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Slutrapport

Mats Tidlund

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Doctoral Thesis in Civil and Architectural Engineering

Geotechnical risk management using the observational method

MATS TIDLUND

Stockholm, Sweden 2021

Geotechnical risk management using the observational method

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Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy at 1.00 p.m. on the 9th of June 2021 in Kollegiesalen, Brinellvägen 8, KTH, Stockholm.

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Abstract

There have been many cost overruns, time delays and quality problems reported from geotechnical engineering projects around the world during recent decades. Many of the reported problems are associated with risks related to the geotechnical conditions. To achieve a safe and cost-effective project with the desired quality, it is vital to adequately manage the geotechnical risks.

The management of geotechnical risks includes a prediction of the geotechnical behavior. When it is difficult to predict the geotechnical behavior, the European design code, Eurocode 7, suggests the application of the observational method to verify the design. The main principle of this method is the use of observations and predefined measures to modify the design to comply with actual geotechnical conditions. Earlier research suggests that the observational method has the potential to manage geotechnical risks successfully, but the lack of guidelines related to its implementation has restricted the use of the method.

The aim of this thesis is to enable a successful management of geotechnical risks in geotechnical engineering projects to improve quality and decrease costs related to geotechnical uncertainties.

The research methodology used in the thesis was a multiple case study that included three geotechnical engineering projects. The case study was conducted in two steps, first an analysis of written information regarding the geotechnical risk management process in the projects, and then semi-structured interviews with key individuals involved in the geotechnical risk management process.

The main research contribution is an increased knowledge of the key aspects for successful management of geotechnical risks, and the application of the observational method. Among other things, the thesis also discusses (1) the influence of the contractual framework on the management of geotechnical risks and application of the observational method, (2) management aspects of the observational method, and (3) the recommended roles of the actors involved in the risk management process.

Keywords
risk, risk management, geotechnical engineering, contractual framework, observational method.

Sammanfattning

Under de senaste årtiondena har det rapporterats många kostnadsöverskridanden, tidsfördröjningar och kvalitetsproblem i projekt som innehåller byggande i jord och berg. Många av de rapporterade problemen är förknippande med risker relaterade till de geotekniska förhållandena. För att uppnå ett säkert och kostnadseffektivt projekt med önskad kvalitet är det avgörande att de geotekniska riskerna hanteras på ett lämpligt sätt.

Hanteringen av geotekniska risker inkluderar en förutsägelse av det geotekniska beteendet. När det geotekniska beteendet är svårt att förutsäga, föreslår den europeiska standarden Eurokod 7 tillämpning av observationsmetoden för att verifiera konstruktionen. Den huvudsakliga principen med metoden är att använda observationer och förutbestämda åtgärder för att anpassa konstruktionen till de verkliga geotekniska förhållandena. Tidigare forskning tyder på att observationsmetoden har potential att framgångsrikt hantera geotekniska risker, men avsaknaden av riktlinjer för implementering har begränsat användningen av metoden.

Syftet med denna doktorsavhandling är att möjliggöra en framgångsrik hantering av geotekniska risker i projekt som innehåller byggande i jord och berg för att förbättra kvaliteten och minska kostnader relaterade till geotekniska osäkerheter.

Forskningsmetodiken som användes i avhandlingen var en multipel fallstudie som inkluderade tre projekt innehållandes geotekniska arbeten. Fallstudien genomfördes i två steg, först en analys av skriftlig information avseende hanteringen av geotekniska risker i projekten och därefter halvstrukturerade intervjuer med nyckelpersoner som var involverade i den geotekniska riskhanteringsprocessen.

Avhandlingen ger ökad kunskap om nyckelfaktorer för en framgångsrik hantering av geotekniska risker och implementering av observationsmetoden. Avhandlingen diskuterar bland annat (1) hur det kontraktuella ramverket påverkar hanteringen av geotekniska risker och implementeringen av observationsmetoden, (2) aspekter på projektledning när observationsmetoden används, samt (3) de roller som de inblandade parterna har i riskhanteringsprocessen.

Nyckelord

risk, riskhantering, geoteknik, kontrakt, observationsmetoden.

Preface

The topic for the present thesis is management of geotechnical risks in civil engineering projects in general, and the management of geotechnical risks using the observational method in particular. The thesis includes a literature review of the concept of risk and risk management to create a basis for further studies of the management of geotechnical risks, as well as a literature review regarding the observational method.

The thesis also includes a case study of the geotechnical risk management process in three geotechnical engineering projects. The literature review and the case studies form a foundation for the subsequent chapters, including a discussion and recommendations regarding the allocation of risks between the actors involved in a geotechnical engineering project, as well as the roles of the actors in the risk management process, with the aim of creating opportunities for a successful management of geotechnical risks and application of the observational method. The thesis has resulted in recommendations regarding the management of geotechnical risks using the observational method.

The work presented in this thesis is partly presented in the licentiate thesis “Management of Geotechnical Risks in Infrastructure Projects: An Introductory Study” by the author in 2005.

Stockholm, May 2021

Mats Tidlund (formerly Mats Carlsson)

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I also wish to express gratitude to my friends and colleagues at KTH and Skanska for valuable help and discussions during the work. Finally, I would like to express my gratitude to my family for their endless patience throughout the thesis.

Appended Paper A

Tidlund M, Spross J and Larsson S, 2021, Observational Method as Risk Management Tool: The Hvalfjörður Tunnel Project, Iceland.

Submitted to *Engineering Geology*

I analyzed the case studies and wrote the paper, assisted by Spross and Larsson.

Other publications

Carlsson M, Hintze S and Olsson L, 2004, Application of System Analysis in Geotechnical Engineering - An Example from the South Link Road Construction, In: *Proceedings of the Nordic Geotechnical Meeting, Ystad, Sweden*, pp. J39-J49.

Hintze S, **Carlsson M** and Stille H, 2004, Risk and System Analysis Model in Geotechnical Engineering - A Tool for Better Understanding and Decisions, In: *Proceedings of the International Association of Bridge and Structural Engineering Symposium, Shanghai, China*, pp. 314-315.

Carlsson M, Hintze S and Stille H, 2005, On Risk Management in Large Infrastructure Projects, In: *Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, Japan*, pp. 2 785-2 788.

Contents

1. Introduction

During recent decades there have been many time and cost overruns in construction projects around the world and the quality has become less than expected in many projects, see e.g. Kastbjerg (1994), Whyte & Tonks (1994), Nylén (1996 & 1999), van Staveren (2006), Lundman (2011), Flyvbjerg (2014), Tonks et al. (2017) and Johnson & Babu (2020). The time and cost overruns do not seem to have decreased with time, despite the developments in the construction industry. In addition, many projects are struggling with problematic environmental, political and public acceptance, different types of accidents, disputes and claim situations. Experiences from completed projects show that a large amount of these problems arise in the early planning and design phase and are realized in the construction phase of the project (Chan et al. 1997 and Smith 2008).

These statements are supported by observations from the construction industry around the world:

- A study of 180 projects in the 1960s, undertaken by Merewitz and presented by Kastbjerg (1994), showed that cost overruns of 50% were frequent. The magnitude of the cost overruns tended to increase with the size and complexity of the projects and was larger in projects using state-of-art technology.
- Kastbjerg (1994) studied 41 infrastructure projects and concluded that approximately 32% of the studied projects had a cost overrun of between 50 and 100%.
- The cost for errors is approximately 8% of the total construction cost in the Swedish construction industry and almost 80% of this cost is due to conditions established before the execution phase. A few large failures answer for most of the total cost of errors, as approximately 10% of the errors answer for 90% of the cost. If the uncertainty

causing the failure could be transformed into a calculable risk, approximately one third of the cost of failures could be avoided (Nylén 1996 & 1999).

- According to SGI (2013), the annual cost for damage related to unexpected geotechnical behavior in Sweden is about 100 million euro.
- Van Staveren (2013) has reported a cost of approximately 1 billion euro per year in the Netherlands related to geotechnical failures.

In Sweden, the Swedish Transport Administration has analyzed completed contracts since 2014 regarding the final cost compared to the tender cost (Trafikverket 2020). The ratio between the final costs and the tender cost in 180 contracts of over 10 million SEK in 2019 was approximately 1.32 in monetary terms, i.e. the tender cost was on average exceeded by 32%. This was an increase from 22% in 2018 and from 20% in 2014. The analysis shows that the main causes for the cost increases during 2019 were changes in scope and content (35%), material costs (36%), and changes in quantities (26%). During 2017 and 2018 the main cause, around 50%, was changes in quantity. The cost increases have generally been the same or larger in remeasurement contracts compared to fixed price contracts. The cost deviations have been found to be larger in projects that span over a long time.

The reasons for the reported cost and time overruns are partly due to changes in scope of the projects, inflation, and political decisions. Flyvbjerg (2008) discusses some reasons for the reported cost and time overruns and maintains that people are often positive when estimating future events (optimism bias) and may consciously underestimate time and costs in order to get permission to continue with the project or to secure financing (strategic misrepresentation). But these reasons do not explain the whole truth. Many of the construction projects today are located in densely populated areas with poor ground and, as a consequence, many of the reported problems are associated with the inability to appropriately manage the geotechnical risks in the planning, design and construction phase (see e.g. Whyte 1995a, Nylén 1996, Hintze 2001, Clayton 2001a & 2001b, Spross et al. 2021). Deficiencies and shortcomings in the design process, site investigations of the geotechnical conditions, and the interpretation of the results from these investigations seem to be responsible for approximately one third of the total cost of errors in construction projects (Nylén 1999). It is important for both the clients and contractors that these geotechnical risks are managed successfully in the future.

Korff (2017) analyzes the failure cost in a large number of deep excavations in the Netherlands and concludes that most of the failures could have been avoided by a proper risk management. Korff emphasizes that appropriate knowledge is essential in the management of risks, which requires learning from individuals and organizations, as well as between projects. In addition, Korff suggests that the knowledge regarding failures and failure costs in underground works can be increased by systematic case studies and monitoring of underground construction works. Flyvbjerg (2014) asserts that many large and complex projects (“megaprojects”) suffer from a “uniqueness bias” among planners and managers, who tend to see their projects as different from other projects, which hinders learning from other projects. Therefore, Flyvbjerg maintains that learning from other projects through case studies is important.

It can be argued that all projects and businesses ventures involve uncertainties and risks of various kinds. But uncertainties and risks affecting costs and time schedules seem to be more frequent in projects including geotechnical engineering works than in other types of projects. Many geotechnical engineering projects are characterized by varying and difficult conditions, long project time schedules, varying, and sometimes diffuse, demands and needs, complex contracts, high technical levels, long lifetimes, large and multifaceted organizations, as well as political, public and environmental focus. Another characteristic that affects the management of geotechnical risks in many projects is a strong project orientation, where the project is carried out under new, and sometimes unknown, conditions. Furthermore, the construction process generally includes many different actors, sometimes with conflicting interests and limited experience of working with each other.

Risks in geotechnical engineering projects may, in general, originate from geological, hydrogeological, technological, contractual, and/or organizational conditions, and these conditions are often related to each other. The uncertainties and the complex interaction between these result in severe technical and financial risks in many projects. As the project increases in scope, these uncertainties and obstacles seem to increase as well.

The uncertainties due to insufficient information or incomplete knowledge of, for example, geotechnical conditions and geotechnical behavior can affect the technical, occupational, and financial performance of a project. If these uncertainties are not handled adequately, they may lead to disputes during project execution, reconstruction of part of the works, delay in completion, environmental damage, and quality problems, and may affect the health and safety of the workers involved. These events will probably result in negative consequences, e.g. loss of revenue or goodwill, additional costs for construction, operation or maintenance, or time delays. The costs that originate from these risks must be borne by the contractor, the designer, the client, or the society.

Due to the existence of geotechnical risks and uncertainties, several authors, e.g. Reilly (1996), Anderson (1997), Sturk (1998), Hintze (2001), Clayton (2001b), Chapman & Ward (2004), and van Staveren (2006, 2009 & 2013), have proposed a method of project management with a risk focus for geotechnical engineering projects. To achieve a more cost-effective product and a more predictable outcome of projects to a predictable cost, it is essential to handle the existing geotechnical risks appropriately. However, in the light of the mentioned characteristics of many geotechnical engineering projects, the geotechnical risk management process is not simple to perform. The process involves many different actors with different knowledge and experiences, includes many different types of risks, and extends over relative long periods of time. General risk management methods and guidelines may be useful, but these should be supported by case studies to assist geotechnical engineers with interpretation and application (Spross et al. 2015).

Most clients, contractors and engineers executing geotechnical works are probably aware of the presence of geotechnical risks and uncertainties. However, a systematic management of geotechnical risks has not yet been accepted as a necessary tool in everyday work, as it is often regarded as a task for experts and large projects only (Spross et al. 2015, Stille 2017). The management of geotechnical risks is often performed on a different basis in different projects, depending on tradition, culture, individual knowledge and experience, as well as the perceived ability to manage the identified risks. Unmanaged risks may, for example, lead to a product with unsatisfactory functions for the client, and to large costs during the construction phase and at the end of the project, e.g. maintenance costs. Due to the increasing location of geotechnical engineering projects in urban areas, with environmental and public focus as well as construction in poor ground, it will be important to manage the geotechnical risks appropriately in the future.

Observations have been used by engineers to deal with geotechnical risks and to observe the performance of structures since the early days of civil engineering. In these days, modifications of the design based on observations were often made by a “trial-and-error process” or “ad hoc” process. With the development of modern soil mechanics, an integrated process of predicting, monitoring, reviewing and modifying the design gradually evolved. This process was eventually called the observational method by Peck (1969a & 1969b).

The benefits of using the observational method to manage geotechnical risks have been discussed by Terzaghi (1961), Terzaghi & Peck (1967), Peck (1969a & 1969b), Baecher (1981), Whitman (1984), Ladd (1991), Blockley (1994), Chowdhury (1995), Godfrey & Halcrow (1996), Nicholson et al. (1999), Powderham (2002a & 2002b), Moritz & Schubert (2009), Spross & Larsson (2014), Miranda et al. (2015), Spross & Johansson (2017), and Powderham & O’Brien (2020). The observational method emphasizes the idea that not all the risks can be managed before the start of construction, and that the design and construction scheme may be expected to change during construction to manage the risks. As the name indicates, this method includes observations during the project execution aiming to increase knowledge and, thus, reduce the geotechnical uncertainties in order to manage the geotechnical risks.

