply the observational method properly, some basic requirements regarding the nature of the project are clear. Peck (1969) points out a crucial limitation: the method is not applicable if the design cannot be changed during construction. Another general prerequisite is that a design based on the observational method must offer a more advantageous deal than the other possible ("more robust") designs. The whole construction process must be analysed; for example, it must be considered that extensive instrumentation might slow down the project and that preparing contingency actions will demand more time during the design process. How to analyse when the observational method is favourable is the topic of Paper F.

Peck (1969) differs between two main categories of projects where the observational method can be used. The *best-way-out* applications are for cases when an unexpected event has occurred to a project designed with another method and the observational method offers the most attractive way to proceed from there. The other category, Peck refers to as *ab initio*, which implies that the observational method already at the beginning of the project is seen as the most favourable design method.

2.4.2. Parameter values for preliminary design

Peck (1969) suggests the use of the most probable parameter values to describe the conditions, when applying the observational method. At times, however, this assumption might seem too risky. Powderham (1994) has therefore promoted the use of more conservative values in the preliminary design. This gives the opportunity to progressively modify the design *towards* the most optimal solution, instead of requiring quick action to avoid a critical failure. The design can however still be less conservative than a conventional design approach would suggest. Szavits Nossan (2006) provides an elaborate discussion on this matter and Serra & Miranda (2013) have recently exemplified it in a case study of a shallow tunnel. Powderham's approach is supported by Nicholson et al. (1999).

2.4.3. Proper measurement and data interpretation

The main benefit of the observational method comes from the possibility to use measurements and observations to reduce geotechnical and constructional uncertainties. With less uncertainty, the design is more likely to be economically optimal in fulfilling the performance requirements. Powderham (1994) concludes from previous case studies that although reduced safety margins sometimes is inferred against the method, an enlarged and improved monitoring program could actually increase the safety during construction, as it improves the understanding of the present conditions at the site.

The quality of the measurements is a vital factor when applying the observational method. In addition to avoiding practical issues such as instrumentation malfunction and poor handling of measurement equipment, which easily occur when the importance of the measurements are not properly emphasised to the staff on site (Peck 1969), proper monitoring plans require careful theoretical considerations. Badly located equipment will not give any useful results, no matter how fine it measures. In some less formal lecture notes, Peck (1970) expresses his serious worries about the development of field observation routines. Peck's conclusion[5] effectively highlights the importance of knowing what you are doing.

In addition, Stille & Holmberg (2010) point out that the uncertainty of the measured parameter must be of epistemic nature rather than aleatory; that is, the uncertainty must be reducible with measurements and not completely random (this is further discussed in section 3.3.1).

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[5] "It concerns me that the legitimate use of instrumentation may be set back by a rising tide of disillusionment on the part of those who have been persuaded to embark on elaborate [field observation] programs that promise too much. It concerns me that too many programs are based on the number of instruments to be used rather than on the questions to be answered. It concerns me that sophistication and automation are substituted for patient proof-testing of equipment under field conditions. To the extent that such practices prevail, they must be discouraged so that the observational approach itself will not be discredited. We need to carry out a vast amount of observational work, but what we do should be done for a purpose and done well."

Quoted from the conclusion of Peck's (1970) lecture notes from an ASCE seminar on field observations in foundation design and construction.

2.4.4. Good relations and communication between involved parties

It is often emphasised that the observational method requires a good internal culture within the project. All involved parties must together strive towards a common goal for the project to be successful (Powderham 1994, Nicholson et al. 1999, Chapman & Green 2004, Hartlén et al. 2012). Conversely, the opposite causality is also inferred; using the observational method may, in itself, promote greater motivation and teamwork within the project (Powderham 2002).

The possibility to support and encourage good communication between all involved parties is linked to the kind of contract used in the project. A contract type that separates the designer from the constructor is consequently making communication trickier. Relevant contractual features which could make the observational method easier to apply have been discussed by Hammond & Thorn (1994), Powderham & Nicholson (1996), Einstein (1996), and – from a Swedish perspective – Kadefors & Bröchner (2008). Some examples are fair risk sharing between the involved parties, an advanced pricing strategy that acknowledges variations, and working as a team and letting all parties benefit from improvements and savings.

2.4.5. Project characteristics in successful applications

To find the project characteristics that are associated with successful application of the observational method, Korff et al. (2013) studied a number of projects, in which the method was used. They concluded that the method is better for serviceability limit states than for ultimate limit states, because the previous is less critical. Observation of a sudden brittle, ultimate failure can be challenging, as the timeframe to put in contingency actions is very limited or non-existent. A ductile behaviour is therefore often preferable. Projects with a stepwise or multistage production process can be advantageous, because it allows learning from previous steps in the construction process. Reports on successful application of the observational method (or related, less strictly defined observational approaches) have been provided in e.g. Nicholson (1996), Powderham (1998, 2002), Nicholson et al. (1999), Peck (2001), Moritz & Schubert (2009), Wu (2011), Hartlén et al. (2012), Serra & Miranda (2013), Prästings et al. (2014), Miranda et al. (2015), and in Papers A and C.

2.5. Observational method in Eurocode 7

Being defined in Eurocode 7 (CEN 2004), the observational method is today an accepted alternative to conventional design methods for geotechnical structures. The

Eurocode definition, however, is slightly different from Peck's version ("P" in the following indicates a principle, which must not be violated):

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

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

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

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

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

Notably, the Eurocode definition of the method is very general; in fact, even more so than Peck's version. However, to accommodate all kinds of geotechnical design issues, where each project has its unique features, a general definition is necessary. More surprising is that available design guidelines, e.g. Frank et al. (2004), do not give any further advice on how to apply the method. For example, there is no advice on how to show that the design fulfils the five requirements in (2) in the definition, or how to make sure that the final design of the completed structure fulfils the society's requirements on structural safety by having an appropriate safety margin. These issues are further discussed in Papers D, E, and F, and in section 6.3. Practical application of the current definition of the observational method in Eurocode 7 is discussed in Papers A, C, D and E.

2.6. Observational method in underground excavation

2.6.1. Difficulties in rock engineering application

Most documented uses of the observational method have until now been related to structures in soil; formal application in design of underground excavations has been very rare, even though observations and measurements of the ground behaviour are needed in almost all underground projects (Schubert 2008). Notably, according to Palmström & Stille (2007), the observational method should be applied according to a formal definition to be successful, rather than a less strict learn-as-you-go method, as they find that the latter often leads to unexpected time delays and cost increases.

In principle, difficulties in predicting the geotechnical behaviour can for underground excavations mainly be attributed to variation in rock quality, the interaction between the rock mass and support, and in the quality of the executed support measures (Palmström & Stille 2010). Stille & Holmberg (2010) exemplify this with three possible design situations in rock engineering:

- assessing rock support from rock mass classifications,
- assessing the required thickness of shotcrete lining for rock support, and
- assessing local stability in tunnels based on deformation measurements analysed with Bayesian updating; this is further elaborated in Stille & Holmberg (2008) and Holmberg & Stille (2009).

Stille & Holmberg (2010) conclude that formal implementation of the observational method in the design of underground excavations should not impose any significant problems to the design process, but rather strengthen today's design practices. Palmström & Stille (2010) add an increased demand for better transparency and traceability in the projects, and, as discussed above, a need to overcome the current contractual constraints. Schubert (2008) emphasises that the field of ground characterisation would need significant development. For example, having selected tunnel support without considering the mechanical processes in the ground makes it hard to find the most suitable contingency action.

Some recent discussions of observational method application in tunnelling projects include Maidl et al. (2011), Zetterlund (2014), Miranda et al. (2015), and Papers A and E.

2.6.2. The new Austrian tunnelling method (NATM)

The NATM is in principle an empirical approach for tunnelling, developed from practical experience. It is sometimes viewed as an application of the observational method[6]. Palmström & Stille (2010) give a summary of the basic principles of the NATM. The method was developed during the years 1957–1964, originally for tunnelling in weak or squeezing ground. The essence of the method is to choose a suitable support method from a set of predefined standard methods. The choice is based on the (subjectively) observed ground behaviour at the tunnel front. Although observation is a key aspect, the NATM does generally not include the probabilistic considerations required in formal application of the observational method in accordance to Eurocode 7. Therefore, the NATM is sometimes seen as a less strictly defined "observational approach". NATM is however more in line with Peck's interpretation of the observational method, which is further discussed in section 6.1.

From a contractual point of view, the NATM shows some features that are useful for formal application of the observational method. For example, flexible contractual arrangements that allow changes in payment depending on the applied support and construction methods are essential for both of them. However, such arrangements may not be acceptable in all countries; Bieniawski (1984) recognises this as the reason for the limited use of the NATM in the United States.

2.7. Observational method in dam engineering

The number of documented case studies, in which the observational method has been used on dam structures, is very limited. Peck (1969) discusses the design of a dam, for which the observational method *almost* was chosen; however, the idea was abandoned when the designer could not find suitable contingency actions for all crucial eventualities. Two other exceptions are Hachich & Vanmarcke (1983) and Buckby et al. (2015). The former combined Bayesian updating (section 3.4) with a reformulated observational approach to analyse the flow pattern through an embankment dam based on pore pressure data, and from this they assessed the safety of the earth slope. The latter used an observational approach for the remedial grouting of a concrete dam foundation.

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[6] Muir Wood (1990) prefers the term "incremental support" in favour of "NATM", because the latter sometimes is used for any support with rock bolts, mesh and shotcrete, also when observational approaches are not applied.

Of interest, but not yet further developed, is the notion proposed by Powderham (1994). He suggests that it could be useful to continue the observational method into the operational phase for long-term monitoring with predefined contingency actions for landslips, dams, and buildings. Having already instrumented the site extensively, it is natural to make use of this as much as possible.