Due to well-planned observations during the construction phase, the observational method can generally manage unforeseeable conditions better than traditional design methods. Projects where the risks have been properly identified, analyzed and evaluated, and where the observational method has been used to manage the risks have showed that the observational method has a potential to ensure a safe and cost-effective execution of geotechnical engineering projects, see e.g. Chen et al. (2015), Lacasse & DiBiagio (2019), Duncan & Brandon (2019), and Powderham & O'Brien (2020). However, the use of the observational method have been restricted due to a lack of recommendations regarding the implementation of the method, particular regarding its connection to risk management and contractual aspects according to Spross & Larsson (2004), Kadefors & Bröchner (2008), and Spross et al. (2021). In addition, cases of successful implementation of the observational method are rarely published.

1.1. Objectives

The aim of the thesis is to facilitate an improved management of geotechnical risks in construction projects in order to improve the quality of geotechnical works and to decrease costs and time overruns related to geotechnical risks.

The objectives are to:

- Present case studies regarding geotechnical risk management in executed geotechnical engineering projects to find strengths and weaknesses of the applied risk management processes.
- Discuss the application of the observational method in the case studies regarding how this method can be a tool for managing geotechnical risks.
- Identify the most relevant aspects to strive for when applying the observational method in a geotechnical engineering project.

- Study how the observational method can be used in different contractual frameworks and identify contractual obstacles that can hinder an efficient use of the method.
- Present recommendations regarding the role of the actors involved in the risk management process in geotechnical engineering projects.

1.2. Methodology

1.2.1. Introduction

In order to achieve the objectives, the thesis was carried out in two steps: a literature review followed by a multiple case study. The multiple case study includes three cases referred to as “case studies” in the thesis. A multiple case study was chosen as research method due to the complexity of the risk management process in geotechnical engineering projects. Yin (2018) states that case study is an appropriate research methodology in complex situations and/or contexts where it is difficult to study a specific phenomenon. The case studies included semi-structured interviews with key individuals involved in the risk management process in the case studies.

1.2.2. Literature review

The purpose of a literature review is generally to gain an understanding of existing research in a field and to discuss relevant topics or areas of research. Conducting a literature review helps the author to build knowledge in a specific research field. A literature review can also identify key questions about a topic that need further research and determine what approaches might be of most benefit in further developing a topic. Gough et al. (2017) outline four main activities in a systematic literature review: identifying relevant research, systematically critiquing research reports, synthesizing findings and understanding conclusion form the research.

The work started with a literature review covering the concept of risk and uncertainty, as well as the risk management process in general and the management of risks in geotechnical engineering projects in particular.

The result of the literature search was structured and analyzed based on the different steps in the risk management process in ISO 31000 (CEN 2018). After the first literature review, a complementary review was performed regarding the contractual framework in construction projects as the first literature review revealed the importance of an appropriate risk allocation for the result of the risk management process. Additionally, the complementary literature review included the observational method in geotechnical engineering as it became clear that the observational method has successfully been adopted to manage geotechnical risks. Based on these reviews, key factors for a successful management of geotechnical risks and principles for the applicability of the observational method were identified.

1.2.3. Case studies

There are many definitions of case studies as a research method presented in the literature. Ridder (2017) concludes that although case studies provide a better understanding of phenomena regarding context-dependent knowledge (Flyvbjerg 2006, Andersen & Kragh 2010), there is still confusion regarding the definition, content and adequate utilization of case study methodology (Welch et al. 2011).

Yin (2018) describes a case study as an empirical inquiry that investigates a current phenomenon within its real-life context. Stake (1995, 2006) defines case study research as "the study of the particularity and complexity of a single case, coming to understand its activity within important circumstances". Merriam (2009) includes what is studied and the result of the research when defining case study research as: "... an in-depth description and analysis of a bounded system". Harrison et al. (2017) consider different designs of case studies and conclude that with the capacity to tailor approaches, case studies can address a wide range of questions that ask *why*, *what* and *how* ,and assist researchers to explore, explain, describe, evaluate, and theorize about complex issues in different contexts.

In a case study, it is empirically gained information rather than theory that leads to knowledge. The aim of a case study is generally not to falsify hypotheses or theories but to, based on patterns and explanations found in the specific case, find explanations and conclusions valid in similar situations. A description of different types of case studies is presented in Stake (1995, 2005 & 2006), Merriam (2009) and Yin (2018). Case studies may either be exploratory, descriptive or explanatory depending on the aim and depth of the study and the information available (Yin 2018). Case studies can generally be either typical for the whole domain (e.g. of processes or projects), an extreme phenomenon worth studying, a unique opportunity for the researcher ("right place at right time") or a convenient choice due to access to information and/or limited time and resources. Depending on the time frame, a case study may either be based on historical data, data from an ongoing phenomenon/process or a longitudinal study over several years examining variations over time.

The benefits and limitations of case studies have been discussed by, for example, Flyvbjerg (2006, 2012) and Yin (2018). A general benefit of case studies according to Yin (2018), is that a complex phenomenon or process can be studied in its real context. Due to the complexity in these situations, results and effects may not be isolated to a specific cause. In addition, a case study can show the complexity that characterizes reality, and result in qualitative information which may be more accessible and easier to interpret than quantitative data.

Yin (2018) states that a general limitation of using case studies as a research method is that it may be difficult to get access to interesting cases and adequate information. In addition, case studies are often complex with a lot of data and information to analyze. Consequently, it may be difficult to know how the data and information should be analyzed since the studies are often inductive and abductive, rather than deductive, i.e. the case studies aim to draw general conclusions based on a number of individual cases (induction) instead of testing a theory or hypothesis (deduction). Abductive reasoning involves deciding what the most likely implication is based on a set of observations. Furthermore, people in the case studies may change their behavior to fit the aim of the study, which means that the researcher will not have access to genuine cases. Additionally, a limitation of case studies based on historical data is that successful projects are sometimes well documented and reported, while unsuccessful cases are not. The reason for this is probably the fact that the case studies are usually reported by individuals directly involved in the project and an unsatisfactory result might be considered as a personal failure.

Even if some researchers are critical of case studies a research method, other researchers claim that the case study method is undervalued and has an important role in different fields of research. Flyvbjerg (2006, 2012) discusses five common misunderstandings of case study research which undermine the credibility and use of this research method:

a) “General theoretical knowledge is more valuable than concrete case knowledge.

b) One cannot generalize on the basis of an individual case; therefore, the case study cannot contribute to scientific development.

c) The case study is most useful for generating hypotheses; that is, in the first stage of a total research process, while other methods are more suitable for hypotheses testing and theory building.

d) The case study contains a bias toward verification, that is, a tendency to confirm the researcher’s preconceived notions.

e) It is often difficult to summarize and develop general propositions and theories on the basis of specific case studies.”

Flyvberg (2006, 2012) corrects these misunderstandings and concludes that:

> “... a scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and a discipline without exemplars is an ineffective one.”

Yin (2018) discusses the potential and difficulties of using a case study in scientific research and states that the suitability of a case study as a research method depends on the type of case and how it was chosen. Guba (1981) concludes that research using case studies should meet the four criteria for establishing trustworthiness. These four criteria are similar to the eight "hallmarks of scientific research" presented by Sekaran (2003). Other researchers claim that all these criteria do not have to be met and suggest different other criteria to be fulfilled, see e.g. Shenton (2004). However, many researchers seem to agree with the four criteria presented by Guba (1981):

a) *Credibility* – aims at internal validity, i.e. if the author is measuring what was intended. This is often considered to be the most important criterion. This criterion may be fulfilled by using, for example, triangulation and/or member checking.

b) *Transferability* – aims at external validity or generalizability, i.e. how well one study can be applied to other studies. Shenton (2004) claims that it is impossible to generalize findings from a a case study, because it is specific to such a small population and environment. On the other hand, Stake (2005) argues that a single case, even if it is unique, can be used to generalize since it could be an example of a broader group.

c) *Dependability* – aims at reliability, i.e. obtaining the same results when repeating the same study and following the same procedures. An inquiry audit, or external audit, may be used to handle this criterion. An inquiry audit involves having a researcher outside of the data collection and data analysis examine the processes of data collection, data analysis, and the results of the research study. This is done to confirm the accuracy of the findings and to ensure the findings are supported by the data collected.

d) *Confirmability* – aims at objectivity, i.e. the researcher must stay objective and not subjective. There are several techniques to deal with this criterion, e.g. audit trail and reflexivity.

1.2.4. Methodological reflections

To identify key features in the management of geotechnical risks used in geotechnical engineering projects, a literature review and three case studies were performed. As a research method, a literature review has some potential shortcomings that must be acknowledged. Those shortcomings concerning the literature sampling criteria and analysis, e.g. sampling bias, must particularly be considered, see Denyer & Tranfield (2009) and Mostafa et al. (2016). For example, a literature review may be incomplete, especially in a work like this thesis covering a wide range of topics. Consequently, certain relevant publications can be missing in the literature review if, for example, the searched keywords are not included in the publications or if synonyms for the searched keywords have been used in the publications. Associated studies in other research fields can also be missing due to the author's inability to relate the research topic to other relevant topics. Also, cognitive bias can never be eliminated and, thus, there may be drawbacks in the analysis and utilization of the information.

The potential shortcomings of literature review as a research method was considered by using a wide range of keywords in the literature search and search engines, e.g. Google Scholar, that cover a wide variety of disciplines and sources of information. The problem with cognitive bias was addressed by using a systematic method for selecting studies for the review, e.g. predetermined searched keywords and combination of keywords, and criteria for inclusion and exclusion of publications.

The case studies are based on historical information and chosen with the aim of being explanatory and representative for the whole domain of geotechnical engineering projects. The ambition was to choose projects including different types of geotechnical works, different parties involved and both good and bad examples of geotechnical risk management. However, the availability of information also influenced the choice of case studies. When the work with the thesis started, there were these three projects and one more to choose between where I had access to the necessary information, i.e. tender documents, contractual documents, geotechnical documents including site investigations and documentation from the risk management process in the tender, design and construction phase. The fourth project was not studied since it was similar to one of the other projects as it, for example, involved the same type of work, client and contractor. I was not involved in the design and execution of none of the studied projects.

In the first phase of the case studies, written material from the projects was studied, i.e. the tender documents, contractual documents, geotechnical documents and documentation from the risk management process. The material was analyzed with the aim of finding strengths and shortcomings in the management of geotechnical risks and the implementation of the observational method as a basis for a general improvement of the risk management process including the observational method, as well as the following work, e.g. the interviews. The material was structured based on the risk management process in ISO 31000 (CEN 2018) and I tried to recreate the risk management process based on the traces it left in the documents. The analysis was also based on the key factors identified in the literature review. Additionally, the risk management process in the different phases of the case studies was compared to study how the risk management process was implemented and if there were any obstacles to the implementation.

The second phase of the case studies consisted of semi-structured interviews, see e.g. Harvey-Jordan & Long (2001) and Schmidt (2004). The interviews were conducted in 2004 and 2005 during the first part of this study presented in Carlsson (2005). The interviews were more in the form of a discussion rather than a strict interview. The interview instrument in the Appendix was used as a guide of areas available to discuss. The interview instrument was based on the findings in the literature review and the first phase of the case studies. Interesting facts were followed up directly instead of strictly following the instrument. The documentation from the interviews consisted of handwritten notes.

Interviews were conducted with the contractor's project manager, the individual responsible for the risk management process, and the geotechnical engineer in charge. In the case studies that included several contractors in a joint-venture, interviews were conducted with individuals from the Swedish contractor. All participants attended the interview voluntarily and all data were treated strictly confidential after the interview occasion. The purpose of the interviews was to reveal their view of the geotechnical risk management in these projects, e.g. their view of risk allocation, risk communication and cooperation that all affect the risk management process, as well as to uncover important issues and considerations not included in the written material. The data from the interviews was analyzed based on the findings in the literature review and the first phase and utilized both to confirm findings in literature review and the first phase and to capture other aspects that were not included in the written material.

The third phase of the case studies consisted of synthesis and presentation of the result from the first two phases of the case studies. The result is presented in chronological order, from the planning phase to the construction phase, to illustrate the geotechnical risk management process performed by the different parties and how the risk treatment actions determined in early project phases were implemented in the construction phase. The applicability of the observational method was evaluated by comparing the characteristics of the cases with the proposed principles for the applicability of the method. The latter is presented because there is a lack of guidelines and recommendations regarding the implementation of the observational method in geotechnical engineering projects including both technical, organizational, contractual and management aspects.

The thesis fulfills the criteria presented by Guba (1981) in the following ways. The credibility criterion was fulfilled by triangulation, e.g. by using different information collection methods to check the consistency of the findings, e.g. written material and interviews. The dependability criterion was fulfilled by documentation of the study and discussions with my supervisors and experts in risk management and geotechnical engineering. The confirmability criterion was fulfilled by using an audit trail, i.e.

detailing the process of data collection, data analysis and interpretation of the data. Regarding the transferability criteria, it may be argued that three case studies are too few to obtain a general view of the management of geotechnical risks in the construction industry. However, the case studies include different types of geotechnical works and clients, designers and contractors from different countries. Therefore, I believe that the findings from the case studies are not specific for the case studies and that the conclusions may be used in a broader context.

1.3. Limitations

The topic of risk management is an extensive subject and, consequently, the present thesis is limited to certain specific issues. The structure of the thesis is outlined in the next section, but some general limitations are presented in this section.

The general perspective in the thesis is on geotechnical risks affecting the client and the contractor, both technically and economically. The literature review aims at, in general, studying the process of the management of geotechnical uncertainties and risks present in geotechnical engineering projects. Nevertheless, the literature review also considers the concept of risk and uncertainty and the risk management process on a fundamental level. However, a complete review of all concepts and methods in risk management may not be achieved in the framework of one chapter. Additionally, risks related to environment, organization, financial arrangements, occupational and construction methods are not considered in detail.

The case studies include an analysis of the risk management process performed in the three projects; they focus mainly on the technical and contractual aspects in general, and risks related to the geotechnical conditions in particular.

1.4. Structure

To reach its aim and objectives, the thesis presents a literature review on risk and risk management in general, and in geotechnical engineering in particular, as well as a study of three executed geotechnical engineering projects. The literature survey includes the concept of risk and uncertainty as well as the management, perception, and acceptance of risks, both on a general level and on a more detailed level, including the specific issues that are significant in geotechnical engineering. In the literature, the observational method has been suggested as an appropriate method to manage geotechnical risks in projects where the geotechnical uncertainty is substantial; this is therefore given special attention in Chapter 4.

Chapter 2, The concept of risk management, includes a literature review mainly related to the concept of risk and uncertainty, as well as risk management on a general level. The objective of the chapter is to create a picture of the key factors which govern a successful management of risks, as well as the different factors affecting the risk management process. This acquired knowledge is the basis of the following chapters. The chapter includes the concept of risk and uncertainty, the risk management process, risk perception, risk acceptance, and risk communication.

Chapter 3, Risk management in geotechnical engineering, is a literature review dealing with management of risks in geotechnical engineering. The objective of the chapter is not to present a complete review of all existing risks and uncertainties in geotechnical engineering but to provide a fundamental basis of knowledge of these and to identify the most critical risks in geotechnical engineering projects. Furthermore, the methods of project risk management are presented to illustrate some useful examples of these methods, not to be a complete review of all existing methods.