The original purpose of the research behind Paper B was to develop a framework for how the observational method could be used in safety reassessments of existing concrete dams (exemplified with the spillways in Figure 2.2). The working hypothesis that was used for this application is presented in Spross et al. (2013). If a safety reassessment based on conventional design assumptions had indicated an insufficient safety level, the suggestion was to consider the dam to be an "unfinished" structure. Measurements or other types of observations could then be used to establish the actual conditions at the site (unlike the conservative empirical relations used in conventional dam safety analyses). By treating the measurement data in accordance to the framework of the observational method, it was to achieve a sufficient safety margin.

While working in compliance with this hypothesis, it became evident that the uplift pressure under the dam did not qualify as a suitable control parameter, because previous believed to be possible to settle whether stability-enhancing modifications were needed measurements were found unsuitable to predict the future behaviour in many cases.

This became the topic of Paper B. The implications on the applicability of the observational method are discussed in section 6.2.

Figure 2.2. The spillways of Akkats in Lule älv River in northern Sweden are examples of concrete dam structures. (Photo: © Daniel Vorndran, 2015)

3. PROBABILISTIC SAFETY ASSESSMENTS

> *‘‘Probability is the most important concept in modern science, especially as nobody has the slightest notion of what it means.”*
>
> – Bertrand Russell (1929).

3.1. Probability of failure versus safety factor

Traditionally in civil engineering, structural safety has been assessed with a deterministic safety factor, FS, often defined as the ratio between the resistance, R, and applied load, S. If average values[7] are used, the ratio is referred to as the central safety factor:

$$FS = \frac{\mu_{\mathrm{R}}}{\mu_{\mathrm{S}}}. \tag{3.1}$$

The basic principle is to design the structure with a sufficient safety margin, so that any uncertainties in the assessment of either the resistance or the load do not threaten to cause failure (Elishakoff 2004). The stipulated safety factor for a given structural component is commonly a result of judgement and experience from occasional failures. In theory, large uncertainties require large safety factors. However, the safety factors agreed on in design codes and guidelines are not calibrated to each other; thus, equal safety factors do not necessarily imply equal safety level. In addition, they generally do not consider the present uncertainty in each individual case. Hence, a large safety factor might “unnecessarily” be applied, even though the level of uncertainty is low or, worse, a too low safety factor in a case with large uncertainties.

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[7] Alternatively, “characteristic values” for R and S are based on, for example, the 5 and 95 percentiles, respectively. Which percentile to use would be clear from the applicable design code (Melchers 1999).

Such inconsistencies have paved the way for probabilistic safety assessments, which more directly address the aim of structural safety assessments: minimising the probability of failure (Doorn & Hansson 2011). Admitting that both R and S are random variables, this can be expressed as the probability that the load exceeds the resistance, which is known as the probability of failure:

$$p_{\mathrm{F}} = P[G(R,S) \leq 0] = P(R - S \leq 0)\,, \tag{3.2}$$

where $G(R, S)$ is the limit state function, which defines the limit between safe behaviour and failure of the structure. Formally, for a general case where the structure consists of a system of j components and failure occurs when some combination c_{k} of the components fails, Equation (3.2) is generalised to (Der Kiureghian 2005)

$$p_{\mathrm{F}} = \int_{\Omega} f_{\mathbf{X}}(\boldsymbol{x})\mathrm{d}\boldsymbol{x}\,, \tag{3.3}$$

where $\boldsymbol{x}$ is the realisation of $\boldsymbol{X}$, which contains all relevant random variables of the limit state, $f_{\mathbf{X}}(\boldsymbol{x})$ is the joint probability density function of $\boldsymbol{X}$, and Ω is the region for the failure event, which with this system formulation is defined by

$$\Omega \equiv \bigcup_{k} \bigcap_{j \in c_{\mathrm{k}}} \{G_{\mathrm{j}}(\boldsymbol{X}) \leq 0\}\,. \tag{3.4}$$

Equation (3.3) is normally not possible to integrate analytically, but a number of approximate methods are available. The most common methods are presented in section 3.6.

Both the deterministic and the probabilistic approaches have their respective advantages and disadvantages (Doorn & Hansson 2011); for example, probabilistic design methods allow comparison between structures, whereas safety factors may provide margins also for unquantifiable uncertainties, such as unknown failure mechanisms. However, probabilistic analyses are currently coming into favour, at least as a complement to the deterministic approach. Given the references to probability in the definition of the observational method, the probabilistic approach is a natural choice for this application.

3.2. On probability of failure as a concept

3.2.1. The meaning of failure

Regardless of applied approach to assess safety – either deterministic or probabilistic – there must be a clear conception of the meaning of “failure”. For many applications, the word “failure” may be misleading, because the associated behaviour may not be the sudden, violent catastrophe that comes to mind. “Failure” should here rather be interpreted as “failure to satisfy the performance requirements”. For example, Mašín (2015) uses the term “[probability of] unsatisfactory performance” for this concept. However, for simplicity, I follow the convention and use the term “failure” in this report.

3.2.2. Bayesian, nominal or frequentistic interpretation?

At first sight, the concept of probability of failure may seem straightforward enough, but a calculated p_F should, in fact, in most cases not be interpreted as a measure of failure frequency (Vrouwenvelder 2002). That would require a stationary world with large amounts of statistical data from similar structures combined with significant theoretical evidence. For structural design, where every project has its unique features, the frequentistic interpretation of failure probability is therefore not viable.

The Bayesian view on statistics offers another interpretation (Vrouwenvelder 2002, Baecher & Christian 2003). A calculated p_F should then be seen as the best possible expression of degree of belief in failure of the structure. The analysis requires, however, that the degree of belief of the possible values of all involved variables is assessed accurately. The effect is that the safety assessments for a large number of structures will be correct on the average, although few safety assessments will reflect the inherent, true p_F of the individual structure. Thus, the fundamental difference between the frequentistic and the Bayesian approaches is that a frequentist considers nature to be full of unknown constants that can be found after many repeated trials, while a Bayesian interprets the states of nature as random variables to which probability statements can be as-signed.

A third option is the nominal interpretation (Vrouwenvelder 2002). This interpretation is required when the reliability assessment is not taking all relevant uncertainties into account; hence, it is acknowledged that the calculated p_F is not aiming to reflect the true probability of failure in any sense. This is convenient when a simplified reliability assessment is carried out, either because the actual situation would be too troublesome to model accurately or because the understanding of the expected behaviour is limited.

The Bayesian interpretation is the most useful for design of geotechnical structures, according to Vrouwenvelder (2002) and Baecher & Christian (2003). Notably, an interpretation that reflects the true p_{F} is required in economic optimisation problems. This is clear from Paper F, where a Bayesian interpretation is made.

3.2.3. Impact of reliability interpretation on acceptance criteria

Depending on whether the Bayesian or nominal interpretation of p_{F} is made, the acceptable p_{F} – hereafter referred to as target probability of failure, $p_{\mathrm{F,T}}$ – will be different. With a Bayesian interpretation, the $p_{\mathrm{F,T}}$ straightforwardly corresponds to the acceptable degree of belief in failure. However, for the nominal interpretation, the convenience of not having to model the situation accurately implies a major drawback: to be useful in practice, nominal p_{F} calculations must be preceded by thorough calibration of $p_{\mathrm{F,T}}$ and description of the design procedure in a design code, so arbitrariness in safety-related design decisions is avoided.

3.3. Sources of uncertainty in geotechnical design

3.3.1. Aleatory and epistemic uncertainties

Executing probabilistic safety assessments, there are different sources of uncertainty that must be taken into account. Generally, they are divided into two main categories: aleatory and epistemic uncertainty (Der Kiureghian & Ditlevsen 2009, Baecher 2016). The former category is named after the Latin word for dice thrower, *aleator*, and refers to an unpredictable, random behaviour, implying that no matter how much is spent on investigation, this uncertainty will not be reduced. The opposite is valid for epistemic uncertainty, which comes from the Greek word for knowledge (ἐπιστήμη). Epistemic uncertainty refers to lack of knowledge about the property and will consequently decrease as more investigations are performed.

Many sources of uncertainty are categorised as epistemic in geotechnical engineering. The three main categories of epistemic uncertainty are characterisation uncertainty, model uncertainty, and parameter uncertainty (Baecher & Christian 2003). Characterisation uncertainty relates to how the site investigation is interpreted and depends on for example measurement error or unrepresentative data samples. Model uncertainty depends on how well the applied mathematical model represents the reality.

Parameter uncertainty is related to the error introduced when the property of interest has to be estimated from test data or by transformation with empirical factors.

A special case is spatial variability, which often is categorised as aleatory uncertainty. This may be exemplified with an arbitrary volume of rock or soil (or any material). At first, very little is known about its properties; thus, the uncertainty about them is large. Investigating the properties of the volume, the knowledge about the properties may increase, which means that the epistemic uncertainty decreases. However, at some point, the uncertainty can no longer be reduced, because the remaining variability is related to the actual spatial variation within the material. The observant notes that the spatial variability hardly is random; once the property is known in every point in the volume, there is no uncertainty at all (except for variation with time, but that aspect is disregarded here). However, interpreting this variability as aleatory uncertainty is a way to *model* the spatial variability within a defined volume, implying that the property value at an arbitrary point can be seen as a random variable.

Because of the nature of the geological material, two points in close proximity tend to be correlated and therefore have similar properties. This correlation of a variable with itself over space is known as autocorrelation. It implies that the variability will be dependent on the scale. For example, if the considered volume is smaller than the scale of fluctuation, the variability of the property within that volume tends to be smaller than the large-scale variability (Baecher & Christian 2003). Spatial correlation has a significant impact on, for example, slope stability analyses (Griffiths & Fenton 2004, Ching & Phoon 2013, Ching et al. 2013), and bearing capacity analyses of foundations (Fenton et al. 2016).

For manufactured materials, such as concrete and steel, the categorisation into aleatory or epistemic uncertainty depends on the situation. Der Kiureghian & Ditlevsen (2009) exemplify with the compressive strength of concrete. If the concrete is that of an existing building, it can be tested and the related uncertainty can be reduced; hence, the uncertainty is epistemic (and its spatial variability can be modelled as aleatory). On the other hand, if the concrete is that of a future building, the uncertainty is aleatory, because its strength cannot be tested. However, once the building is realised, the aleatory uncertainty transforms into epistemic, as testing of its strength now is possible.

3.3.2. Criticism of stochastic models for epistemic uncertainty

The modelling of epistemic uncertainties with stochastic models (e.g. probability distributions) that normally is the case in reliability-based design was criticised by Bedi (2013). He found that applying stochastic models to epistemic uncertainties is not faithful to the (lack of) available information. Therefore, he suggested that non-probabilistic modelling methods should be used for these cases, so that the applied analysis method reflects the amount of information available. As a consequence, he concluded that the mathematical toolbox of the rock engineer must be expanded to include also interval analysis, possibilistic analysis ("fuzzy numbers", first introduced by Zadeh (1965)), and probability boxes ("p-boxes"). However, applying these non-traditional methods for decision making in practice is still challenging; one reason identified by Bedi (2013) is the lack of acceptance criteria for the calculated measures of safety with the respective methods.

Other proponents of using fuzzy mathematics in rock engineering include Harrison & Hudson (2010), who studied its application to spalling, and Park et al. (2012), who studied its application to rock slopes.

3.3.3. Methods of statistical inference to describe the real world

The actual assessment of a parameter and its corresponding uncertainty is normally based on measuring and monitoring results. The techniques and procedures that are used to draw conclusions about the real word from the available data are known as methods of statistical inference. They are described in most textbooks on statistics: see for example Benjamin & Cornell (1970), Baecher & Christian (2003), or Ang & Tang (2007). Note that the difference between the frequentistic and Bayesian interpretations also applies to statistical inference.

Common inference methods include estimation of probability distribution and its statistical moments, as well as regression and correlation analyses. Examples are found in Paper B, in which Bayesian linear regression is used to estimate the annual maximum pore water pressure under a concrete dam; in Paper D, in which Bayesian sampling theory is used to estimate the mean and variance of the deformation modulus in a rock mass; and in Paper E, in which Bayesian linear regression is used to estimate the final radial deformation of a tunnel based on measurements performed during the sequential excavation procedure.

In reliability-based design, a crucial aspect is how to characterise the geotechnical variability and the uncertainty of the applied measurement techniques (Phoon et al. 2016). Typically, a geotechnical parameter is estimated by applying a transformation model on a measured test parameter. A recent example is given in Krounis et al. (2016), in which the cohesion in a bonded concrete–rock contact was evaluated from direct tension tests.

In general terms, the mean value of the desired parameter Y may be modelled as a product of the measured mean value, $\bar{X}$, a transformation model, C, and a random error factor, ε:

$$\bar{Y} = \bar{X} C \varepsilon \,. \tag{3.5}$$

The ε collects the total uncertainty in $\bar{Y}$ and depends on (Figure 3.2)

1. $\varepsilon_{\mathrm{inh}}$, which is the inherent variability of the measured property after averaging it over the failure domain,
2. $\varepsilon_{\mathrm{st}}$, which is the statistical uncertainty in the estimation of $\bar{X}$,
3. $\varepsilon_{\mathrm{me}}$, which is the measurement error, and
4. $\varepsilon_{\mathrm{tr}}$, which is the uncertainty in the transformation model between the measured parameter X and the evaluated $\bar{Y}$ (i.e. the error in C).

Then, ε may be modelled as a product of its individual components:

$$\varepsilon = \varepsilon_{\mathrm{inh}} \varepsilon_{\mathrm{st}} \varepsilon_{\mathrm{me}} \varepsilon_{\mathrm{tr}} \,, \tag{3.6}$$

for which each error component has a mean value $\mu_{\varepsilon,\mathrm{i}} = 1$ and a standard deviation, $\sigma_{\varepsilon,\mathrm{i}}$. Assuming uncorrelated error components, this model conveniently allows the total uncertainty of $\bar{Y}$ to be approximated by summing the squares of the respective coefficients of variation of the error components, ε_{i} (Benjamin & Cornell 1970):

$$COV_{\bar{\mathrm{Y}}}^2 \approx COV_{\mathrm{inh}}^2 + COV_{\mathrm{st}}^2 + COV_{\mathrm{me}}^2 + COV_{\mathrm{tr}}^2 \,. \tag{3.7}$$

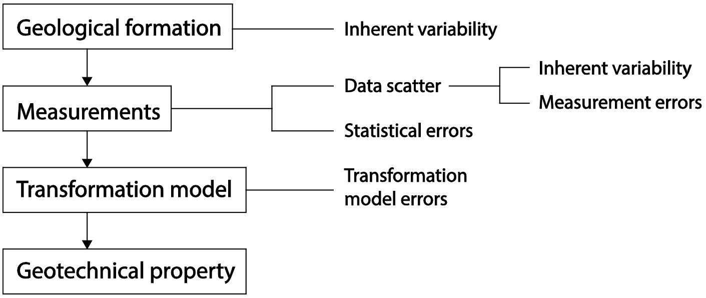

Figure 3.2. Categorisation of errors in the estimation of a geotechnical property based on measurements in a geological formation.

The complete evaluation of Equation (3.7) requires the autocorrelation to be taken into account, which can be done with a variance reduction factor (Vanmarcke 1977, 2010); however, its application is not within the scope of this report.

An alternative to Equations (3.5)–(3.6) is to model the error components as zero-mean random variables and add them together (Phoon & Kulhawy 1999):

$$\bar{Y} = (C + \varepsilon_{\mathrm{tr}})(\bar{X} + \varepsilon_{\mathrm{inh}} + \varepsilon_{\mathrm{st}} + \varepsilon_{\mathrm{me}})\,; \tag{3.8}$$

however, this makes the convenient approximate summing of *COV*s of Equation (3.7) not applicable. Instead, the uncertainty of $\bar{Y}$ would need to be evaluated in terms of its variance, which can be rather cumbersome, especially if the transformation model *C* is complex.

Recent applications of Equation (3.7) include Müller et al. (2014), Müller et al. (2015), Altarejos-García et al. (2015), Prästings et al. (2016), and Krounis (2016). A simplified application of Equation (3.8), in which the transformation model is disregarded, is included in Paper D. The transformation uncertainty, which often is significant in geotechnical applications, was recently studied in detail by Ching et al. (2016) and they demonstrated that this uncertainty component may vary in space.

3.4. Bayesian updating with additional information

3.4.1. General procedure

The Bayesian interpretation has the advantage of allowing the combination of subjective knowledge, such as expert judgement, with more objective data from measured observations. The procedure is described extensively from a civil engineer's perspective in Ang & Tang (2007).

The procedure implies that a crude prior estimation of a relevant quantity (e.g. a mechanical property) can be updated with observations of the quantity of interest to get a more accurate estimation. The connection to the observational method is easily seen: measurements during construction can be used to update preliminary design assumptions from pre-investigations or expert judgement. By reducing uncertainties, calculated p_{F} are in most cases improved. The economic value of this uncertainty reduction provides the conceptual basis for applying the observational method. The economic aspect is further elaborated in chapter 4.

In principle, gaining additional information, *Z*, implies that the calculated p_{F} should take also this new information into account. This implies an updating of Equation (3.3):

$$p_{\mathrm{F|Z}} = \int_{\Omega_{\mathrm{Z}}} f_{\mathrm{X|Z}}(\boldsymbol{x})\mathrm{d}\boldsymbol{x}\,, \tag{3.9}$$

where Ω_Z is the updated failure region making the limit state functions conditional on *Z*, and $f_{\mathrm{X|Z}}(\boldsymbol{x})$ is the updated joint probability density function given the information *Z*.

To perform the updating of $f_{\mathrm{X|Z}}(\boldsymbol{x})$, Bayes's rule (Bayes 1763)[8] may be applied:

$$f_{\mathrm{X|Z}}(\boldsymbol{x}) = \frac{L(\boldsymbol{x}) f_{\mathrm{X}}(\boldsymbol{x})}{\int L(\boldsymbol{x}) f_{\mathrm{X}}(\boldsymbol{x})\mathrm{d}\boldsymbol{x}}, \tag{3.10}$$

where $L(\boldsymbol{x})$ is the likelihood of observing *Z*, given the variable $\boldsymbol{X}$.

Applications of Bayesian updating together with the observational method and similar approaches are shown by e.g. Hachich & Vanmarcke (1983), Baecher & Ladd (1997), Stille & Holmberg (2008), Wu (2011), Zetterlund et al. (2011), Wu et al. (2014), and in Papers D, E, and F.

3.4.2. Information types and some computational aspects

New numerical information is often gained as either equality or inequality information, such that the unknown outcome of $\boldsymbol{X}$ is known to belong to some subset of the possible outcome. Equality information implies that the gained data consist of a specific measurement (e.g. measuring a particular deformation). Inequality information implies that the gained data only show that the measured parameter is below or above some specified threshold value.

In general terms, equality and inequality information, respectively, may be written as

$$Z = \{h(\boldsymbol{X}) = 0\} \tag{3.11}$$

and

$$Z = \{h(\boldsymbol{X}) \leq 0\}\,, \tag{3.12}$$

---

[8] This rule originates from an essay written by the English statistician, philosopher, and Presbyterian minister Thomas Bayes. The essay was edited and sent to the Royal Society by Richard Price after Bayes's death.

where the function $h(\boldsymbol{X})$ describes how the measured data correspond to the mechanical model. The concept is further discussed in e.g. Ditlevsen & Madsen (2007), Straub (2011), Papaioannou & Straub (2012), and Straub (2014).