Chapter 4, The observational method in geotechnical engineering, includes a description of the observational method in geotechnical engineering. The objective of this chapter is to present the fundamental features of the observational method in geotechnical engineering and to identify the key features for a successful implementation of the observational method in order to manage geotechnical risks.

Chapter 5, Introduction to the case studies, includes an introduction to and overview of the case studies.

Chapters 6-8, Case studies, present the risk management process in three executed geotechnical engineering projects on a rather fundamental level. The studied projects are the contract SL10 of the Southern Link Road Construction in Stockholm, Sweden (Chapter 6); the contract MC1A of the Delhi Metro project in New Delhi, India (Chapter 7); and the construction of a road tunnel under the fjord Hvalfjörður located north of Reykjavik in Iceland (Chapter 8). Chapter 8 includes the abstract from the submitted paper presented in the Appendix at the end of the thesis. The aim of the case study chapters is to identify deficiencies and areas for improvements in the risk management processes in these projects, to identify the key tasks of the actors that promote a successful management of geotechnical risks, as well as to study the applicability of the observational method in these projects given the key aspects presented in the conclusions in Chapter 4. The identified shortcomings and factors of success are further discussed in Chapter 9. The experiences and conclusions regarding the risk management process made in each project are summarized in each section.

Chapter 9, Discussion and recommendations, discusses the shortcomings of the methods for management of geotechnical risk used today, the allocation of risk between the actors involved in a geotechnical engineering project, and provides recommendations for a successful risk management process in geotechnical engineering. The objective of the chapter is to identify the shortcomings of the risk management in geotechnical engineering today in order to discuss the key tasks for the actors involved in the risk management process. The recommendations are based on the literature review, the case studies and the interviews.

Chapter 10, Concluding remarks and proposals for future work, presents the general conclusions from previous chapters and discusses some of the ways of continuing this research.

2. The concept of risk management

2.1. Introduction

Risks are present everywhere and an unavoidable part of our everyday life. The presence of risks affects our behavior. Sometimes we stop and decide how to deal with them and sometimes we ignore them. Acting individually, we often want some benefit in order to accept some kind of risk. Acting collectively, we make similar trade-offs. Many people will deny a risk, or dispute it, even when the evidence of high risk is clear. Moreover, people will generally risk a lot to prevent a loss, but they will usually risk very little if the only perceived outcome is a possible gain. This psychological mechanism, a desire to maintain the status quo, helps to explain the obstacles that any rational risk analysis must confront. This behavior also involves the sensitivity of society towards technological risks. People generally expect risks to be so-called zero-risk or at least that today’s risk are manageable. According to Brandl (2004), the first demand is unrealistic, and the second can only be partly achieved.

Early theories of risk, so called calculated risk, have been adopted in the insurance and betting industry since the beginning of the 20th century. The study of risk came up as a new field of applied science in the late 1950s due to a growing public concern with new technologies and increasing environmental damage (Hansson 1993). Methods for risk management were first developed and used in industries where a failure could have severe consequences, e.g. the nuclear, aeronautical and space industry. The need for risk management was also growing because of planned changes in the characteristics of systems and facilities. Small systems with long introduction times and local consequences were partly replaced by larger systems with shorter introduction times and large consequences, which affected more people in society. The experience and empirical data of these new systems were also scarce.

To deal with these changes and new prerequisites, researchers from different areas integrated in a new interdisciplinary field called risk analysis. The aim of this new field of study was to increase knowledge about risks in general. In the beginning, the research was primarily focused on the psychological factors of risks. This research was followed by studies of risk perception, decision theory, and risk communication. Risk management evolved as a discipline in the United States in the 1960s due to increasing costs for business insurances, which resulted in a demand for preventive measures to reduce business risks and create new management processes (Otway 1987). This early research has been developed over recent decades and is used widely today.

The interest in the management of risks influencing the project objectives started to grow in the construction industry in the 1990s due to the increasing number of complex projects, including substantial uncertainties and risks, e.g. the development of large-scale infrastructure projects in urban areas. Risks related to structural failure have however been considered before the 1990s. The early methods for risk management in civil engineering were, to a large extent, informal and subjective. Due to lack of knowledge and experience, as well as economical and personal resources in the risk management process, Andersson (1988) asserts that most risk management in the past has been performed on an intuitive basis, based on engineering judgement. However, there is a trend towards more objective methods which aim to take the entire lifecycle of a project into consideration. The risk management process is influenced by many factors, e.g. meaning and interpretation of the concept of risk and uncertainty, individuals' perception of risk, and the accepted level of risk.

The research in the field of risk management has generally focused on finding more efficient ways of managing risks in projects. There are numerous tools and methods available depending on the area of application, the sophistication of which varies. In the construction industry, the number of methods has increased during recent years, but their application has been rare in practice, according to Laryea & Hughes

(2008). Since there is often a lack of statistics and quantitative measures, the analysis is often based on experience, subjective judgement, and/or intuition. Despite this fact, the aim of many risk management methods is often to quantify the risk. However, the quality of the quantification is no better than the way it has been calculated, even if the general perception is that the reliability is greater than a comparable description in words.

The management of risks and uncertainties in future geotechnical engineering projects will probably become a more complicated process than before due to increasing dependence on advanced technology and the location of construction projects in urban areas, with tight time schedules and rigid cost limits. The physical constraints and technological challenges will become more demanding and there will also be the need to take a much wider range of interests into consideration in the planning, design, and execution phase. In addition, an increasing consideration has to be taken regarding public interests and relations. Therefore, there will be a greater range of risks to be considered and the management of the risks will become more diverse.

2.2. The concept of risk

The concept of risk originates from the economic theory of incomplete information. According to Knight (1921) “a situation is said to include risk if the randomness facing an economic agent can be expressed in terms of specific numerical probabilities”. These probabilities can be objectively specified or reflect the individual’s own subjective beliefs. On the contrary, situations include uncertainty when the agent cannot or does not assign actual probabilities to the alternative possible occurrences.

The word risk is an ambiguous and multidimensional word, having various meanings to different individuals, and is used with different meaning in different businesses and in everyday language. Research has shown large discrepancies between the public and experts when it comes to the definition of the word risk and the perception of risks. Risks are generally connected to uncertainty and to lack of knowledge, and the knowledge about risk is therefore, in a sense, the knowledge of the unknown. Many researchers have tried to make the concept of risk as objective as possible, but on a fundamental level it is an essentially value-laden concept since risk often takes a “threat perspective”. However, risk has a positive side as well, opportunity, which often is ignored.

The word risk is, as mentioned above, used with different meanings which are not sufficiently distinguished between. The word is usually related to a decision situation with several alternatives. In everyday language, risk can be used to describe an unwanted event which may occur, the cause of an unwanted event which may occur, the probability (or likelihood) of an unwanted event which may occur, or the consequence of an adverse event which may occur.

Several attempts have been made to establish broadly accepted definitions of key terms related to concepts fundamental for the risk field, see e.g. Thompson et al. (2005). Aven (2012, 2016) concludes that a scientific field or discipline needs to stand solidly on well-defined and universally understood terms and concepts. However, experience has shown that it is not realistic to agree on one unified set of definitions of the risk concept as the definition used should be related to the present decision situation.

The Society for Risk Analysis presents several qualitative definitions of risk (SRA 2018):

a) “the possibility of an unfortunate occurrence,
b) the potential for realization of unwanted, negative consequences of an event,
c) exposure to a proposition (e.g. the occurrence of a loss) of which one is uncertain,
d) the consequences of the activity and associated uncertainties,
e) uncertainty about and severity of the consequences of an activity with respect to something that human’s value,
f) the occurrences of some specified consequences of the activity and associated uncertainties,

g) the deviation from a reference value and associated uncertainties."

The consequences are often seen in relation to some reference values, e.g. planned values or objectives, and the focus is generally on negative, undesirable consequences in these definitions. To describe or measure risk, i.e. to make judgements about how large or small the risk is, SRA (2018) presents various metrics, the suitability of which depend on the situation:

1) "The combination of probability and magnitude/severity of consequences.
2) The triplet (s_i, p_i, c_i), where s_i is the *i*th scenario, p_i is the probability of that scenario, and c_i is the consequence of the *i*th scenario, i=1,2, …N.
3) The triplet (C', Q, K), where C' is some specified consequences, Q a measure of uncertainty associated with C' (typically probability) and K the background knowledge that supports C' and Q (which includes a judgement of the strength of this knowledge).
4) Expected consequences (damage, loss), for example computed by:
    i. Expected number of fatalities in a specific period of time or the expected number of fatalities per unit of exposure time.
    ii. The product of the probability of the hazard occurring and the probability that the relevant object is exposed given the hazard, and the expected damage given that the hazard occurs and the object is exposed to it (the last term is a vulnerability metric).
    iii. Expected disutility.
5) A possibility distribution for the damage (for example a triangular possibility distribution)."

The first metric, i.e. 1) the combination of probability and magnitude/severity of consequences, is similar to an expectation value of the risk. An expectation value is a probability-weighted value, which has the benefit of being additive. This definition is often used in risk-benefit analysis in systematic comparisons of risks with benefits. This is also the standard meaning of risk in many industries.

Slovic (2000) and Hansson (2004) claim that there are at least two limitations with the expectation value approach. First, probability-weighing is controversial. Events with very low probability and very large consequences can be perceived very differently from events with moderate probability and consequences. For example, proponents of a precautionary approach against risks maintain that the management of large but improbable accidents should be given higher priority than what would follow from an expectation value analysis. Second, the expectation value approach only assesses risks according to their probability and consequence. Studies have shown that the calculated risk is not the only aspect of the implicit decision basis according to Corotis (2003). For most people, factors other than the calculated risk level effect their decisions regarding risk, e.g. how risks and benefits are distributed or connected, and social factors. So, if the expectation value method is used, it must be remembered that the size of the risk is not all that is needed to judge whether a risk can be accepted or not. Additional information about its social context is also needed.

The second metric, i.e. 2) the set of triplets {scenario, probability, consequence}, was presented by Kaplan & Garrick (1981). Here, risk is, on a fundamental level, probability and consequence, not probability times consequence as in the expectation value. They define risk as the answers to three questions: What can go wrong (scenario)? How likely is it to go wrong (probability)? If it does go wrong, what are the consequences (consequence)? Kaplan & Garrick suggest that a single number is not enough to communicate the idea of risk. To fully communicate risks, the risks must be related to a specific scenario with some probability and consequence.

ISO 31000 (CEN 2018) defines risk as "the effect of uncertainty on objectives". Today, this is probably the most widely used definition of risk in technological contexts and the definition that is adopted in this thesis. It is possible to interpret this definition in different ways. One interpretation is as a special case of those considered above, e.g. d) or g), with the consequences seen in relation to the objectives. This definition includes both positive and negative deviations from the expected. Sometimes only the negative effect of risk is considered to be consistent with most engineers' perception of the risk concept, as the positive effect of risk, the opportunity, is rarely rewarded with the current contractual arrangements. Therefore, the potential gain of accounting for opportunity is limited. The objectives can have different aspects, e.g. financial, health and safety, and time-related, and can apply at different levels, e.g. strategic, project, and processes. According to ISO 31000, risk is often characterized by reference to potential events and the associated consequences or a combination of these. In addition, risk is often expressed in terms of the combination of the likelihood of occurrence of an event and the associated consequence.

Ward and Chapman (2003) discuss the meaning of the word risk in the context of project management. They argue that the current risk management processes induce a restricted focus on the management of project uncertainty. The reasons for this are that the word "risk" is usually associated with events rather than more general sources of significant uncertainty, and because it often has a threat perspective. Furthermore, they argue that a focus on "uncertainty" rather than risk could enhance project risk management, providing an important difference in perspective, including, but not limited to, an enhanced focus on opportunity management. Due to the ambiguous interpretation and underlying appraisal they suggest the use of the more generally applicable word "uncertainty" instead of the word "risk", and that the established concept of project risk management should be transformed into project uncertainty management. Uncertainty management is about identifying and managing all sources of uncertainty which influence the perception of threats and opportunities. The key concern is the understanding of where and why uncertainty is important in a project context, and where it is not.

In many situations, e.g. in engineering applications, risks are so strongly associated with probabilities that the word risk sometimes is used to represent the probability of an event rather than the event itself. According to the traditional definition of probability, the probability of an event is the relative frequency of this event from an infinite number of repetitive trials. This is the definition of the "objectivist" or "frequentist" school, which views the probability as something external. In reality, there are seldom an infinite number of trials. Significant for many technological systems is that there are none or few data available since many systems are only built in small numbers, and accidents or incidents rarely occur. As a consequence, there are no long and stable series of data and the estimation of risks cannot be based on logical models or empirical data. If a limited amount of information is available, subjective probabilities, Bayesian statistics, or expert judgements may be used. These represent the "subjectivist's" view of probability as an internal state, i.e. a state of knowledge or state of confidence. To describe the chance of something happening, likelihood is often used as a broader term instead of probability, since probability is often interpreted as a mathematical term.

2.3. The risk management process

An effective risk management methodology requires involvement of the entire project team and help from external experts knowledgeable in existing risk areas. The risk management process should consider technical issues as well as human elements and organizational issues. Successful risk management projects generally have the following characteristics according to Lewin (1998):

- Feasible, stable and well understood requirements.
- Experienced and highly skilled personnel.
- A close relationship between all actors involved in the project.

- A planned and structured risk management process.
- A project strategy consistent with accepted risk level and risk handling strategies.
- Continual reassessment of project risks and associated risks during the entire project.
- Aids to monitor effectiveness of risk handling strategies.
- Formal documentation and communication.

The risk management process is most effective when it is started during pre-project planning, e.g. feasibility study, to ensure that as many critical risks as possible are identified and addressed, with mitigation actions incorporated into the project plan, see e.g. Clayton (2001a, 2001b) and Kolveit & Grønhaug (2004). Furthermore, in an early project phase, the possibility to influence is high and the accumulated resources used low. As the project progresses, new information improves insight into the risk areas. This allows development of more effective project strategies. The work carried out in the planning and tender stages must be utilized and updated during the start-up and construction phases. Therefore, a successful risk management is dependent on early planning and continuous and strict execution. Comprehensive planning and monitoring enable an organized, comprehensive, and iterative approach for identifying and evaluating the risks. This also gives adequate handling options, which are necessary for optimizing the project strategy.