When new information is provided of either equality or inequality type, the updating in Equation (3.9) becomes rather straightforward, because the explicit computation of $L(\boldsymbol{x})$ in Equation (3.10) can be avoided. The conditional $p_{\mathrm{F|Z}}$ may instead be obtained from the definition of conditional probability,

$$p_{\mathrm{F|Z}} = \frac{P(F \cap Z)}{P(Z)}, \tag{3.13}$$

because $h(\boldsymbol{X})$ can then be seen as a limit state function that describes the event Z. Thereby, Equation (3.13) can be solved with any structural re-liability method. For example, if a structure has the limit state $G_1(\boldsymbol{X}) = 0$ and Z is of inequality type, we have that

$$p_{\mathrm{F|Z}} = \frac{P(\{G_1(\boldsymbol{X}) \leq 0\} \cap \{h(\boldsymbol{X}) \leq 0\})}{P(h(\boldsymbol{X}) \leq 0)}, \tag{3.14}$$

for which the numerator is analysed as a parallel-system multiple failure mode (cf. Equation (3.21)) and the denominator as a single failure mode.
A simple example is having the inequality information from a proof-load testing of a structure, for which failure occurs when the limit state $G_1(\boldsymbol{X}) = R - S \leq 0$ (Figure 3.3a). The test shows that the strength, R, is greater than the known proof load, s_{test}. The corresponding information expressed as a limit state function is $h(\boldsymbol{X}) = s_{\text{test}} - R \leq 0$ (Figure 3.3b). With this information, $p_{\mathrm{F|Z}}$ may be evaluated with Equation (3.14). As indicated in Figure 3.3c, $p_{\mathrm{F|Z}}$ may, for the special case of this example, also be evaluated by truncating the probability distribution of R at s_{test} such that

$$p_{\mathrm{F|Z}} = P(G_1''(\boldsymbol{X}) = R_{\text{trunc}} - S \leq 0). \tag{3.15}$$

where $G_1''(\boldsymbol{X})$ is the updated limit state function. Another example of updating with inequality information is found in Paper F.

Note that the degree of uncertainty in the observation has an effect on the effectiveness of the updating procedure. For example, if there is significant

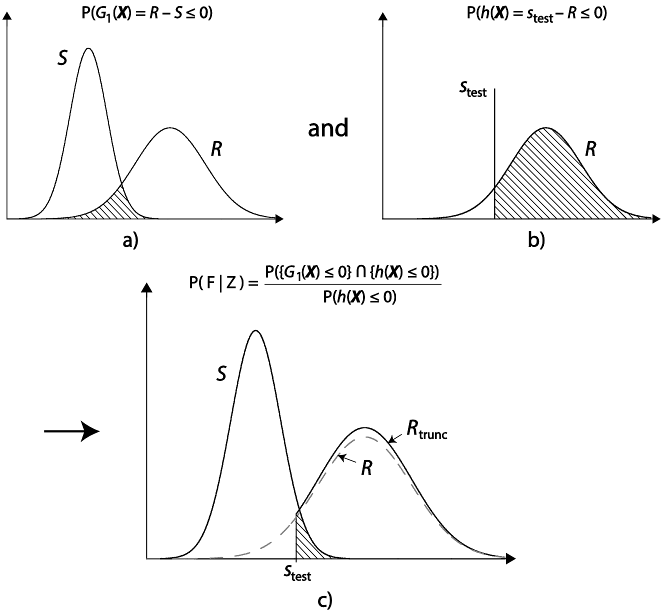

Figure 3.3. Illustration of the components of Equation (3.14). The hatched areas indicate potential failure regions of the limit states. a) Limit state of the structure. b) Limit state corresponding to the information gained from the proof-load test. c) The updated potential failure region.

measurement error in the observations, the effect of Z on $p_{\mathrm{F|Z}}$ may be limited (Hall 1988). In such cases, performing the measurements may not be worth the cost. This is an example of a decision-theoretical problem that may be analysed with the methods discussed in Chapter 4 and Paper F.

3.5. Effect of human errors

Human errors are involved in most recorded structural failures – at least partially. Melchers (2013) summarises the literature about human errors and human intervention in structural safety. The causes to structural failure because of human errors range from natural variability in task performance to ignorance of fundamental structural behaviour (“gross errors”). Despite their significant effect on structural safety, human errors are normally not accounted for in probabilistic design, even though they must be, if the reliability assessment aims to capture the reality. In fact, this as an argument for applying deterministic safety factors, because probabilistic methods tend to neglect aspects of structural safety that cannot easily be described by probabilities (Doorn & Hansson 2011).

One way to account for human errors in probabilistic design is to make a nominal interpretation of the calculated p_{F} (see section 3.2.2) and properly calibrate the design procedure, so that an appropriate safety margin for human errors is applied (Melchers 1999).

The probability of gross errors may also be reduced through the project's risk management work. For example, risk management procedures may include internal and external auditing of the design (Feng & Hudson 2011), and quality control of the executed work. A recent example of how this can be executed in practice for an excavation within sheet-pile walls is presented in Spross et al. (2015). In the presented example, the risk management work follows the procedure suggested by the Swedish Geo-technical Society (SGF 2014). However, formal procedures for com-bining risk management work with structural reliability theory are yet to be developed; Melchers (2013) outlines a few ways to approach this issue.

3.6. Methods for computing the probability of failure

3.6.1. Levels of detail

When all parameters in the limit state function, $G(\boldsymbol{X})$, have been modelled as probability distributions (or constants, if the effect of the variability is judged insignificant for the result), the p_{F} of the analysed limit state can be computed from Equation (3.3); though, the explicit computation of this integral is rarely feasible. There is, however, a number of approximate methods available for its evaluation and they are extensively described in textbooks on structural reliability theory, e.g. Melchers (1999), Nikolaidis et al. (2005), Ditlevsen & Madsen (2007), and Fenton & Griffiths (2008). The methods can be categorised into several levels, depending on their respective complexity:

- Level I methods are often referred to as semi-probabilistic. They model uncertainty with a characteristic value and a partial factor for each variable. This is a common approach in design codes, e.g. the Eurocodes.
- Level II methods model uncertainty with mean values, standard deviations, and correlation coefficients of the random parameters. The parameters are assumed to be normally distributed. An example is the first-order second-moment method (FOSM).

- Level III methods model uncertainty with the joint probability distribution function of all random parameters. Two examples are the first-order reliability method (FORM)[9] and Monte Carlo simulation.
- Level IV methods are level III methods that take the consequences of the failure into account and thereby provide a tool for cost–benefit analyses.

The categorisation of methods differs slightly from author to author in the literature. Notably, though Fenton & Griffiths (2008) define only three levels, their third level is even more complex than the fourth level listed here, as it combines Monte Carlo simulation with "sophisticated non-linear multidimension finite-element models".

In this report, two common level III methods are used: Monte Carlo simulation and FORM. They are briefly described in the following.

3.6.2. Monte Carlo simulation

In a Monte Carlo simulation, a mathematical operator containing the random variables is repeatedly calculated. For each repetition, a sample is generated from each probability distribution of the random variables, after which the limit state function, $G(\boldsymbol{X})$, is evaluated with the samples, $\hat{\boldsymbol{x}}$, representing one possible combination of the random variables. If $G(\hat{\boldsymbol{x}}) \leq 0$, this particular outcome of the random variables gives "failure". Thereby, the p_F can be calculated as the ratio of the number of repetitions causing failure and the total number of repetitions.

The accuracy of a Monte Carlo simulation depends on the number of repetitions in relation to the mean probability of failure, $\bar{p}_{\mathrm{F}}$; the larger sample, the more accurate result. Requiring a certain accuracy in terms of coefficient of variation of the p_F, the required number of repetitions, *N*, can be determined from (Ang & Tang 2007)

$$COV_{\mathrm{P(F)}} = \sqrt{\frac{1 - \bar{p}_{\mathrm{F}}}{N\,\bar{p}_{\mathrm{F}}}}. \tag{3.16}$$

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[9] In Eurocode EN 1990 (CEN 2010), FORM is referred to as a level II method. The reason is likely historical: the transformation into normal distribution that is required when applying FORM with non-normally distributed parameters is an extension of FOSM. This thesis follows the suggestion by Melchers (1999) to differentiate between FOSM and FORM because FOSM presumes normally distributed parameters and FORM does not.

3.6.3. First-order reliability method

FORM has been developed from a family of approximate methods that can be used to compute probabilities of failure. These methods are commonly referred to as “first-order second-moment methods” (FOSM), because they linearise the limit state functions (hence “first-order”) and approximate the probability distributions of the random variables with their first two statistical moments (the mean value and standard deviation). FOSM implies the calculation of the safety index, β, which relates to the probability of failure with

$$p_{\mathrm{F}} = \Phi(-\beta) = \Phi\left(-\frac{\mu_{\mathrm{G}}}{\sigma_{\mathrm{G}}}\right), \tag{3.17}$$

where Φ is the standard normal distribution function, and μ_{G} and σ_{G} are the mean and standard deviation of the limit state function, respectively. For linear limit state functions with normally distributed random variables, Equation (3.17) gives the exact probability of failure (in the Bayesian sense). In all other cases, the relation is approximate.

A significant improvement to FOSM was proposed by Hasofer & Lind (1974). By transforming all variables and the limit state function into standard normal space, they created an invariant format for the computation of the safety index. Thereby, the safety index became independent of algebraic reformulations of the limit state function.

The limitation to normal distributions was later overcome by adopting approaches that transform correlated non-normal distributions into corresponding independent normal distributions (Hohenbichler & Rackwitz 1981). Some common approaches are the Rosenblatt transformation for non-normal distributions and the Cholesky approach to create independent variables. The Hasofer-Lind format constitutes together with such transformations the coherent methodology that is generally known as FORM. Despite these improvements, it is still an approximate method. Some illustrative examples of how its accuracy is affected by distribution types and linear correlation between variables are provided by Huang & Griffiths (2011).

The basic principle of FORM is as follows: when all random variables have been transformed into independent variables in standard normal space, the limit state function is approximated with a linear hyperplane. The safety index is then defined as the shortest distance from the origin to the hyperplane. Thus, we have the minimisation problem:

$$\beta = \min_{G_{\mathrm{U}}(\boldsymbol{U}) = 0} \sqrt{\sum_{i=1}^{n} u_{\mathrm{i}}^2}\,, \tag{3.18}$$

where $G_{\mathrm{U}}(\boldsymbol{U}) = 0$ is the linearised limit state function in a standard normal space, *U*, of *n* dimensions, with correspondingly transformed variables in a vector, $\boldsymbol{U}$, and u_{i} represents coordinates on the limit state hyperplane. The set of u_{i} that satisfies Equation (3.18) is often referred to as the "design point", $\boldsymbol{u}^*$.

An important feature of FORM is the generation of sensitivity factors ("α-values"). They relate to β with

$$u_{\mathrm{i}}^* = -\,\alpha_{\mathrm{i}}\beta\,. \tag{3.19}$$

For uncorrelated random variables, the individual sensitivity factors α_{i} can be interpreted as relative measures of how sensitive the limit state function is to changes in the respective variable u_{i}. Sensitivity factors are also useful in determining the correlation between load cases or failure modes, as shown in Equation (3.22).

Today, computer software may compute the safety index and the related probability of failure, applying the Hasofer–Lind approach together with the complete set of available transformations when necessary. In the work with this research project, I have used the commercial software Comrel 8.10 (RCP).

3.7. System reliability

3.7.1. The joint effect of several failure modes

In a complete structural reliability analysis, the joint effect of several failure modes or load cases must often be considered. Sometimes it is beneficial to consider each structural design problem separately and analyse their interaction with a system approach. In general terms, the system probability of failure can be assessed with Equation (3.3).

Systems can be idealised into two types: series and parallel systems. An important aspect of system analysis is how the various structural components, load cases, and failure modes are combined in series and parallel subsystems. For complex systems, the overall safety can be very hard to assess properly, for example because of correlation effects or possible redistribution of the load when one component fails. It is therefore important to recognise that the calculated results relate to an idealised system that may differ significantly from the real world.

The difference between the theoretical model and the real world should, ideally, only consist of a random scatter caused by the minor factors that were not taken into account in the model. However, in practice, systematic effects from input parameters such as geometrical considerations are often making this scatter non-random (Phoon et al. 2016).

3.7.2. Probability of failure for series and parallel systems

The essence of a system reliability analysis concerns the computation of the system probability of failure. For a series system of *n* components (or load cases or failure modes), Equation (3.3) can be rewritten as (Hohenbichler & Rackwitz 1983)

$$p_{\mathrm{F,s}} = P\left[\bigcup_{i=1}^{n} G_{\mathrm{i}}(\boldsymbol{X}) \leq 0\right] = 1 - \Phi_{\mathrm{n}}(\boldsymbol{\beta};\, \boldsymbol{\rho})\,, \tag{3.20}$$

where $p_{\mathrm{F,s}}$ is the probability of failure of a series system, $\boldsymbol{\beta}$ is a vector of safety indices related to each individual component, $\boldsymbol{\rho}$ is a matrix giving the correlation between the components, and Φ_{n} is the standardised normal distribution function in *n* dimensions. Similarly, the equation for a parallel system is

$$p_{\mathrm{F,p}} = P\left[\bigcap_{i=1}^{n} G_{\mathrm{i}}(\boldsymbol{X}) \leq 0\right] = \Phi_{\mathrm{n}}(-\boldsymbol{\beta};\, \boldsymbol{\rho})\,. \tag{3.21}$$

The statistical correlation between the limit states is dependent on to which degree the limit states include the same random variables: the correlation coefficient matrix of size $n \times n$ is given by

$$\boldsymbol{\rho} = \left[\rho_{ij}\right] = \boldsymbol{\alpha}_{\mathrm{i}}^{\mathrm{T}} \boldsymbol{\alpha}_{\mathrm{j}} \tag{3.22}$$

for each combination of two limit states *i* and *j*. In Equation (3.22), $\boldsymbol{\alpha}_{\mathrm{i}}$ and $\boldsymbol{\alpha}_{\mathrm{j}}$ are vectors of sensitivity factors from the respective limit state analysis, as defined in Equation (3.19).

As the multi-dimensional standardised normal distribution function Φ_{n} requires a substantial amount of numerical calculation when many (>4) limit states are involved, it is often convenient to approximate the probability of failure with bounds. Simple bounds (Cornell 1967) frame the result with the uncorrelated and fully correlated cases, while Ditlevsen bounds (Ditlevsen 1979) produces narrower bounds.

For an example of a system reliability analysis, the reader is referred to Paper B, in which the system reliability of two load cases (sliding failure of a concrete dam given either normal or exceptional uplift pressure) is evaluated numerically from the bivariate standardised normal distribution function. The corresponding simple bounds are also presented.

3.7.3. Conditional probabilities of failure

Many limit states are conditional on a certain event. One example is extreme load cases that only affect the structure rarely. As probabilities of failure usually are given in the unit “per year”, the return period, *T*, of the event causing the limit state must be included in the analysis to convert the limit states to comparable units. Then, p_{F} can be seen as a function of *T*. One approach is to use the definition of conditional probability:

$$p_{\mathrm{F}}(T) = P(F \mid E)P(E) = \Phi(-\beta)\frac{1}{T}, \tag{3.23}$$

where $P(F \mid E)$ indicates the probability of failure of the structure given the occurrence of event *E*. The approach is used in Paper B to account for the extreme load case of exceptional uplift pressure caused by clogged drains.

3.8. Probabilistic safety analyses in dam engineering

The probabilistic approach to assess structural safety in dam engineering has gained increasing attention during the last decade. In dam engineering, probabilistic analyses are usually associated with a quantitative risk analysis, for which modern guidelines have been published in several countries (ANCOLD 2003, USBR 2011, SPANCOLD 2012, FERC 2016). An implication of these guidelines is that the decision making on dam safety is turning to become risk-informed in these countries. In Sweden, there is currently ongoing work to develop reliability-based design guidelines for concrete dams (Westberg Wilde & Johansson 2015).

A collection of recent studies related to probabilistic dam safety analyses are presented in the following. Jeppsson (2003) studied how reliability theory can be used to assess the safety and residual service life of damaged concrete structures, such as dams. Bernstone et al. (2009) proposed applications of piezometric pressure measurements in safety assessments and management of concrete dams. Some findings of Jeppsson (2003) and Bernstone et al. (2009) on the use of piezometric pressure measurements are further developed and discussed in Paper B.

Westberg (2010) used a system approach to analyse the structural reliability of concrete dams in the context of risk management. A case study from this project is published as Westberg Wilde & Johansson (2013). A similar approach is taken by Peyras et al. (2012). Altarejos-García et al. (2012) made an extensive study of how the choice of both reliability model level (section 3.6.1) and behaviour model for the dam and foundation affects the calculated safety. Su et al. (2013) included progressive deterioration functions into a probabilistic system analysis of an existing concrete dam to assess its remaining service life. Klun et al. (2016) promoted the use of the response surface method in safety analyses of hydraulic structures.

In a recent Ph.D. project, Krounis (2016) studied how cohesion in the concrete–rock interface can be accounted for in probabilistic sliding stability reassessments. This work was also published as Krounis et al. (2016).

3.9. Probabilistic safety analyses in underground excavation in rock

The development of reliability-based design of structures in soil in the 1970s and 1980s – Wu & Kraft (1970), Alonso (1976), Vanmarcke (1980), and Olsson (1986), to mention a few – was later followed by the same development in underground rock engineering. An early contribution to probabilistic rock engineering design is the Ph.D. thesis of Kohno (1989), which discusses how probabilistic methods can be used to manage uncertainties in pre-investigations, design, and operation of tunnels.

Early work was also made by Laso et al. (1995), who introduced probabilistic methods for tunnel support design with the ground–support interaction diagram; though, the discussed application was tunnels in soil. Rock tunnel applications and various computational aspects were discussed by Hoek (1998) and, later, by Li & Low (2010), and Lü et al. (2013). Griffiths et al. (2002) studied the influence of spatially varying strength on underground pillar stability by combining random field theory with finite element modelling in a Monte Carlo framework.

Contributions during the last decade include Lü & Low (2011) who used the response surface method to bridge the gap in rock engineering between non-linear numerical methods and probabilistic analyses, and Su et al. (2011), who also addressed the non-linear behaviour of rock, but suggested a methodology to evaluate implicit limit state functions. Nomi-kos & Sofianos (2011) proposed analytical solutions to the probability distributions of some safety factors used in underground excavation.

In recent years, the research contribution of Langford's (2013) Ph.D. project on reliability methods for design of underground structures have resulted in a number of publications. To mention a few, Langford & Diederichs (2013) suggested a reliability-based design approach for tunnel lining combining finite element simulation with the point estimate method; Langford & Diederichs (2015a) suggested regression methods to quantify the uncertainty in rock mass strength using Hoek–Brown envelopes; and Langford & Diederichs (2015b) suggested a reliability-based design approach to evaluate the excavation response and support performance in brittle ground.

Reliability-based approaches also gained attention at workshops arranged as parts of the EUROCK symposia in 2014 and 2015. The workshop in 2014 discussed the applicability of Eurocode 7 to rock engineering design. In terms of reliability-based approaches, the discussion was mainly focused on the partial factor method. For example, Bedi & Orr (2014) discussed and questioned the applicability of partial factors to rock engineering design because of significant epistemic uncertainties, and Bozorgzadeh & Harrison (2014) discussed how characteristic values for the strength of anisotropic rock can be derived. Paper D was also presented at this workshop.