A firm base for systematic risk management is the recognition that uncertainties always will exist (Lewin 1998). In addition, a successful risk management system requires that the needs and demands of the client are specified and well understood. Policies should be formulated, and the project organization should be composed to meet these needs and demands. Furthermore, the risk management actions should be designed in the planning phase and implemented into the project plan, and the performance should be measured and reviewed during the execution of the project according to HSE (1997). The entire process, and especially the review, should be assisted by an independent expert group, “review team”, consisting of experts not directly involved in the project but with experience from similar projects (Figure 1).

As for the word risk, there are several definitions of the risk management process and the activities included. In ISO 31000 (CEN 2018), the risk management process is defined as a:

> “Systematic application of management policies, procedures and practices to the activities of communication, consulting, establishing the context, and identifying, analyzing, evaluating, treating, monitoring and reviewing risk.”

ISO 31000 provides principles and guidelines on risk management which may be applied in any industry or sector and used by any stakeholder, e.g. public/private and organization/individual. Since the standard should be applicable in all situations and businesses, it is written on a general level. As a consequence, the risk management process should be adjusted to the project or business at hand.

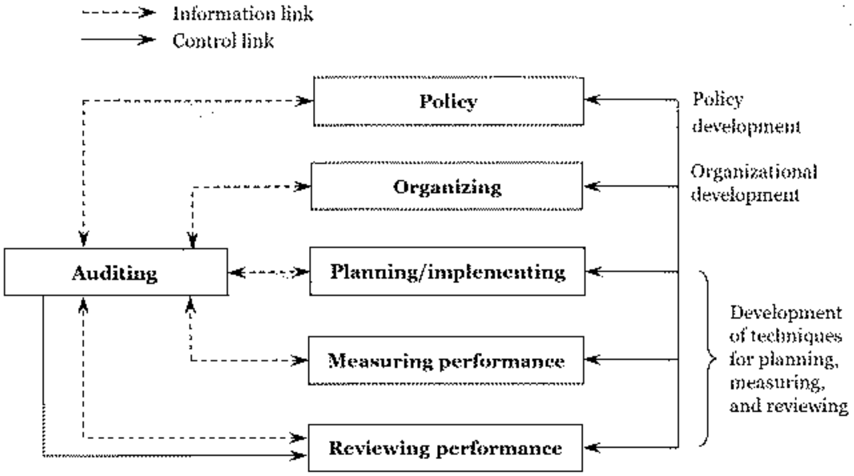


Figure 1: The key elements of a successful risk management system.

ISO 31000 includes 11 principles that all levels of an organization should comply with for an effective risk management process. The risk management process should be an integrated part of all organizational processes. This means that the risk management process should not be an isolated activity separated from the main activities and processes of the organization (or project). The risk management process should be systematic, structured, and timely, as well as transparent and inclusive. This implies that the risk management process should be clearly defined and documented and that all individuals involved in an organization, project, or task should be aware of the risks and the way they should be addressed.

According to ISO 31000, an enhanced risk management process will ensure that an organization has an up-to-date, correct, and comprehensive understanding of the risks and, in addition, that the risks do not violate any maximum acceptable levels. The result will consist of continual improvements, full accountability of risks, application of risk management in all decision making, continual communication, and full integration into the organization's governance structure.

ISO 31000 consists of a framework that aims to provide an effective management of risks by the application of the proposed risk management process. The framework consists of five universal components which should be adapted to the specific conditions and needs of the organization, project, or task. The five components are:

- Mandate and commitment.
- Design of framework for managing risks (e.g. policy, resources, and communication).
- Implementing risk management.
- Monitoring and review of the framework.
- Continual improvement of the framework.

The risk management process, according to ISO 31000, should be a cyclic process including establishing the context, risk identification, risk analysis, risk evaluation, risk treatment, communication and control, and monitoring and review (Figure 2). The overall process of risk assessment includes risk identification, risk analysis, and risk evaluation. The risk management process should be applied in all phases of a project.

2.4. Establishing the context

During the establishment of the internal and external context, the objectives and the significant internal and external parameters should be defined, and the scope and risk criteria should be determined. Many of those parameters are similar to those considered in the establishment of the risk management framework but here they need to be more detailed.

The internal context is anything in the organization or project that may influence the risk management. The internal context may include culture, organizational structure, objective, policies, and contractual relationships.

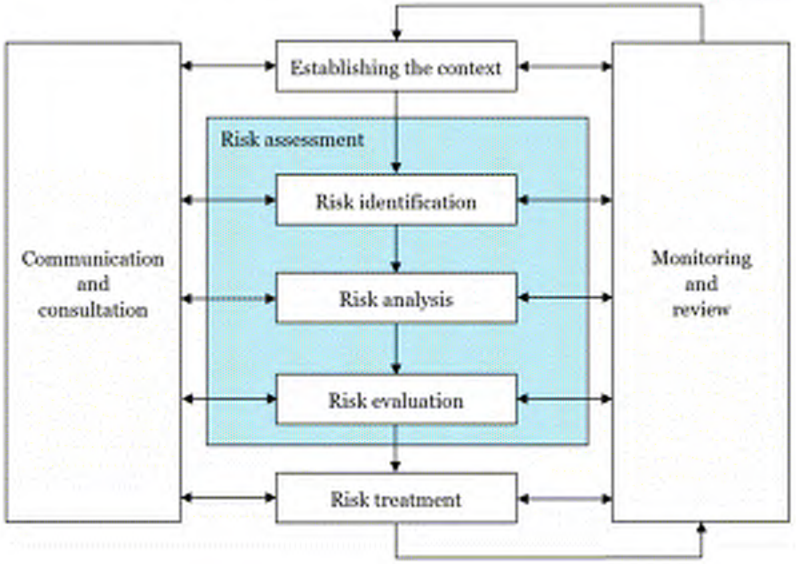


Figure 2: The risk management process according to ISO 31000.

The external context is the external environment in which an organization or project acts and tries to reach its objectives, e.g. the political, legal, social, and competitive environment.

2.5. Risk identification

Risk identification is the process of finding, recognizing, and describing risks (ISO 31000). The aim of risk identification is to identify sources of risk, areas of impact, events and their causes, and potential consequences. Risk identification is often considered to be the most important step in risk management since if a risk is not identified it cannot be managed later. The risk identification should result in a list of risks that may affect the objectives. Risk identification tools and techniques adapted to present risks, objectives, and information at hand should be used. People with adequate knowledge and experience in risk management principles and geotechnical engineering should be involved. Methods for risk identification in geotechnical engineering projects have been discussed by, for example, van Staveren (2006) and SGF (2017).

According to a study by Whyte (1995b), the cost for the risk identification phase is often between 0.2 and 0.5% of the total budget of a construction project. However, the cost for damage due to unexpected events may easily exceed 10% of the total value of the project. Of course, these figures depend on the size and complexity of the project at hand. Nevertheless, the relation between the cost for risk identification and cost for damage due to unexpected events is probably similar in different types of projects. Therefore, for the success of a project, it is essential that the identification of risks is performed properly and by the individuals best suited for the task.

The identification of risks is a process of a structured speculation of all possible critical conditions that might affect the project. The individuals involved should be encouraged to have a holistic view and a positive attitude to identify risks, a spirit of "creative pessimism" (SGF 2017). Risk identification recognizes the existence of hazards and opportunities as well as defining their characteristics. According to Lewin (1998), the aims of the risk identification are to:

- Identify all significant types and sources of risk and uncertainty associated with each of the investment objectives and the key parameters relating to these objectives.
- Determine the causes and the initiating events of each risk.
- Decide how different risks are related to each other and how risks should be classified and grouped for estimation.

The process of identifying risks should be iterative with an increasing level of detail, according to Lewin (1998). First, the risks associated to each objective, key parameter or principal activity are identified and documented. It is essential that every aspect of the project is analyzed. The first attempt should be free from checklists and other constraining documents, e.g. in the form of "brainstorming" sessions, to avoid restraining the process. Risk specialists and other individuals who may add value to the process should attend. After that, the identified risks are documented. Second, the process in the first step is repeated with the support of checklists, risk matrices or other risk identification tools. Identified risks should be listed in the risk register for further review and analysis, with a first indication of the significance of each risk and degree of dependency between the risks. A risk register is a way of gathering all the risk data so that the information can be effectively communicated in the project. Any new assumptions identified at this stage should be entered into the risk register. A risk register typically includes the following (after Clayton 2001b):

- The identified hazards in the project.
- The damage events resulting from these hazards.
- An estimation of the risk.
- The risk mitigation plan and mitigation actions with the objective of keeping the risks at an acceptable level.

- The time for implementing the mitigation actions and who is responsible for the implementation (i.e. the risk owner).
- The expected effect of the response.
- The party that carries the economical consequence of the risk if it should be realized, and an estimation of the cost associated with the handling of the risk.

The process of risk identification may be based on either experience of similar projects, on discussions with qualified and experienced individuals or organizations, or by using risk identification tools. To structure the risk identification process, the risks can be grouped into general and specific risks. The general risks can be considered on a general level for the entire project, while the specific risks must be considered for each part of the project. It is important to examine and identify project specific risks by reducing them to a level of detail that permits an evaluator to understand the significance of any risk and identify its origins and causes. Risks that may have adverse consequences for the outcome of the project must be identified, as well as the opportunities for improvements.

Risk management is sometimes considered to be the answer to all problems, but it is not. It cannot hope to identify all risks in a project. Experience shows that these unidentified risks are often the most dangerous risks for the viability of the project. Even though extensive work is done to identify all risk, there will always be risks that are not foreseen and therefore not identified. However, often the unidentified risks are not completely unforeseen as they may arise from issues that have been poorly managed or incorrectly assessed earlier. Therefore, one of the most crucial issues for the risk identification process is to identify as many of the risks as possible. However, as unidentified risks always exist, the risk management process, the working activities, and the organization must be flexible enough to include these in the risk management process as they are identified at a later stage.

2.6. Risk analysis

Risk analysis is the process of investigating the nature of risk and determining the level of risk (ISO 31000). Risk analysis is a problem definition phase in the risk management process, which quantifies potential risks in terms of probability and consequence. The risk analysis may be used with different objectives in different phases of a project. In the design phases it can be used as a design tool. In the operating phase the risk analysis can be used to maintain the risk focus, to analyze problems and the effects of changes. The risk analysis should increase the understanding of the identified risks and provide an input to the next step, risk evaluation, and to decisions regarding risk treatment methods and strategies.

The risk analysis provides the framework and the tools to understand the risks through a description of the process of events which can lead to damage. The possible chains of events and consequences should be analyzed and described unambiguously. Furthermore, the risk analysis should describe events that may initiate and lead to a realization of a hazard. The risk analysis begins with a detailed study of the risks that have been recognized in the risk identification phase. The objective is to gather enough information about the risks in order to estimate the probability of occurrence and the consequence severity on, for example, project objectives, costs, time schedule, quality, environment, and occupational health and safety.

The success of the risk analysis is dependent on a thorough search for existing information as well as ensuring that sufficient knowledge and experience is brought to estimate probabilities and consequences. High-quality communication and transferring of correct information are other key factors to carrying out successful projects.

A conclusive knowledge of the risks may not be obtained in complex projects, sometimes not even when the project is finished. Therefore, the probability of the risks is unknown to a large extent. When there is statistically enough experience of an event, its probability can be determined by collecting and analyzing that experience. For new and untested technologies or technologies used in a new situation this method is not appropriate. One common way to avoid these difficulties is to estimate the probability of failures through a careful investigation of the various chains of events that may lead to such failures, so-called fault and event trees. By combining the probabilities of various sub events in such a chain, the total probability of an event can be estimated. Hansson (2004) discusses some problems with this approach. First, an event can happen in more ways than we can reasonably imagine. Thus, there is no method by which all chains of events that may lead to an accident in a complex technological system can be identified. Another problem is that the total probability can be difficult to determine, even if we know the probability of each individual event, due to correlation between the events. Despite these difficulties, the use of fault and event trees can be an efficient way to identify weaknesses in a complex technological system. It is important, though, to keep in mind that an exhaustive list of negative events may not be obtained, and, therefore, the total risk levels cannot by determined in this way.

Technological risks depend not only on the behavior of the components in a system, but also on human behavior. The risk associated with a specific technology can differ drastically between organizations with different attitudes towards risk and safety. In addition, human behavior is often much more difficult to predict than technological components. Another issue that should be considered is that it is humans that make estimates of probabilities. Psychological studies indicate that there is a strong belief in the estimates of probabilities by experts and that the possibility that the estimates are wrong tends to be ignored. Therefore, it is essential to make a clear distinction between those probabilities that originate in experts' estimates and those that come from observed events. Furthermore, the estimation of probabilities is influenced by bias, for example due to perceptual factors and heuristics.

The probability and consequences may be classified according to a specified classification system in order to prioritize the risks. The classification system should be designed in agreement with the requirement and the characteristics of the project. The design of the classification systems may be based on statistics, experience from similar projects, and/or on expert judgement. Probability classification may be made as the number of events in relation to a specific unit, e.g. per year, per thousand working hours, or per section of work; see example in Table 1.

Table 1: An example of classification of likelihood of occurrence (after Clayton 2001b).

Probability classification		
Class	Likelihood	Chance (per section of work)
1	Negligible	<1 in 100
2	Unlikely	1 in 100 to 1 in 10
3	Likely	1 in 10 to 1 in 2
4	Probable	>1 in 2

The classification of consequences can be done in a similar way as for the probability; see examples in Table 2. Typically, the selection of consequence classes and the severity of these vary due to the scope and nature of the project, as well as the nature of the consequence. For example, the units of the consequence classes are generally different for the different consequences of structural failure, injury of workers, damage to property, economic loss, or loss of goodwill.

Table 2: An example of classification of consequences (after Clayton 2001b).

Consequence classification		
Scale	Effect	Increase of cost or time (% of total cost or time)
1	Very low	<1%
2	Low	1-4%
3	High	4-10%
4	Very high	> 10%

If a qualitative analysis is considered too coarse to provide reliable risk estimates, a quantitative analysis is required. However, it is a difficult task to quantify the identified risks. The total risk may be estimated as the sum of the risks of all identified hazards, where the risk is the product of its probability and consequences. However, Hansson (2004) claims that there is a strong belief in quantitative data among many individuals, and especially engineers. In addition, there are many uncertainties involved in risk estimation and, in many situations, there is a lack of information to base the risk estimation on. In these situations, it is impossible to determine the "exact risk", and the risk based on experience and/or expert judgement must be used. If there are discrepancies in the data quality and data sources, a quantitative analysis is not always to be preferred, and a well-performed qualitative analysis can be used with the same level of detail. Regardless of what kind of method is used, the documentation of the risk analysis should include a discussion of the quality of the data and data sources that are used in the analysis.

2.7. Risk evaluation

In ISO 31000, risk evaluation is described as the "process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or magnitude is acceptable or tolerable". The aim of risk evaluation is to decide which risks need treatment and then the priority for the treatment implementation. Risk evaluation includes the comparison of the level of risk from the risk analysis with the risk criteria set during the established of the context. The risk owner should normally be responsible for the risk evaluation. The risk owner should be the actor that has the possibility to manage a risk and the authority to make decisions regarding the risk. The risk owner should also have the appropriate knowledge and experience to manage a specific risk, as well as the financial capacity.

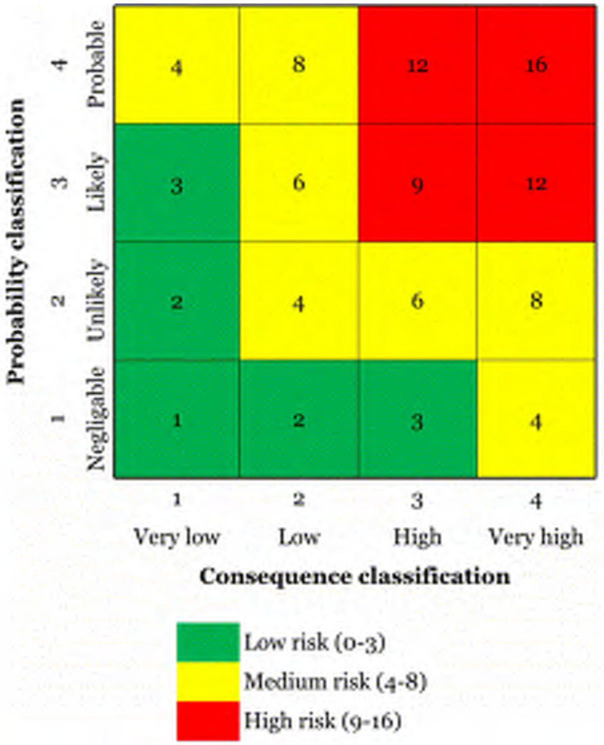
In ISO 31000, risk criteria are described as terms of reference against which the significance of a risk is evaluated and are defined to distinguish between acceptable and non-acceptable risks. The risk criteria are based on the internal and external context and may be derived from organizational objectives, standards, laws, and policies. The risk tolerance depends on the risk perception of each individual and organization. Therefore, it is necessary to establish a scale of risk for each organization involved in the project and for each risk.

The decision-making process regarding acceptable risks is a process involving a series of basic steps. The steps can be used at different levels of detail and with varying degrees of formality, depending on the situation. The key to a successful decision process is to complete each step in the most simple and practical way to provide the information the decision maker needs. Experts on risk analysis should be consulted when formal decision analysis is applied according to SGF (2017). In risk-based decision making, all factors that affect a decision must be considered. Formal decision analysis generally includes four main steps (Raiffa 1970):

- Identification of decision alternatives.
- Definition of decision criteria.
- Analysis of possible outcomes.
- Estimation of probability of outcomes.

Firstly, an identification and definition of all the possible decision alternatives is made. This can be facilitated by the use of decision analysis tools, e.g. decision tree analysis and event tree analysis (see e.g. Raiffa 1970 and Hansson 1991). Secondly, a definition of the decision criteria on which the decision will be based has to be established. Thirdly, an analysis of possible outcomes is conducted where each decision alternative is evaluated with respect to the appropriate decision criteria. The fourth and last step consists of an estimation of the probability of each possible outcome. Then, the decision alternatives may be ranked with respect to the decision criterion. The decision process ends with a basis for decision or recommendations to the decision maker, which will support the decision maker to make the most optimal decision.

The risk classification can be either qualitative or quantitative, depending on the level of analysis and formal demands. A risk matrix is often used in qualitative risk classification (Figure 3). A risk matrix is used to define the level of risk by considering the category of probability or likelihood against the category of consequence severity. This is a rather simple tool to increase visibility of risks and assist management decision making. The risk matrix should be designed specifically for each project based on the accepted risk level and the overall risk policy in the project, as well as the scope and extent of the project; see Cox (2008). The likelihood classes and consequence classes of the risk matrix should be clearly defined (SGF 2017). The total risk exposure should also be considered in the risk evaluation.



Probability classification	1 Very low	2 Low	3 High	4 Very high
4 Probable	🟨 4	🟨 8	🟥 12	🟥 16
3 Likely	🟩 3	🟨 6	🟥 9	🟥 12
2 Unlikely	🟩 2	🟨 4	🟨 6	🟨 8
1 Negligable	🟩 1	🟩 2	🟩 3	🟨 4

Consequence classification

🟩 Low risk (0-3)
🟨 Medium risk (4-8)
🟥 High risk (9-16)

Figure 3: An example of a 4 x 4 risk matrix.

2.7.1. Risk acceptance

The decisions that are made in the risk management process are not only dependent on the likelihood and consequence of the risk, but also on the risk acceptance of the decision makers. Thus, when the risks have been analyzed, it must be determined whether the risks are acceptable or not based on risk criteria. The decision that a decision maker is willing to make is dependent on the specific risk level that can be accepted by that individual, the client, or society. In order to make the most suitable decisions, it is important to determine the risk criteria before any decisions regarding budget, time schedule, technical solutions, construction methods, etc. are made.

The willingness of a decision maker to accept a specific risk governs the risk acceptance. The actual actions of an individual or an organization facing a risk reveal the risk acceptance, which can be divided into three categories: risk averse, risk neutral, or risk taking (Figure 4). A risk averse individual or organization tries to avoid risks and has a negative attitude towards them. A risk neutral individual takes on an average number of risks and has a neutral attitude towards them. A risk-taking individual or organization has a strategy of taking risks and a positive attitude towards them. The willingness to accept risks generally decreases with increasing risk level.

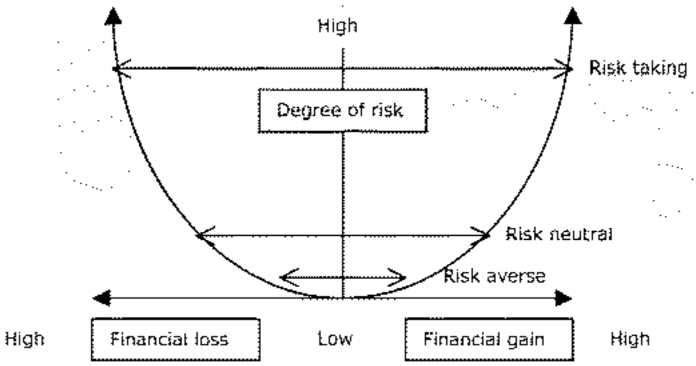


Figure 4: Risk acceptance for different types of decision makers (CIRIA 2002).

The decision makers attitude towards the risk can, in a similar way, be evaluated by an estimation of the risk premium. The risk premium can be defined as the decision maker's willingness to pay an amount of money over the expected monetary value to avoid a risk. With this definition of the risk premium, a risk-avoiding decision maker has a positive risk premium and a risk-taking decision maker a negative risk premium. A risk-neutral decision maker will usually use the maximum expected monetary outcome as a decision criterion.

The risk acceptance is determined by many factors, some inherited and some acquired, e.g. the risk perception of the individual or organization facing a risk, the risk criteria, and the existing knowledge and experience of similar decision situations. Furthermore, the accepted risk level is different among different individuals, groups and societies, and is dependent not only on personal factors, but also on technical, economic, social, and psychological factors. Generally, there seems to be a low willingness to accept risks among individuals, i.e. the human being seems to be risk avoiding in nature; however, risk neutrality may be assumed for individuals when the sacrifice or expected loss is small. An organization generally accepts a higher risk level than individuals in the organization. Thus, the risk acceptance of individuals is often risk averse, while risk neutrality or even risk taking characterize organizations (Rowe 1977). Akintoye & MacLeod (1997) conducted an extensive interview with the focus on risk acceptance and found that decision makers in the construction industry seem to be mostly risk averse.

2.8. Risk treatment

Risk treatment is the process to modify the unacceptable risks based on the previous steps in the risk management process. Risk treatment is an iterative process of selecting of one or more actions for handling the identified risks and the implementation of these actions (Figure 5). Risk treatment includes specific methods and techniques to deal with risks that have been found unacceptable during the risk evaluation. An important task of this phase is the process of recognizing at what stage and in what way risks can be managed, and who is most suitable to do so.

Risk treatment may involve one or more of the following actions (ISO 31000):

- Avoidance of the risk by deciding not to start or continue with a risky activity (risk avoidance).
- Taking or increasing the risk in order to pursue an opportunity (risk retention or risk exploration).
- Sharing the risk with another party, e.g. by a contract, insurance, or financing (risk transferring or risk sharing).
- Retaining the risk by informed decisions (risk retention).
- Removing the risk source or changing the likelihood or consequence of the risk (risk mitigation).

Risk avoidance means that the risks are avoided through a complete avoidance of a risky activity, e.g. by changing the location or excluding a specific activity; this is sometimes called risk elimination.

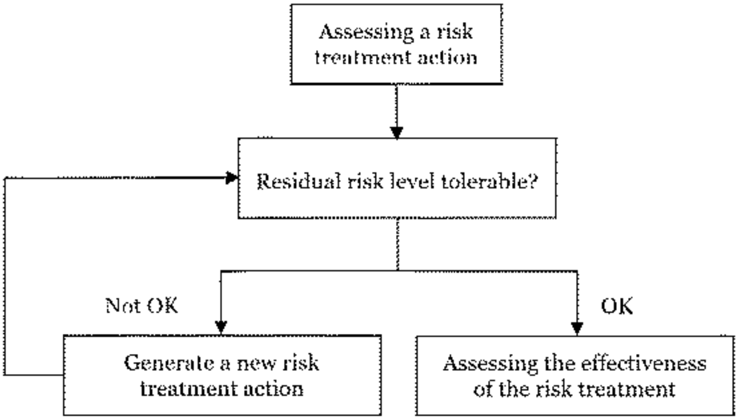


Figure 5: The iterative process of risk treatment (after ISO 31000).

If a *risk retention* or *risk exploration* strategy is used, the risks are left untreated, or even increased, in order to perceive a potential benefit that exceeds the risk. *Risk transferring* means that the risks are transferred to another individual or organization willing to take the risk, e.g. through an insurance. In *risk sharing*, the risks are shared with another individual or organization, e.g. by a joint venture. This treatment action is a combination of risk transfer and risk retention. *Risk retention* is a conscious choice of taking no action to handle a specific risk and is sometimes called risk passiveness. *Risk mitigation* means that the risk is reduced or eliminated by reducing its probability of occurrence and/or its consequence (Figure 6). Risk mitigation is sometimes restricted to the concept of reducing the consequence, and risk attenuation is used for reducing the probability. This is because they not only represent different axes on the probability-consequence map, but they also operate in different areas, with mitigation usually via commercial/contractual mechanisms and attenuation via technical solutions (Lewin 1998).

These risk treatment actions are not mutually exclusive, i.e. two or more options can be used in combination to treat a risk; nor are they appropriate in all circumstances, i.e. they have to be adjusted to the context and the nature of the risk. The risk treatment actions should be chosen with respect to cost versus benefit of a specific action. The choice of an appropriate risk treatment action should also consider critical risks that cannot be economically motivated but have to be treated anyway, i.e. risks with large negative consequences but low probability.

The failure or ineffectiveness of a risk treatment action can be a significant risk that has to be handled, e.g. by monitoring. It must also be considered that risk treatment action can create new risk and/or modify existing risks. Therefore, it is important that decisions makers and stakeholders are informed of the residual risks, which should be documented, monitored, reviewed, and treated further. Monitoring and review are important to ensure that the risk treatment actions are effective, to obtain further information, and to detect changes in, for example, the risk itself, the risk criteria, and the context.

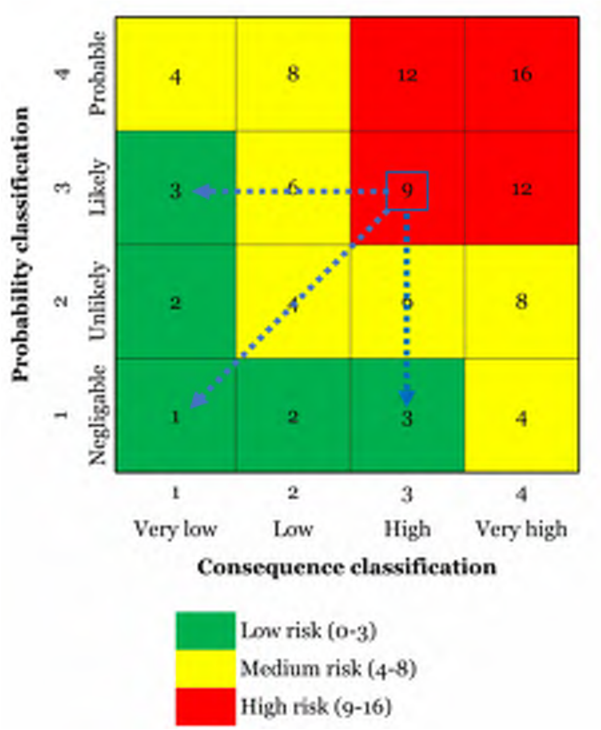


Figure 6: Example of risk mitigation by reducing the probability and/or consequence.

Risk mitigation is often the risk treatment action that first comes to mind in the context of risk management. The procedure for risk mitigation is different based on whether it is the probability or consequence that shall be reduced. Reducing the probability means that the probability of an initiating event is reduced. This probability can be reduced by, for example, using appropriate techniques or equipment in relation to the present conditions. Reducing the consequence may be achieved by conducting preventive actions. Examples of preventive actions are underpinning of existing buildings and pre-planning of countermeasures.

According to a survey conducted by Baker et al. (1999), risk mitigation was the most common risk treatment action in construction projects. Almost 90% of the companies in the survey used risk mitigation as the most important risk treatment action. Risk transfer and risk sharing were used by around 55% of the companies, and risk avoidance and risk retention by approximately 30% each. However, Baker et al. (1999) concluded that when construction companies try to eliminate risk, they generally do so either by not placing a bid or tendering at a high price.

A survey by the Confederation of British Industry in 1994 revealed that many companies in the British construction industry were using a high minimum acceptable rate of return instead of managing the risks in the tender phase. The rate of return was used to judge the acceptability of the project in the hope that this would provide a built-in contingency margin to cover the risks. However, this rather rough approach of risk management has several drawbacks. First, it excludes projects with low risks and with good return that is lower than the acceptable rate of return. Second, risk treatment of risks is the key to effective risk management, and most risks can be treated in some way.

The choice of not treating the risks is a rather defensive approach that will not increase knowledge and competitiveness in the long run. This survey also showed that in many projects, the risk treatment was sometimes undertaken only at a rather superficial level. It is normally not enough just to “take a margin” for risk since this results in little risk treatment being performed, and low risk awareness in the project. This would probably also lead to increasing project costs in the long run and lower quality.