The workshop in 2015 was themed "Design practices for the 21st century"; though, there was a strong emphasis on reliability-based design (Harrison 2015). The workshop contributions included discussions of how to establish limit state functions for progressive rock slope failures (Gambino & Harrison 2015) and how to manage the parameter variability when designing underground openings (El Matarawi & Harrison 2015; Paper E).

4. BAYESIAN STATISTICAL DECISION THEORY

> *"We believe that without the Bayesian approach, decisions under uncertainty have been and will remain essentially arbitrary, as evidenced by the fact that, in most statistical practice, consequences and performance characteristics receive mere lip service while decisions are actually made by treating the numbers 0.05 and 0.95 with the same superstitious awe that is usually reserved for the number 13."*
>
> – Howard Raiffa & Robert Schleifer (1961).

4.1. Introduction

Probabilistic analyses are all very well, but in the end, the engineer must come to a decision. The decision may be to increase the maintenance frequency of a concrete dam drainage system, to excavate a certain tunnel radius, or to go with a certain design approach. To allow for rational construction methods and sustainable use of resources, these decisions require a sound basis that minimises both the long-term cost and the effect on the environment.

This chapter is not meant to cover all aspects of Bayesian statistical decision theory; for that, there are excellent, comprehensive textbooks such as Raiffa & Schlaifer (1961) and Benjamin & Cornell (1970). This chapter presents only the decision-theoretic concepts applied in Paper F.

4.2. The decision problem

4.2.1. Background

How to make an optimal choice when uncertainty is present has been discussed for centuries. An early example is Pascal's wager[10], which was formulated in 1670. Its

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[10] The wager infers that all humans must bet on that God either does or does not exist. According to Pascal, the rational decision is to bet on God's existence (if it has a nonzero probability) and to be a good

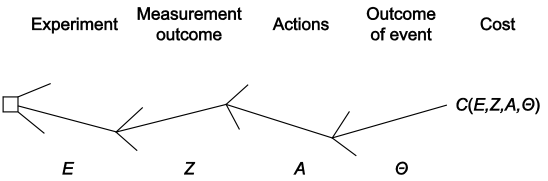

Figure 4.1. The four phases of a decision tree.

conclusion is that the rational decision maker should identify and evaluate the probability and value of every possible outcome of the available actions and then take the action that maximises the expected value.

The decision analyses in this research project are based on the expected utility hypothesis proposed by von Neumann & Morgenstern (1944), but with some simplifications. The optimal decision is still the one that maximises the expected utility, $\mathrm{E}(U)$, but it is assumed that all utility can be expressed as monetary costs, C, and that utility is directly proportional to C. This makes the decision maker risk-neutral (in contrast, a risk-averse decision maker would prefer more certain, but smaller, gain to higher expected gain associated with high uncertainty). The optimal risk-neutral decision minimises the expected cost, $\mathrm{E}(C)$.

4.2.2. Finding the optimal design

The decision problem discussed in this research project is how to identify the structural design, measurements, and contingency actions that correspond to the minimised $\mathrm{E}(C)$ among all possible design considerations, where the observational method is one available option. This is known as a pre-posterior decision analysis. In principle, the analysis compares the expected utilities (or costs) of all possible design and execution alternatives. To visualise the alternatives, a decision tree is commonly used (Figure 4.1). In the context of structural design, the *possible* course of events that the decision tree illustrates consists of the following four phases:

1. A decision to perform an “experiment” from the set of available experiments, $\mathbb{E} = \{e_1, \dots, e_\mathrm{n}\}$, to gain additional information, Z (cf. section 3.4). In the

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(*cont'd*) Christian, because the possible gain of doing so is infinite happiness in eternity and the cost of being a good Christian is only finite. The other alternative – betting against God’s existence – implies risking an eternity in hell, which no Earthly, ungodly pleasures can outweigh.

context of structural design, the classic denotation “experiment” that commonly is used in decision analysis should be interpreted widely, so this concept includes any design consideration.

2. A measurement result, z_i, which occurs with the probability $\mathrm{P}(z_\mathrm{i}|\ \mathbb{E})$. In case the design does not include any measurement, this phase becomes a dummy.
3. A decision based on z_i to take an action from the set of available actions, $\mathbb{A} = \{a_1, \dots, a_\mathrm{n}\}$.
4. Unveiling of the “state of the world”, θ_j, which in this context is failure or non-failure of the structure conditional on the executed design, the measurement result, and taken actions. Thereby, θ_j occurs with the conditional probability $\mathrm{P}(\theta_\mathrm{j}|\mathbb{E},Z,\mathbb{A})$.

Each θ_j is associated with a utility in terms of a cost, $C_\mathrm{j}(\mathbb{E},Z,\mathbb{A},\theta_\mathrm{j})$. Performing the pre-posterior analysis, the expected cost of each design combination d_k in the set $\mathbb{D} = \{\mathbb{E}, \mathbb{A}\}$ is given by weighing the costs in accordance to their respective probability of occurrence:

$$\mathrm{E}(C_\mathrm{k}|\mathbb{D}_\mathrm{k}) = \sum_{j=1}^{n} C_\mathrm{j}\big(\mathbb{E}, Z, \mathbb{A}, \theta_\mathrm{j}\big)\mathrm{P}\big(\theta_\mathrm{j}|\mathbb{E}, Z, \mathbb{A}\big)\,. \tag{4.1}$$

This allows comparison of all possible design options in $\mathbb{D}$. The optimisation problem of finding the most favourable (i.e., most economic) design alternative that should be prepared, $\mathbb{D}_\mathrm{opt}$, is given by

$$\mathbb{D}_\mathrm{opt} = \arg\min_{\mathbb{D}} \sum_{j=1}^{n} C_\mathrm{j}\big(\mathbb{E}, Z, \mathbb{A}, \theta_\mathrm{j}\big)\mathrm{P}\big(\theta_\mathrm{j}|\mathbb{E}, Z, \mathbb{A}\big)\,. \tag{4.2}$$

It follows that the expected cost associated with this optimal decision is given by evaluating Equation (4.1) for the optimal design alternative:

$$\mathrm{E}\big(C_\mathrm{opt}\big) = \sum_{j=1}^{n} C_\mathrm{j}\big(e_\mathrm{opt}, Z, a_\mathrm{opt}, \theta_\mathrm{j}\big)\mathrm{P}\big(\theta_\mathrm{j}|e_\mathrm{opt}, Z, a_\mathrm{opt}\big)\,. \tag{4.3}$$

4.3. Bayesian decision theory in rock engineering

Although introduced to rock engineering already in the 1970s (Einstein et al. 1978), application of Bayesian decision theory has not been widely studied in this field. Some notable exceptions are Einstein (1996), who discussed how to include the effect of uncertainties in the decision making in rock engineering projects, and Sturk et al. (1996), who showed how formal decision analysis tools can be applied in a tunnelling project. Practical application of decision analysis in tunnel engineering was also discussed by Isaksson & Stille (2005) and Karam et al. (2007a, 2007b). Recently, in her doctoral thesis, Zetterlund (2014) thoroughly discussed the application of value-of-information analysis to decision making in tunnelling projects. Her work was also published in journals (Zetterlund et al. 2011, Zetterlund et al. 2015).

5. SUMMARY OF RESEARCH PAPERS

> *"What is often forgotten is that the observational method is an adjunct to design, not a substitute for it."*
>
> – Ralph B. Peck (NGI 2000).

5.1. Paper A

> Spross, J. & Larsson, S. 2014. On the observational method for groundwater control in the Northern Link tunnel project, Stockholm, Sweden. *Bulletin of Engineering Geology and the Environment, 73*(2), 401–408.

This journal paper presents a case study on how the groundwater control in the Northern Link tunnel project in Stockholm was carried out to comply with the demand for low impact on the surroundings. The adopted procedure is discussed in relation to the potential application of the observational method, one Eurocode principle at a time. Although the actual implementation mainly agreed with the definition of the observational method, some deviations were found. For example, the range of possible groundwater inflow was never assessed, and consequently it was not shown before construction is started that the groundwater inflow likely would be less than the acceptable limits. Still, the paper concludes that adopting the observational method for groundwater control would mostly imply a formalisation of today's procedures.

5.2. Paper B

> Spross, J., Johansson, F. & Larsson, S. 2014. On the use of pore pressure measurements in safety reassessments of concrete dams founded on rock. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 8*(2), 117–128.

This journal paper discusses the merit of using measured pore pressure data in safety reassessments of concrete dams founded on rock. The performed reliability analysis combines the measured data with the probability of an extreme uplift increase due to either malfunctioning drainage system (Figure 5.1), deteriorated grout curtain, or both, in a system analysis. The result makes it evident that the probability of sliding failure of the dam is closely related to how often an extreme increase in uplift occurs. The effect is exemplified with a case study of a spillway monolith in a Swedish concrete dam. The paper concludes that to allow the use of measured pore pressure in a safety reassessment, it must be ensured that the probability of an extreme uplift increase remains sufficiently small. This could potentially be achieved with an extensive monitoring program, although it would be difficult to prove that the monitoring is extensive enough. However, a proper monitoring program will be beneficial to the dam safety anyhow, by reducing the probability of the extreme event occurring. The implications of these findings on the applicability of the observational method for decision-making on stability-enhancing modi-fications of dams are discussed in section 6.2.