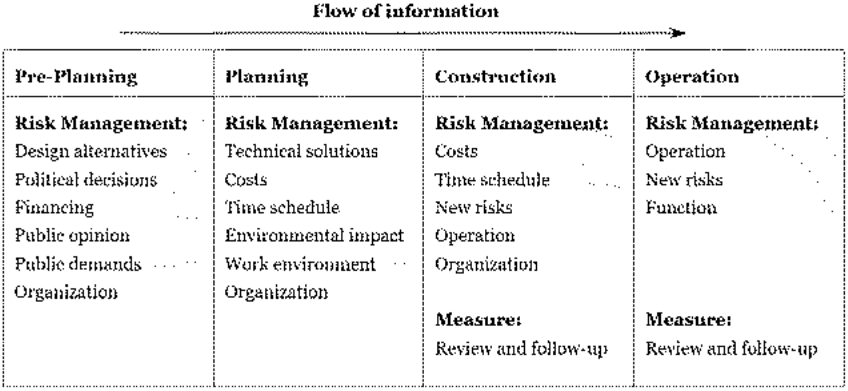
According to Lewin (1998), a specific project risk group should be put together at the beginning of the project in order to manage a risk that exceeds the acceptable risk levels. The risk treatment process begins with an identification and evaluation of risk treatment actions, which are gathered and formulated in a risk treatment plan. These should be proposed to the risk owner, who selects the appropriate actions for implementation. The risk treatment plan should be compatible with the risk policy and an integrated part of the management system and should include potential secondary risks generated by a risk treatment action.

2.9. Risk communication and consultation

Risk communication and consultation constitute of a continual and iterative process to provide, share and/or obtain information regarding risks. The purpose of communication and consultation is to assist relevant stakeholders in understanding the risks, the basis on which decisions are made, and the reasons why particular actions are required (ISO 31000). Communication seeks to promote risk awareness and understanding of risk. Consultation involves obtaining feedback and information to support decision making. A consultative team approach may help to establish the context appropriately, understand the interests of the stakeholders, identify and analyze risks as well as ensure an appropriate definition and evaluation of risks. Plans for communication and consultation should be established at an early stage of the risk management process. Communication and consultation with appropriate external and internal stakeholders should take place within and throughout all steps of the risk management process.

CIRIA (2002) states that lack of communication is a severe risk in many projects. The importance of quality-assured communication within projects has been discussed by, for example, Muir Wood (1994). Successful communication rests, among other things, on the characteristics of the sender and receiver of the information, the decision situation, and the environment. A condition for successful communication is an understanding of the obstacles that can prevent the intention of the communication. According to Stille et al. (2003), these can be divided into general, organizational, and personal obstacles.

Since the aim and content of information is different in different phases, the requirements of the information also change during the project progress. For example, the requirement for details generally increases as the project proceeds from pre-planning to construction. The contents of the information regarding the risk management also changes during the project progress (Figure 7). The information should be clear regarding the uncertainty involved, related to the current situation, understandable, and quality assured.



Flow of information

Pre-Planning	Planning	Construction	Operation
Risk Management: Design alternatives Political decisions Financing Public opinion Public demands Organization	**Risk Management:** Technical solutions Costs Time schedule Environmental impact Work environment Organization	**Risk Management:** Costs Time schedule New risks Operation Organization	**Risk Management:** Operation New risks Function
		Measure: Review and follow-up	**Measure:** Review and follow-up

Figure 7: The content of the information of risks in different phases of a project.

Muir Wood (1994) points out the importance of distinguishing between information based on knowledge and information based on assumptions. Otherwise problems may arise in the interpretation and the utilization of the information. However, this is not trivial in many situations in engineering projects due to the rather heavy reliance upon empirical relationships and subjective judgements.

The communication regarding risks should include relevant information from the risk management process, e.g. the identified risks and their nature, probability, consequence, acceptability and treatment, and the basis on which decisions regarding risks have been made. CIRIA (2002) describes a way to ensure that the relevant information regarding risks is distributed to all the relevant actors in a project. First, at least one member of the staff from each organization is appointed to be part of the project risk management team during the entire project. Verification must be obtained that these individuals have received the risk information and understood it, and that those concerned are committed to undertaking the required risk treatment action. Second, a project risk register should be used to gather details of each identified risk, the risk owner, and the risk treatment action. A similar way of working is described by Melvin (1998) where a designated risk engineer is responsible for the communication and treatment of the risks throughout the entire project.

To increase the awareness and commitment of the risk management process, risks should be considered at all relevant meetings and/or at special risk meetings. To increase the risk awareness among the site personnel, risks should be communicated and discussed at daily briefings before the works start.

2.10. Risk monitoring and review

The purpose of monitoring and review is to assure and improve the quality and effectiveness of the risk management process. According to ISO 31000, continuous monitoring and review of the risk management process and its outcomes should be a planned part of the risk management process, with responsibilities clearly defined. Monitoring and review should take place in all stages of the process, and include planning, gathering and analyzing information, recording results, and providing feedback.

The monitoring and review process should include all aspects of the risk management process in order to:

- Ensure that controls are effective and efficient in both design and operation.
- Obtain information to improve the risk management process.
- Analyze learning lessons from events, changes, trends, successes, and failures.
- Detect changes in context, both internal and external, including changes to the risk itself and risk criteria, which may lead to revised risk analysis, risk evaluation and/or risk treatment.
- Identify emerging risks.

A key task at this stage of the risk management process is the monitoring of risks included in the risk register and the risk treatment plan. The identified risks need to be monitored regularly, including those in the remaining stages of the investment lifecycle, not only the risks occurring in the present stage. The risk monitoring process is a continuous process of monitoring and re-estimation of risks, initiating events, damage indicators, and treatment actions. Monitoring results may also provide a basis for developing additional treatment actions, identifying new risks, or abandoning some identified risks. As the project progresses, the monitoring process should identify the need for additional risk treatment options.

An effective monitoring effort provides information that shows the result of the treatment actions and which hazards are on their way to becoming actual problems. The information should be available in sufficient time for the risk owner to take corrective actions, since it generally elapses some time before the corrective actions become effective. Any significant changes in already identified risks or new risks that are identified should be reported and assessed as soon as possible.

Regular monitoring of the risks can be undertaken by studying events, situations, or changes (trends), which could potentially affect risks during the normal management and progress of a project. These trends must be systematically identified, analyzed, and monitored on a regular basis, and should be considered at regular progress meetings involving key members of the risk management team. It is important that the results from the monitoring are analyzed by individuals with appropriate knowledge and experience. It is often valuable to have a geotechnical engineer or a team of geotechnical engineers on site to follow up the geotechnical conditions and to analyze the monitoring results. Close cooperation with the designer is required to implement the results from the monitoring in the design and risk management process (Stille 2017).

Bröchner et al. (2006) found it useful to use a board of external experts/reviewers in design-and-build projects to support the analysis of monitoring results and the geotechnical conditions, and to manage the geotechnical risks. The experts/reviewers in the board should be independent and have great integrity, and should be involved from an early project phase, preferably before the construction phase.

2.11. Risk perception

The risk management process is influenced by people's subjective judgement about the characteristics and severity of a risk. Studies have shown that different individuals perceive risk differently, and that the same individuals perceive risk differently in different situations. Three groups of theory have been developed: psychology theories, cultural theories, and interdisciplinary theories.

The research on risk perception started in the 1970s and was mainly based on quantitative methods, e.g. questionnaires. In the studies of risk perception, a standard approach is to compare the degree of severity that individuals assign to different risks factors, so-called subjective risk, to the expectation values that have been calculated for the same risk factors, so-called objective risk. The underlying assumption is that there is an objective and knowable risk level that can be calculated with the expectation value method. Corotis (2003) asserts that this is a questionable assumption since it is argued that there no objective risk exists, since the risk is relative and only exists in the minds of individuals or society

The individual's perception of risk depends on several factors (Douglas & Wildavsky 1982, Rosenberg 1989 and Slovic 2000). Some of these are:

- Voluntary or involuntary risk.
- Known or unknown risk.
- Potential damage.
- Expected utility.
- The time factor, i.e. present or future risks.
- Who the risk affects, e.g. society or the individual personally.
- Personal factors either inherited or acquired, e.g. gender, age, education, experience, personality, and attitudes.
- Social factors divided into egalitarian, hierarchic, individualistic, and fatalistic factors, e.g. morals, values and social group.

- Accessibility.
- Attitudes towards the party that is causing the risk.
- The decision maker’s perceived ability to manage the risks.

The literature reveals the following conclusions regarding the factors influencing the perception of risk (Rowe 1977, Starr & Whipple 1980, Harr 1987, Rosenberg 1989 and Hansson 2002):

- A voluntary risk is generally preferred to an involuntary risk, even if the voluntary risk has a higher estimated risk level.
- The accepted risk level is larger if the risk affects someone else.
- Risks with new techniques are perceived to be more severe than risks with widespread techniques.
- Risks with large probability and small consequences are preferred to risks with small probability and large consequences, even if the risk level is the same.
- There is an upper limit for which consequences are accepted, despite the probability of occurrence.
- Experts have a different attitude towards risk than people in general.
- People in general are quite rational when it comes to risks they are familiar with, but irrational when it comes to unknown risks.
- Risks that can affect us in the near future are perceived more severe than risks in the distant future.
- The demand for risk reducing action depends on the extent of the damage.
- Risks that are accessible are considered to be more probable.

The probability of failure or damage is usually small in most civil engineering projects, while the consequences may be severe. A risk situation including a potential damage event with a small probability of occurrence but with a serious consequence has shown to be especially difficult to evaluate. This is because the probability generally loses its meaning when it becomes very low. Most decision makers are indifferent to an event having a probability of occurrence of 10^{-4} or 10^{-6}, even though the probability is much higher in the first case (Star & Whipple 1980). Studies of risk perception have also shown that small probabilities seem to be overestimated by most decision makers. Sjöberg (1978) states that since it is often much easier to understand and estimate the consequence of a risk, the consequence part is often given more value than the probability part. However, the existence of very small probabilities is a special characteristic that must be handled explicitly.

2.12. Conclusions

2.12.1. The concept of risk

The word risk is an ambiguous and multidimensional word, having different meanings to different individuals, and is used with different meaning in different businesses and in everyday language. Furthermore, the word risk is a value-laden word which has a negative meaning to most people and often takes a “threat perspective”. Research has shown large discrepancies between the public and experts when it comes to the definition and meaning of the word risk, as well as the perception of risks.

To enable effective risk management, the word risk should be strictly defined. Preferably, the definition in ISO 31000 (CEN 2018) should be used in geotechnical engineering projects, where risk is defined as “the effect of uncertainty on objectives”. Risk should be characterized by reference to potential events or a specific scenario and expressed in terms of a combination of the consequences of an event and the likelihood, or probability, of occurrence.

2.12.2. The risk management process

Risk management is used in many businesses to control risks and uncertainties. The risk management process is influenced by many factors, for example the meaning and interpretation of the word risk, the risk management methodology, individuals' perception of different types of risks, the accepted risk levels, and the communication of risks. The risk management process should be applied in all phases of a project, from feasibility study to design, construction, operation, maintenance and dismantling.

There are conflicts of interests and resources in all projects, and in many of them the management of geotechnical risks will probably not be the most important issue. However, in many geotechnical engineering projects, a structured management of geotechnical risks will result in reductions in cost and time, and improvements quality. A convenient way of managing geotechnical risks would be to use existing risk management frameworks, e.g. ISO 31000. The success of the risk management process depends on the effectiveness and applicability of the framework that has been adopted.

The aim of risk management is generally to manage the uncertainties to deliver the desired results with increased certainty. The risk management should be complemented with effective project management to achieve all the desirable outcomes of a project, e.g. in terms of costs, time, quality, and function. The fundamental characteristic of the risk management process is that it is a circular and continuous process, while the traditional construction process could be described as a linear sequential process with a deterministic approach. The integration of these is challenging and seems to fail in many projects.

The risk management process generally consists of four main parts: risk identification, risk analysis, risk evaluation, and risk treatment. The process should be monitored and reviewed continually to ensure effectiveness and quality. The first three parts are sometimes referred to as risk assessment. The context should be established before the start of the risk identification, i.e. the objectives of the risk management process, external and internal parameters to consider, and the scope and risk criteria for the remaining process.

Due to the special characteristics of geotechnical engineering projects, one person's subjective and informal management of risks is generally not enough to enable the success of the project. The risk management must be structured and systematic and involve all key individuals in the project. Personal and financial resources for the risk management process must exist, as well as knowledge and experience of both geotechnical engineering and risk management. The success of the risk management process depends, for example, on:

- An understanding that all activities involve risks.
- An unambiguous definition of the word risk and the risk management process, which is acknowledged by all involved in the project.
- An understanding of the actual problem at hand as well as the fundamental demands and requirements of the project.
- Involvement and commitment of the entire project team and, if necessary, assistance from external experts who are knowledgeable in geotechnical engineering and/or risk management techniques.
- An early implementation of a risk management framework that will give the most benefit as there will be more options for managing the risks if they are identified in an early phase of the project.
- A thorough search for existing information as well as sufficient knowledge and experience is brought to the risk assessment and the selection of risk treatment actions.
- Establishment of procedures to identify and manage "new" risks, i.e. risks that have not been identified earlier.
- An understanding of factors that determine the risk perception and the risk acceptance.

- High-quality communication and transferring of correct information.
- Adequate quality assurance of the risk management process.

2.12.3. Risk identification

Risk identification aims to identify all significant sources of risk and uncertainty associated with each of the objectives and the key parameters relating to these objectives, determine the causes and the initiating events, and to decide how different risks are related to each other. However, the risk identification process cannot hope to identify all risks. Consequently, the risk management process should include a process of identifying “new” risks. The identified risk should be gathered in a risk register together with the corresponding hazard, initiating event, and damage event.

2.12.4. Risk analysis

Risk analysis is the process to understand the nature of risk and to determine the level of risk. The purpose of the risk analysis is to provide the basis for risk evaluation and decisions about risk treatment. Risk analysis includes an estimation of the risks and provides input to an underlying decision problem which, normally, involves not only risk but also other aspects such as costs and benefits. Thus, risk should always be considered within a decision theory context. Risk estimation is a problem definition phase in the risk management process, which quantifies potential risks in terms of probability and consequences. Uncertainties in the risk analysis process should be documented and communicated to decision makers and stakeholders, e.g. divergence of experts, assumptions and availability, quality, and limitations of information.