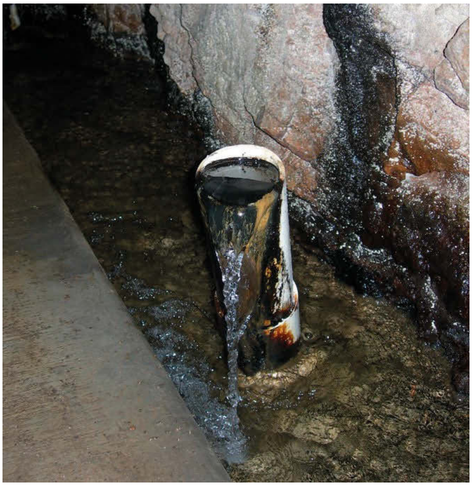

Figure 5.1. Functional drain in a drainage gallery under a gravity dam. (Photo: © Johan Spross)

5.3. Paper C

> Spross, J., Johansson, F., Uotinen, L. K. T. & Rafi, J. Y. 2016. Using observational method to manage safety aspects of remedial grouting of concrete dam foundations. *Geotechnical and Geological Engineering, 34*(5), 1613–1630.

As concrete dams age, the need for remedial grouting to reduce the seepage and uplift pressure in the rock foundations under them increases. Based on a case study of a Swedish dam with very low calculated safety against sliding, this journal paper discusses the application of the observational method (as defined in Eurocode 7) to manage safety aspects during remedial grouting. The studied case was complex in that grouting works posed the risk of causing increased uplift pressure, which could have induced sliding failure along a shallow, persistent, horizontal rock joint in the foundation. The approach applied in the studied case mainly followed the principles of the observational method, except in some highly significant safety aspects for which alternative procedures are suggested and discussed. Implementing these procedures along with the observational method offers a coherent framework to manage the safety aspects of the remedial grouting of concrete dam foundations that is in line with modern risk-informed dam safety policies.

5.4. Paper D

> Spross, J., Johansson, F., Stille, H. & Larsson, S. 2014. Towards an improved observational method. In: L. R. Alejano, A. Perucho, C. Olalla & R. Jiménez (eds.), *EUROCK 2014: Rock Engineering and Rock Mechanics – Structures in and on Rock Masses, Vigo, Spain, 26–29 May 2014*. London: Taylor & Francis group, 1435–1440.

This conference paper addresses an issue reported by for example Powderham (2002): concerns regarding low safety margins associated with the observational method. The concerns per se are not surprising, because the whole point of the observational method is to not have to apply the conservative safety factors of conventional design. Therefore, the authors argue that the observational method should be improved by adding a requirement for an appropriate safety margin of the final structure, taking into account any extra support from applied contingency actions. Following the existing principles, the safety margin will at best be arbitrary, but it might also be completely unknown.

The paper outlines a framework for how the safety margin can be estimated. It is exemplified with a safety analysis of a fictive square rock pillar. The paper discusses the compatibility with the observational method. Good agreement was found; however, more development is needed to properly take any applied contingency actions into account in the safety assessment. The framework was further developed in Papers E and F.

5.5. Paper E

> Bjureland, W., Spross, J., Johansson, F. & Stille, H. 2015. Some aspects of reliability-based design for tunnels using observa-tional method (EC7). In: W. Schubert & A. Kluckner (eds.), *Proceedings of the workshop Design practices for the 21st Century at EUROCK 2015 & 64th Geomechanics Colloquium, Salzburg, 7 October 2015*. Salzburg: ÖGG, 23–29.

This conference paper further discusses the compatibility of the observational method with reliability-based design that was the topic of Paper D. The paper outlines a possible design methodology based on the ground reaction curve concept for axisymmetric circular rock tunnels in hydrostatic in-situ pressure. The focus of the paper is showing how the methodology fulfils the requirements on the observational method in Eurocode 7. The procedure implies observing the rock mass behaviour during the course of excavation and from this predicting the final deformation of the tunnel. Then, contingency actions can be put into operation before the target reliability is violated.

5.6. Paper F

> Spross, J. & Johansson, F. 2016. When is the observational method in geotechnical engineering favourable? Submitted to *Structural Safety*.

Based on the discussions in Paper D regarding safety margin when applying the observational method, this paper introduces a reliability constraint on the observational method and combines it with Bayesian statistical decision theory (Chapter 4). The outcome is a probabilistic optimization methodology that aids the decision-making engineer in choosing between the observational method and conventional design. The methodology suggests an optimal design after comparing the expected utilities of the considered design options. A major feature of the methodology is that it allows the limits of acceptable behaviour to be established based on $p_{\mathrm{F,T}}$.

The methodology is illustrated with a practical example, in which a geotechnical engineer evaluates whether the observational method may be favourable in the design of a rock pillar. It is concluded that the methodology may prove to be a valuable tool for decision-making engineers' everyday work with managing risks in geotechnical projects

6. DISCUSSION

> *"Theory and calculation are not substitute for judgment, but are the basis for sounder judgment."*
>
> – Ralph B. Peck (NGI 2000).

6.1. Can the observational method be simple?

Applying the observational method inevitably implies analysis and interpretation of measurements or other types of observations. In many cases, this requires statistical tools. Depending on how much emphasis that is put on objectivity in the analysis (as opposed to the degree of subjectively applied engineering judgement), the set of statistical tools can be more or less sophisticated. In light of the Eurocode definition of the observational method and the need to include measurements in the design work, I believe that a probabilistic design approach with a Bayesian view on statistics is reasonable, as argued for in Chapter 3. However, this approach is by no means the easiest way to go.

Peck, the originator of the observational method himself, has in papers with compelling titles such as "Where Has All the Judgment Gone?" and "The Observational Method Can Be Simple" (Peck 1980, 2001) argued for less focus on complex theory and "exotic remote-reading sensors", in favour of qualitative judgement based on only the most elemental theory. That is the essence of the observational method, according to Peck.

Even though reliability analysis and Bayesian statistics can seem intimidating, it has the advantage of accepting both expert judgement and observations or measurements in the analyses. As outlined in section 3.4, a prior assumption based on expert judgement may be updated with measurement data. This implies that some of the judgement missed by Peck in today's engineering practice can be taken into account formally *together* with more objective measurements. In addition, the complex nature of today's projects, which to a higher degree must consider the effect on nearby structures, environmental aspects, work conditions, etc., points in favour of more elaborate design methods. In fact, through the Eurocode definition of the observational method and, in particular, the requirement to show “that there is an acceptable probability that the actual behaviour will be within the acceptable limits”, steps have already been taken towards a probabilistic framework. To show that unacceptable behaviour is sufficiently unlikely is hard to do only by judgement. Though, as discussed in Papers A and C and in section 6.3 in the following, deviations from this Eurocode requirement may at times be acceptable, in my opinion, as long as the structural safety is not threatened.

Nevertheless, I agree with Peck in that judgement is still needed to select appropriate parameters for calculations and to check the result, no matter how elaborate the method is. I believe, however, that this can be strengthened by providing robust and practical guidelines that emphasise this aspect of the observational method.

6.2. Predictability of future behaviour

Before applying the observational method, engineering judgement plays a crucial role also in choosing the control parameter to be observed during construction; that is, what can be inferred from the measured data? The conclusion of the case study in Paper B highlights the importance of analysing this thoroughly. Basing a stability assessment of an existing concrete dam on previously measured uplift pressures may give a false impression of satisfactory structural safety, unless the probability of increased uplift pressure caused by clogged drains is accounted for by other means. Consequently, if the measurement data are incapable of predicting the future behaviour of the control parameter, the measurements must not be used for this purpose, as alarm limits would be troublesome to establish to give sufficient time for contingency actions before failure occurs.

Unfortunately, the need for predictability in the control parameter has implications on the working hypothesis that the observational method may be a suitable tool when stability-enhancing modifications of existing concrete dams are considered (section 2.7). If measurements of piezometric pressure cannot predict the long-term future uplift pressure under the dam, the observational method is not suitable for this type of problem. The reason is that if the uplift pressure would increase fast, there would not be enough time to install the stability-enhancing modifications. The importance of considering this lead time is further discussed in sec-tion 6.4.

The issue of low predictability also applies to structures with brittle failure, as such failures may be hard to predict. In such cases, it may be more rational to design with other methods than the observational method, even if the Eurocode statement that "prediction of geotechnical behaviour is difficult" holds true.

6.3. On the principles in Eurocode 7

Eurocode 7 (CEN 2004) states explicitly that all clauses preceded by "P" are "Principles", for which there is no alternative. Consequently, to comply with the Eurocode, the engineer must follow the clauses of the observational method strictly. Clearly, Peck's (1969) freer definition – "the degree to which all these steps can be followed depends on the nature and complexity of the work" – has been tightened up, which implies less acceptance of engineering judgement. The inflexible definition of the Eurocode therefore reduces the number of possible cases where the observational method is applicable.

The second requirement – showing that the geotechnical behaviour with a sufficient probability will be within the acceptable limits – is particularly difficult to fulfil. In the case study of Paper A, for example, the required analysis would have proved so complicated that existing tools were not enough. If the observational method had been intended to use formally, this inflexibility would have implied a real challenge. As the tunnel studied in Paper A was built successfully with a less strictly defined "observational approach", one could argue that such approaches are good enough for many applications. A similar argument is made in Paper C. In that case, the contingency actions were relatively inexpensive, which made the economic risk small if they would be needed often. In addition, the cost was, to some degree, subordinate to the importance of the project. Therefore, I suggest that deviations from the second requirement of the second principle should be allowable, if the unsatisfactory behaviour is of less serious consequence.

The two cases in Paper A and Paper C differ, however, from when there are other design methods available in addition to the observational method. If the probability of having to put contingency actions into operation is virtually unknown, it becomes more difficult to find the more favourable design method. To make best use of the observational method, also the second requirement must therefore be satisfied.

As noted in section 2.5, neither Eurocode 7 nor the available guidelines for its application currently put emphasis on the structural safety aspect of the observational method. In Paper D, it was therefore suggested that Eurocode 7, in addition to its current principles, also should require an appropriate safety margin for the final structure. Although the requirement to establish limits of acceptable behaviour implicitly may be interpreted as a requirement to establish a safety margin, I believe that the safety considerations deserve more attention. To strengthen the observational method in Eurocode 7, a new principle is suggested to be added: a requirement to show that the completed structure is sufficiently safe. Putting a reliability constraint on the observational method in accordance to the methodology presented in Paper F would be one way to satisfy such a requirement.