2.12.5. Risk evaluation

The purpose of risk evaluation is to assist in decision making regarding the acceptability of the risks based on the outcome of the risk analysis. Risk evaluation involves comparing the level of risk found during the risk analysis with the risk criteria established when the context was established in the beginning of the risk management process. The accepted risk level is dependent on the risk perception and risk acceptance of the decision makers. Decisions should be taken in accordance with legal, governing, and other requirements. The risk perception and risk acceptance depend, for example, on the nature of the risk, the knowledge and experience of the risk, and personal, cultural, and social factors. Depending on the risk perception and risk acceptance, decision makers can be divided into those who are risk averse, risk neutral, or risk takers. Most individuals seem to be risk averse while most organizations may be characterized as risk neutral. A risk matrix can be used to increase the visibility of the evaluated risks and to assist in decision making. The risk matrix must be calibrated to the accepted risk level and the overall risk policy in the project, as well as the scope and extent of the project.

2.12.6. Risk treatment

The last part of the risk management process, risk treatment, involves selecting actions to treat the risks that have been found unacceptable and implementing those actions. Risk treatment is a cyclic process of assessing a risk treatment action, evaluating residual risks, generating a new risk treatment action if the residual risks are not acceptable and assessing the effectiveness of the risk treatment. Risk treatment actions include, for example, risk avoidance, risk sharing, or changing the level of risk by changing the likelihood and/or the consequence.

2.12.7. Risk communication

The communication of risks has a major influence on the result of the decided treatment actions, and effective internal and external communication is crucial for the result of the risk management process. Risk communication and consultation constitute of a continual and iterative process to provide, share and/or obtain information regarding risks. The risk information should be clear and relevant, and adapted to the situation at hand and to the receiver of the information.

3. Risk management in geotechnical engineering

3.1. Introduction

Due to the substantial risks and uncertainties generally present in geotechnical engineering, it has become increasingly more common to apply risk management techniques to geotechnical engineering projects. The overall aim of the risk management process in geotechnical engineering projects is to identify, analyze, evaluate, and treat, or accept, the geotechnical risks before they are realized. The performance of a geotechnical engineering project will depend on an understanding and management of the risks involved according to Clayton (2001b). Additionally, the project performance will be influenced by the allocation of the risks among the actors involved in the project.

Risks can, in general, be divided into technical and social risks depending on their source and characteristics. In geotechnical engineering, technical risks are often related to the insufficient or inadequate knowledge of the geotechnical conditions at the site. Other technical risks are related to the design, the contract between the actors involved, the equipment, and the construction method used for the project. Social risks affect people outside the project and the environment. Examples of these are risks of contamination, settlement, vibrations, and noise, as well as risks for bad publicity and loss of goodwill or reputation.

Clayton (2001b) divides the technical and social risks into five different categories:

(i) Risks related to the health and safety of the workers and the public.

(ii) Risks related to the environment.

(iii) Risks related to quality.

(iv) Risks related to the time schedule.

(v) Risks related to the budget of a project.

The first two risk categories are usually regulated through laws and design codes that state that the completed structure shall have satisfactory bearing capacity, stability, and durability, as well as environmental impact and working environment. The threat against damage to property or personal damage of third parties is normally the responsibility of the client. The safety of the individuals involved in the project execution is the concern of the contractor. Generally, it is the responsibility of the client to ensure that the likelihood of damage to the environment is acceptably small. The risks related to the expected function or quality, time schedule, and the budget are managed by the client or the contractor, depending on the contractual arrangement.

The responsibility, or ownership, of the risks often changes with time. In the early planning phase and in the operating phase of a project, the client owns a majority of the risks until the funding is established or a contract is signed. The risks in this phase of a project may be managed through different measures, e.g. insurances, joint ventures, and different economic agreements. When a contract is signed between the client and the contractor, some parts of the risks are transferred to the contractor, depending on the type of contract.

Compared to other civil engineering projects, geotechnical engineering projects generally include larger risks and uncertainties because of the nature of these projects, e.g. varying and difficult conditions and demands, long project time schedules, complex contracts, high technical levels, complex organizations, and political, public, and environmental focus. According to Tengborg (1998), the major risks in geotechnical engineering projects are related to the geotechnical conditions, the construction method, the organization, the contract, and the economic arrangements.

The process from a hazard to damage can be illustrated as in Figure 8. Central concepts in this process are *risk object, hazard, initiating event, warning bells, damage event,* and *damage.*

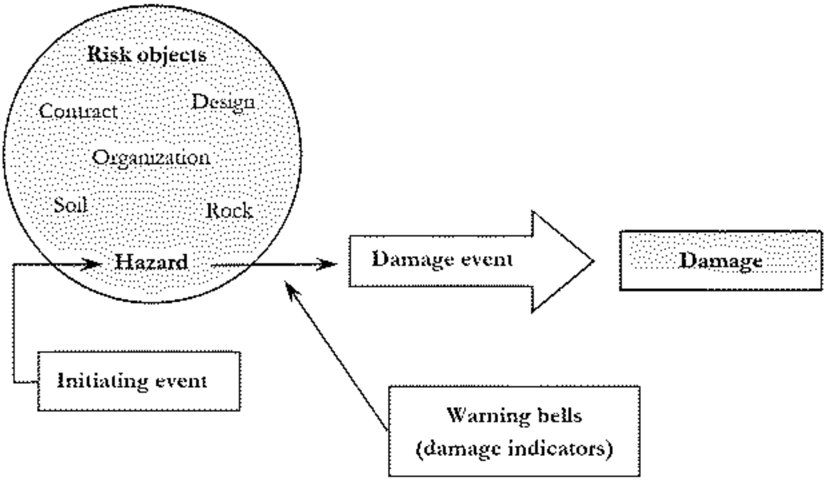


Figure 8: The process from initiating event to damage (after Sturk 1998).

These concepts may be defined as (Sturk 1998):

- A *risk object* is an object that includes hazards which can cause damage. Examples of risk objects are the soil and rock mass, the organization, the contract, or the design.
- A *hazard* is an inherent property of the risk object and is defined as a threat of a potential damage. Examples of hazards are poor rock, fault zones, unclear risk distribution, responsibilities and authorities in a contract, or insufficient competence or experience.
- An *initiating event* is the event that triggers a damage event, e.g. excavation, blasting, or a decision of some kind.
- A *warning bell,* or a "damage indicator", is an indication that a damage event is about to occur, e.g. deformations, vibrations, or flow of water. Warning bells almost always exist for the different types of hazards in geotechnical engineering projects, and it is important to notice them in good time in order to implement appropriate treatment actions.

- A *damage event* is an event that causes damage, e.g. a collapse of a sheet pile wall, deformation of an overloaded structure, or leakage of water in a tunnel.
- The resulting *damage*, i.e. the consequence, is often expressed as economical loss or loss of resources.

Some types of damages are relatively easy to express in monetary terms, e.g. time delays and reconstruction, while others are practically impossible, e.g. costs for negative opinion and the loss of goodwill. In Table 3, some examples of risks in geotechnical engineering projects are presented for these concepts.

Table 3: Examples of risks in geotechnical engineering projects (after Tengborg 1998).

Risk object	**Rock mass**	**Contract**	**Organization**	**Design**
Hazard	Flowing ground	Responsibility of deviations	Description of authorities	Insufficient competence
Initiating event	Excavation	Shortcomings in the site investigation	Inadequate decision	The approval of the design
Damage event	Tunnel collapse	Unjustified demands from the contractor are approved	Collapse in a tunnel	Inadequate design
Damage	Economical loss	Economical loss	Economical loss	Economical loss
Damage object	The client or the contractor	The client	The client or the contractor	The client or the contractor

ISO 31000 includes the term “risk source” instead of “risk object”, and “consequence” instead of “damage”. A risk source is defined as an “element which alone or in combination has the intrinsic potential to give rise to risk”. A risk source can be tangible or intangible. An event is defined as “occurrence or change of a particular set of circumstances”, and consequence as the “outcome of an event affecting objectives”. The other concepts have no counterparts in ISO 31000.

From now on, the terminology according to ISO 31000 is adopted in this thesis, complemented by the terminology presented by Sturk (1998) if no counterpart exists in ISO 31000.

3.2. Characteristics of geotechnical engineering projects

To manage geotechnical risk, it is important to understand the characteristics of geotechnical engineering projects. Many geotechnical engineering projects are characterized by varying and difficult conditions, substantial uncertainties, long project time schedules, varying and diffused demands, high technical levels, large and multifaceted organizations, and political, public, and environmental focus. Additionally, the projects are carried out under new and, sometimes, unknown conditions. Furthermore, the construction process generally includes many different actors who often have limited experience of working with each other, and different and often conflicting interests.

Many work activities in geotechnical engineering projects, e.g. excavations, foundation work, and tunneling, can be characterized as series systems. This means that a work activity is dependent on previous work activities and affects subsequent work activities. Therefore, the construction process is sensitive to changes, as a disturbance or delay in one work activity influences the following work activities. This also means that the hazards are connected to each other in a similar way. Consequently, geotechnical hazards often have disproportional effects on the cost and the time schedule of a project, since problems occurring in one phase affect the subsequent phases. This will often lead to irrecoverable time delays, which lead to extra costs in addition to the costs for changing the design, reconstruction etc.

The magnitude of uncertainties and risks in geotechnical engineering is often considerable and affects the outcome of the project. If the project increases in scope, these uncertainties and risks seem to increase as well (Lewin 1998). The uncertainties due to insufficient information or incomplete knowledge of, for example, geotechnical conditions affect both the technical and economic outcome.

These uncertainties may lead to reconstruction of part of the works, delay in completion, environmental damage, and quality problems, and can affect the health and safety of the workers involved. If these risks are not managed adequately, these unexpected events will probably result in negative consequences, e.g. loss of revenue or goodwill, additional costs for construction, operation or maintenance, or time delays. The costs that originate from these risks have to be borne by the contractor, the designer, the client, or society.

In complex projects, it is often difficult to establish the geotechnical conditions before the start of the design and construction, e.g. due to the heterogeneity and variability of the geotechnical properties and the limited extent of the site investigations. Natural deposits of soil are often characterized by irregular layers of various materials with wide ranges of properties that affect the behavior of the material.

Similarly, rock materials are often characterized by irregular systems of geological faults and fissures that can affect the behavior of the rock. Furthermore, there are difficulties in selecting adequate soil parameters for design and to model the geotechnical behavior, e.g. due to complex soil-structure interaction. The uncertainty in the design can be substantial as well as the difference between the best and worst scenarios. However, if a design is based on the worst scenario there would be a waste of resources in many projects.

The safety of the design must be achieved by implementing a sufficient safety margin. The optimal safety margin for design may be viewed as a problem involving the trade-off between cost and safety. The trade-off considerations could be extended to the planning and execution of the site investigations. More extensive site investigation will generally reduce the uncertainties. At some point, the incremental benefit obtained from further exploration and testing will not yield sufficient increase in the reliability of the prediction and, hence, may not justify its additional cost.

3.3. Uncertainties in geotechnical engineering

The presence of uncertainty is generally higher in geotechnical engineering than other fields of civil engineering since the available data are often incomplete or insufficient and contain variability. In addition, planning and design must rely on predictions or estimations based on idealized models with unknown degrees of model errors relative to reality and, thus, involve additional uncertainty. Geotechnical uncertainties are uncertainties related to the geotechnical conditions. SGF (2017) includes not only uncertainties related to the geotechnical conditions, but also technical uncertainties related to the construction work and the contractual framework in a geotechnical engineering project.

Many phenomena, processes, and events in geotechnical engineering include some form of inherent randomness and heterogeneity, i.e. the outcome of an event is to some extent unpredictable. These phenomena are characterized by field data or experimental data that contain significant variability that represents the natural randomness of an underlying phenomenon, i.e. the observed measurements are different from one experiment (or observation) to another, even though the experiments are carried out in the same way. Therefore, there is usually a range of measured or observed values where some values may occur more frequently than others. The variability in such data or information is statistical in nature, and the realization of a specific value (or a range of values) involves probability.

However, engineering uncertainties are not limited to the variability in the basic variables (Ang & Tang 1975). First, the estimated values of a variable are not free from errors. If there are limited data, the estimate will be nothing more than an educated guess based on experience and the judgements of the engineer. Second, engineers must rely on idealized models of the real conditions for the purpose of decision making or for planning and developing criteria for the design of an engineering system. The idealized models, which may be mathematical, simulation and laboratory models, are imperfect representations of reality and will be inaccurate, with some unknown degree of error. Thus, these models will include uncertainties due the difficulty in the model interpretation. Consequently, the predictions and calculations made on the basis of these models will include uncertainties.

3.3.1. Aleatory and epistemic uncertainty

The categorization and meaning of uncertainties depend on the situation and context. Uncertainty generally arises due to lack of knowledge or variability of properties. Der Kiureghian & Ditlevsen (2009) discuss the concepts of uncertainty and assert that the uncertainties may in general be divided into aleatory uncertainty and epistemic uncertainty. Aleatory originates from the Latin word "alea" meaning dice, referring to a game of chance. The aleatory uncertainty is the inherent uncertainty due to variability or randomness. In geotechnical engineering, the aleatory uncertainty is related to the uncertainty associated with the randomness of the underlying phenomena that govern the geotechnical behavior. This variability is principally the natural randomness of the properties of materials, but also the accuracy in the executed work. The aleatory uncertainty can be quantified by observations, but not reduced.

Epistemic uncertainty is the uncertainty due to the lack of knowledge. Epistemic originates from the Greek work "episteme" meaning knowledge. In geotechnical engineering, the epistemic uncertainty is the uncertainty associated with imperfect models of the real world due to insufficient or imperfect knowledge of reality, e.g. simplified models describing the geotechnical behavior and insufficient knowledge and description of the geotechnical conditions. This type of uncertainty may be reduced if more information is acquired, e.g. through observations. The epistemic uncertainty may be further divided into, for example (Bedford & Cook 2003):

- Parameter uncertainty – the uncertainty about the "true" value of a parameter.
- Model uncertainty – the uncertainty of the reality in the models that are used.

- Volitional uncertainty – the uncertainty that an individual will do what has been agreed on.
- Scenario uncertainty – the uncertainty regarding future events.

These aleatory and epistemic uncertainties can be combined and analyzed as a total uncertainty or treated separately. The concepts and methods are the same for both types, and the basic framework for defining and treating these uncertainties are discussed, for example, by Ang (1970). According to Christian (2004), most problems in geotechnical engineering depend on epistemic uncertainty as the ground is a natural building material with, more or less, unknown properties. It is generally both expensive and time consuming to investigate the ground, and a complete knowledge of its properties cannot be established. This may result in problems and difficulties in establishing the geotechnical behavior.

3.3.2. Description of uncertainty

The uncertainty of a single parameter may be described by a probability distribution. The probability distribution can be discrete or continuous, or a combination, depending on the nature of the uncertainty. However, when dealing with uncertainties in geotechnical engineering, traditional statistical methods are not always appropriate due to the fact that there is rarely adequate data series to base the analysis on. Then other methods must be applied. Often it is possible to fix the parameter values within some boundaries, e.g. the quartiles and the mode, and then assign a distribution, e.g. a triangular distribution. It is also possible to apply subjective assessments by using expert opinions and judgements based on experience and knowledge in a specific area, and the available information (Andersson 1999).