6.4. Alarm limits and lead times

The advantage of putting a reliability constraint on the observational method is clear from the results of Paper F: it allows limits of acceptable behaviour (i.e., the alarm limits for when to put contingency actions into operation) to be established based on considerations of the structural safety. The procedure suggests that limits of acceptable behaviour are established so that p_F is acceptably low (i.e., less than $p_{F,T}$) as long as the limits are not exceeded (Figure 6.1). The observant may object that this implies that if the alarm limit is exceeded, so is also the target probability, which should not be acceptable. In fact, this holds true for some cases – however, not for the example case in Paper F.

The difference between the acceptable and unacceptable situations lies in whether the measurement data are used to assess a future behaviour or only the current situation. An assessment of future behaviour is made in

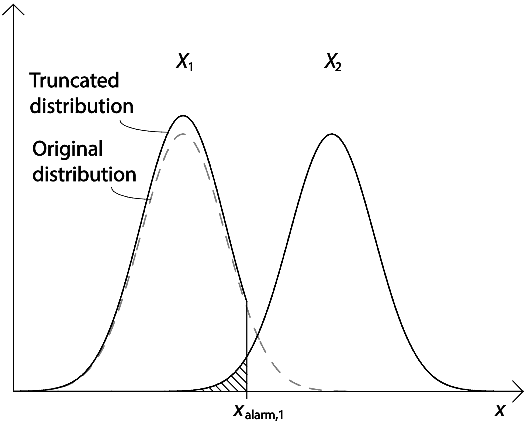

Figure 6.1. To ensure the structural safety, alarm limits should be established so that p_F is acceptable as long as the measured value (x_1) falls below the alarm limit (i.e. potential failure corresponds to the hatched area). The considered limit state is $G = X_2 - X_1$.

Paper F, where deformation measurements in a sequential excavation are used to *predict* the final deformation of a rock pillar and the corresponding alarm limit has been defined for this prediction. Because of the sequential procedure, the decision maker can put the contingency action into operation before the final excavation has been conducted. Thus, there is no risk of violating the $p_{\mathrm{F,T}}$, because the expected unacceptable deformation never occurs.

An assessment of the current situation only may be exemplified with the measurements of uplift pressure during remedial grouting of a dam foundation in Paper C. In this case, the establishment of allowable maximum uplift pressure must account for the lead time of the contingency action to drill relief wells to reduce the pressure, so that the uplift pressure increase can be stopped *before* the required safety margin is violated. The concept is illustrated in Paper C, section 4.1.1.

Note how the case in Paper C differs from the measured piezometric pressure not deemed suitable as a control parameter for the observational method in Paper B (discussed in section 6.2). The difference lies in the lead time between the considered contingency actions. In the remedial grouting case of Paper C, relief wells could be drilled quickly, while the installation of stability-enhancing modifications of Paper B may take longer time than the available margin between the alarm limit and the limit state would allow. Arguably, if the dam owner could show that the planned contingency actions can be put into operation before a sudden uplift pressure increase threatened the dam stability, the observational method would be applicable also for the case in Paper B. The unpredictable nature of the uplift pressure makes such analyses very difficult, however.

Comparing the different situations in Papers B, C, and F, it is clear that the designer must carefully analyse which situation is present before establishing the alarm limits.

6.5. Alarm limits and limit states

The establishment of limits of acceptable behaviour also requires a clear definition of failure, i.e., the unsatisfactory behaviour. For many structures in soil, the unsatisfactory behaviour can easily be described with a computable limit state function consisting of a bearing capacity and a load effect. However, in rock engineering, this is often more difficult.

In some cases, the unsatisfactory behaviour may be instability caused by complex ground behaviour – or even combinations of two or more behaviour types – that is difficult to accurately describe with a limit state function. For example, failure involving flowing water may give this problem (Palmström & Stille 2007). Establishing limit state functions has also proved challenging for progressive rock slope failure (Gambino & Harrison 2015) and for rock–support interaction problems, such as support of underground openings (Lü et al. 2013, El Matarawi & Harrison 2015, Paper E); though, some of the referred papers do present suggestions.

Notably, the suggested limit state functions for underground openings all require an assumption of the "maximum allowable strain" of the rock mass. This is a significant limitation, as the discussed values for this parameter range from 1% for minor instability problems up to as high as 5% for extreme cases of squeezing (Sakurai 1997, Hoek 2001, Lü et al. 2013). As a consequence of this epistemic uncertainty, establishing the alarm limit corresponding to violation of the maximum allowable strain of the rock mass becomes a challenge, unless it is done very conservatively.

A way forward may be found in Gambino & Harrison's (2015) discussion on how to define ultimate and serviceability limit states for rock slope instability. Could, possibly, minor instability problems in the rock mass (with strains in the range of, say, 1–2%) be regarded as a violation of a serviceability limit state, rather than an ultimate limit state? The advantage is that violation of serviceability limit states is more acceptable, which gives less conservative alarm limits. The ultimate limit state would then be reserved for more serious instability problems associated with larger strain and lower $p_{\mathrm{F,T}}$. The same concept could possibly also be applied to the deformation of tunnel support linings.

Though, to complicate the matter further, what $p_{\mathrm{F,T}}$ the society should accept in serviceability and ultimate limit states is yet another topic that needs more research. But this is not an issue limited to rock engineering applications only; it extends to all geotechnical design, see e.g. Fenton et al. (2015) and Fenton et al. (2016).

7. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

> *"Translating the findings of our research into simple concepts and procedures for the guidance of the practicing engineer is, in my opinion, a duty and worthy activity of our profession."*
>
> – Ralph B. Peck (NGI 2000).

7.1. The past 20 years in retrospect

Looking back upon the Géotechnique symposium on the observational method that was held at the 25th anniversary of Peck's 1969 paper, it is obvious that many of the concerns that were discussed 20 years ago still remain. In *The Way Forward*, Powderham & Nicholson (1996) set up the following objectives for future work based on the symposium discussion. In the next section, the findings of the research project are put in relation to these objectives. It can be seen that my work, in fact, addresses most of them.

a) "Establish a clear definition of method including objectives, procedures and terms, with a clear emphasis on safety.
b) Increase awareness of the method's potential and benefits, particularly to clients, contractors and regulatory bodies.
c) Remove contractual constraints.
d) Identify potential for wider use.
e) Initiate focused research projects.
f) Improve performance and interpretation of instrumentation systems.
g) Establish extensive database of case histories."

7.2. Conclusions

7.2.1. Probabilistic framework for the observational method

This report discusses how and when to apply the observational method in rock engineering, focusing in particular on how to ensure the structural safety when using the method, as suggested in objective (a). Paper F presents a probabilistic framework for the observational method. Combining reliability-based design with Bayesian statistical decision theory, a methodology that allows decision makers to compare the merits of the observational method with that of conventional design was developed. In addition, Paper F shows how limits of acceptable behaviour can be established based on an accepted target probability of failure of the structure. Additional contributions to solving how to consider structural safety when establishing alarm limits are found in Paper C.

7.2.2. Applicability of the Eurocode 7 definition

The principles defining the observational method in Eurocode 7 are thoroughly discussed both in this summarising essay and in the research papers. These discussions are also related to objective (a). In particular, the principle that requires showing that the geotechnical behaviour with a sufficient probability is within the acceptable limits is questioned. I found that this requirement occasionally is too strict; in my opinion, not fulfilling this requirement should be acceptable if the construction procedure allows extensive use of the prepared contingency actions so that structural safety is not threatened, and the decision maker is prepared to take the associated economic risk.

The lack of an explicit requirement in Eurocode 7 to show that the completed structure satisfies the society’s safety criteria is also discussed. It was found that adding such a requirement would strengthen the observational method. Applying the methodology presented in Paper F provides one way of showing satisfactory structural safety.

7.2.3. Predictability of control parameters

Regarding objective (f), this report discusses the interpretation of measurement data and, in particular, how the nature of the observed parameters affects the applicability of the observational method. From Paper B, the predictability of the control parameter was identified as a crucial aspect. If continuous measurements are unable to predict the future behaviour, because of possible changes in the surrounding conditions, the measurement data can provide a false sense of safety, which potentially could have serious consequences. The sound judgement of an experienced engineer is therefore of vital importance when the observational method is applied.

7.2.4. Other contributions

The research project also addresses objective (g) by providing case studies of observational method applications in the research papers, objective (d) by suggesting remedial grouting of a concrete dam foundations as a new application, and objective (b) and (e) by being a part of a research project that has been financed by the industry and focused on the observational method.

7.3. Suggestions for future work

Based on the findings of this research project, I suggest the following objectives for future work:

- Improve the applicability of the reliability framework developed for the observational method in Paper F. Recommendations for application in practice are needed, along with illustrative calculation examples and documented case studies. This includes the method's compatibility with numerical modelling, which was not within the scope of this project. The framework could possibly also be extended to consider planned maintenance and long-term monitoring already in the design of new structures, in order to minimise the life cycle cost.
- Define principles for how calculable limit states may be defined with respect to the expected ground behaviour in underground excavation. Toward this end, further studies are also needed of how to estimate the probability density functions of the parameters that affect the limit state.
- Develop a methodology for how to apply the observational method to long-term monitoring of existing structures. This may be a valuable tool in assessments of how they satisfy structural safety criteria.
- Further study the merits of applying the observational method from a risk management perspective. In this report, I have mainly considered the observational method a design tool, but the active design approach with extensive measurements may have other merits, such as identifying human errors in the construction process more easily or giving a better chance of alerting before unpredicted events.

- Suggest and work toward an updated definition of the observational method in Eurocode 7. The new definition should clearly acknowledge the structural safety aspect of observational method application.

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