However, there is a need for caution when using subjectively assigned probability distributions. According to Andersson (1999), a minimum requirement is that the assessment results are not critically dependent on the selected functional form of the density function. Even though the available data are scarce, there are often enough data to make some kind of estimation. Without any uncertainty estimate at all, the quality of the assessment cannot be judged. Even a rough estimation, e.g. in the form of intervals, may be enough in many situations.

If two or more random variables are involved, the degree of dependence between them must be estimated, i.e. how the value of one variable depends on the value of another variable. When dealing with systems, the correlation between the parameters has a major impact on the result. Thus, it is essential to estimate the statistical dependence between the parameters that are included. Furthermore, the uncertainty of one parameter may affect the uncertainty of another.

The input parameters may be chosen in many ways, depending on the purpose of the analysis. Andersson (1999) describes three types of uncertainty estimates: "reasonable", "pessimistic", and "probabilistic" estimates. The purpose of choosing "reasonable" is to explore how the system functions under normal circumstances. A "reasonable" value could be the most likely value and not necessarily the statistical mean or median since these values generally do not represent the most likely outcome. The "reasonable" value can be estimated based on available data or on a model analysis. A "pessimistic" estimate is an estimate of a parameter value that will maximize the consequences. The main advantage of choosing a "pessimistic" value is to avoid a detailed description of a model or phenomenon, which in many cases is difficult. If system performance or safety is concerned, this approach may be suitable. If all parameters are given a "pessimistic" value, the result may be unrealistic. Thus, the selection of "pessimistic" values should be considered carefully and be motivated.

If the results from the analyses with "reasonable" and "pessimistic" values show large deviations, it is necessary to use "probabilistic" estimates, i.e. probabilistic distributions which consider the variability in the properties. When there is little knowledge, experience, or few data present of the underlying stochastic parameters, it is, of course, difficult to make an estimation of the probability distribution. In these situations, the existing information can be used to identify intervals.

3.3.3. Decision making under uncertainty

As a result of these unavoidable uncertainties, decisions in geotechnical engineering have to be made under uncertainty. There are several ways to do this. If worst conditions are assumed, conservative designs will be developed. From a system performance or safety point of view, this approach may be suitable; indeed it has been the basis for a large part of engineering design in the past and can be expected to continue into the future (Ang & Tang 2007).

However, this conservative design approach does not include any information on the uncertainty or risk, or a systematic basis for evaluating the degree of conservativeness. A design that is overly conservative may be excessively costly, while a design that is insufficiently conservative may be expensive but will sacrifice performance or safety. The decisions can be based on a trade-off between different factors, e.g. cost, time, utility, safety, and environmental impact. The optimal decision depends on the decision makers’ decision criteria. The optimal decision could be the decision that minimizes and/or maximizes some or all of these factors. The trade-off (or cost-benefit) analysis should include the effect of the uncertainties on a given decision.

3.4. Risks and hazards in geotechnical engineering

Geotechnical risks may be defined as risks related to uncertainties about the geotechnical uncertainties in the ground. Geotechnical risks may adversely influence the cost and time schedule, health and safety, environment, and the quality of a project. There are many types of risks in geotechnical engineering and, in many projects, the consequence of failing to manage these risks can be severe. Successful geotechnical risk management also requires a comprehensive understanding of the construction sequence and of potential failure mechanisms.

Geotechnical risks often have a substantial influence on performance in a geotechnical engineering project. There are several reasons why geotechnical risks often severely affect the outcome of a geotechnical engineering project. These are mainly because of the special nature of the ground, such as (Clayton 2001b):

- The properties and location of the geotechnical properties are predetermined and basically outside the control of the designer, the client, and the contractor.
- In contrast with man-made materials, e.g. steel or concrete, geotechnical conditions are generally highly variable from place to place, and with the depth.
- The accuracy of many geotechnical design methods is poor despite the developments in recent decades.
- There are many ways in which difficult or unforeseen geotechnical conditions can cause problems in a geotechnical engineering project.
- Different methods of construction and different technical solutions will be affected by changes in the geotechnical conditions in different ways and to different extents.
- Geotechnical engineering works are, in general, executed in an early project phase, and problems will affect subsequent phases in the project.

In addition, many work activities in geotechnical engineering projects can be characterized as series systems. For example, in tunneling no work activity, e.g. drilling, grouting, loading, blasting, mucking, and reinforcement, can be started before the previous activity is finished. This means that any work activity is dependent on the previous work activities and affects the subsequent work activities. Therefore, the construction process is sensitive to changes. Consequently, geotechnical risks often have disproportional effects on the cost and the time schedule of a project, since problems occurring in one phase affect the subsequent phases. This will often lead to irrecoverable time delays, which lead to extra costs in addition to the costs for changing the design, reconstruction, etc.

The cost (or time) in a geotechnical engineering project can be divided into normal and exceptional cost (or time), which could be represented as stochastic variables (Isaksson & Stille 2005). The aim of the risk management process is generally to minimize the exceptional cost. Normal cost (or time) is the cost for construction if no undesirable events occur. The normal cost (or time) may be described as the sum of all costs (or time) related to some production effort. Exceptional cost (or time) is the construction cost if undesirable events do occur, e.g. due to unexpected geotechnical conditions. The exceptional cost is a function of the probability and consequence of an undesirable event. The total cost can be calculated as the sum of normal cost and exceptional cost.

There are many potential hazards in geotechnical engineering. According to Stille (2017), these hazards may be divided into:

- Geological hazards.
- Organizational hazards.
- Contractual hazards.
- Hazards related to construction methods.
- Hazards related to the design.
- Environmental hazards.
- Human hazards.
- Political hazards.

3.5. Management of geotechnical risks

Geotechnical risks must be managed systematically if unwanted consequences are to be avoided. The general procedures for risk management in ISO 31000 (CEN 2018) have been found to be applicable to geotechnical engineering projects, see e.g. van Staveren (2006, 2009, 2013) and Spross et al. (2018). Spross et al. (2020) present a risk management process based on ISO 31000 and SGF (2017); see Figure 9.

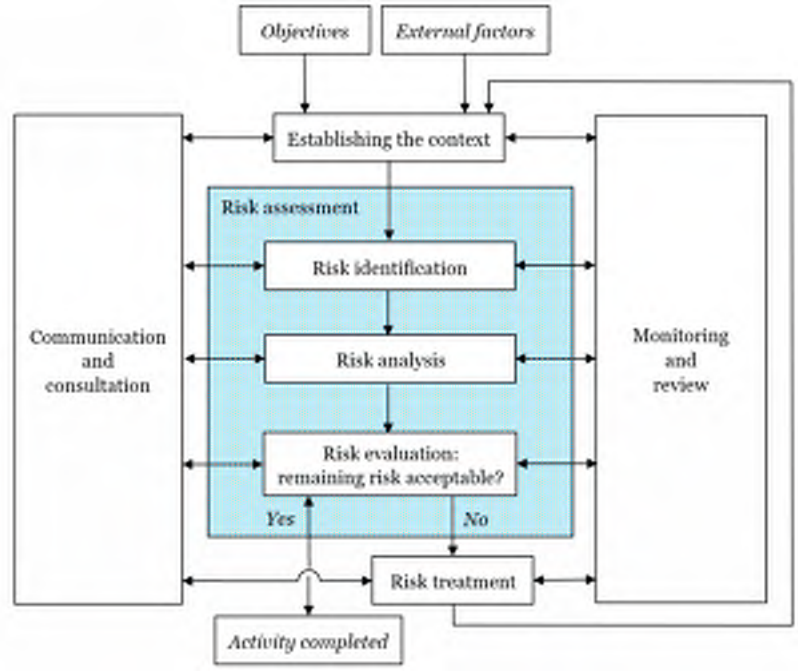


Figure 9: The activities of the cyclic risk management process modified after ISO 31000 (Spross et al. 2020).

The methodology presented in SGF (2017) is based on ISO 31000 (CEN 2018) and considers the different steps in the risk management process in the context of geotechnical engineering projects. The methodology is meant to be a complement and support in applying more general risk management standards to geotechnical engineering projects. The methodology is based on the belief that geotechnical risks are best managed by geotechnical engineers as a part of their everyday work. The promoted philosophy is that geotechnical risks are best understood by people with geotechnical engineering competence and experience who are involved in the project.

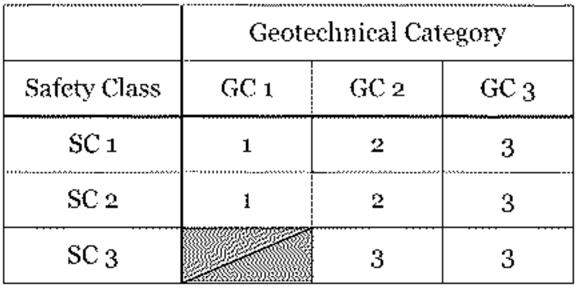
SGF (2017) states that risk management needs to be both systematic and structured and be performed in all projects, both small and large, and should be tailored to the characteristics of each project, e.g. complexity, uncertainties, organization, and resources. In addition, risk management should be a part of the geotechnical engineer’s everyday work and be performed in the whole lifecycle of the project, from feasibility study to operation and maintenance. The report includes both basic requirements and requirements specific for each activity in the risk management process presented in Figure 2. These requirements overlap the requirements in ISO 31000. The basic requirements are:

- The scope and objective of the risk management shall be established.
- The decision maker (risk owner) shall subscribe to the concept of risk.
- Engineers with formal responsibilities shall have essential knowledge of risk management.
- A system for communication and transfer of risk-related information shall be established.

In SGF (2017), the concept of risk management classes is introduced. Risk management classes define the suitable extent of the risk management and the required skills of the involved actors and aims to help the actors to perform an appropriate risk management process. The definition of these classes, 1-3, is based on the probability that satisfactory quality and project goals are reached, and the class should be chosen based on the issue at hand, the extent and nature of the geotechnical uncertainties, and the potential consequences. In risk management class 1, the risks may be identified, analyzed, and evaluated on a general level, while in risk management class 3, the risk management process should be adapted to each specific project or task. In class 2, the risk management process presented in ISO 31000 could be used. The risk management classes are associated with different requirements regarding the knowledge and experience of the actors involved, from an understanding and awareness in class 1, to suitable education and experience in class 2, to support from an expert in geotechnical risk management in class 3.

The appropriate extent of the risk management depends on the amount and characteristics of the uncertainties involved, as well as the potential consequences. The natural variability of the geology and the knowledge of the variability influences the uncertainties. In Eurocode 7, these factors are, to a greater or lesser degree, included in the geotechnical category and the safety class. The geotechnical category depends on the geotechnical complexity, from category 1 (GC 1) including small and relatively simple structures with negligible risk, to category 3 (GC 3) including non-conventional structures and/or complex geotechnical conditions with high risk. The safety class depends on the risk for damage to people, from class 1 (SC 1) including small risk, to class 3 (SC 3) including high risk. Therefore, the appropriate extent of the risk management may be chosen based on the geotechnical category 1-3 and the safety class 1-3, according to SGF (2017); see Table 4.

Table 4: Risk management classes (1-3) based on geotechnical category (GC1-GC3) and safety class (SC1-SC3) (SGF 2017).



	Geotechnical Category		
Safety Class	GC 1	GC 2	GC 3
SC 1	1	2	3
SC 2	1	2	3
SC 3	▨	3	3

In geotechnical category 1, it is often enough to have a basic understanding and awareness of the risks, regardless of the safety class. On the other hand, in geotechnical class 3, including a large number of uncertainties, the risk management process should be adapted to the specific project, the actors involved should have adequate knowledge, experience and training, and should be supported by an expert or a group of experts in geotechnical risk management.

3.6. Risk allocation

3.6.1. General considerations

The allocation of risks among the actors involved in the project influences the risk management process and the project performance. In geotechnical engineering projects, the allocation and the responsibility for the geotechnical risks is of special interest and may be a cause of discussions and disputes. Discussions and disputes may arise if the actual conditions differ from those in the contract or from what reasonably could have been expected.

The allocation of risks is usually governed by the contractual framework between the parties involved, i.e. the type of contract and the type of compensation (payment method). One way of handling the uncertainty regarding the geotechnical conditions is to try to create detailed contracts where the geotechnical conditions are specified, and risks are identified and allocated among the parties involved. Thus, the contractual framework is a significant element in the risk management process.

There is a conflict of interest involved in a geotechnical engineering project. For the contractor, the general goal is to execute a project in order to maximize the profit over a long time period. The contractor generally focuses on issues regarding production, cost, time, and the health and safety of the workers. On the other hand, the general goal for the client is to get a specified product or function with a given quality at the lowest price possible within the time schedule. This conflict of interest will normally make the risk allocation difficult, in combination with the fact that no actor will take on risks for free.

An appropriate and fair distribution of risk between the client and the contractor eliminates many of the conflicts which may occur when there are a number of unknown factors. Ultimately, the client receives the agreed product, and the contractor is compensated for the work that was done. Any deviation from the specified conditions is an invitation for disputes and claims, particularly in projects where it is difficult to make an accurate description of the geotechnical conditions. If the risks are not adequately allocated in the contract or if the risk owner is not established, claims and disputes may be some of the consequences during construction. The contractors may also add a high-risk premium to their tenders to cover the costs of geotechnical risks. It is important that the client and the contractor have a mutual understanding of risks, as risk contingencies in a tender generally increase the tender price or extend the time schedule, or both. The contract should aim to foresee and answer the contingencies arising from the original prerequisites, to eliminate any future discussion over regulation of construction time or costs.

The traditional idea of risk allocation in construction projects is that the risks should by allocated to the actor best able to anticipate and control the risk, i.e. the risk owner, taking into account that this actor should be able to carry the risk (see e.g. Abrahamson 1973 & 1984, Ward et al. (1991) and Cooper et al. 2006). For example, the actor carrying the risk should have adequate knowledge, resources and financial capacity. According to the British Tunnelling Association (2003), the client should generally be responsible for the geotechnical risks in tunneling projects. The International Tunneling Insurance Group (2006) also advises against forwarding the geotechnical risks to the contractor. In the US, it is common that the contractor is responsible for the geotechnical conditions and the associated risk (van Staveren 2006). Bröchner et al. (2006) assert that it is better that the client takes a greater part of the geotechnical risks unless the contractor is given an opportunity to manage those risks.

Perez et al. (2017) state that project complexity often leads to unequal risk allocation between the contractual parties and their literature review identified major problems in relation to the fairness and equality of the risk allocation process. They claim that most existing studies have been conducted from the client’s perspective rather than that of contractors or consultants. According to their study, approximately half the respondents felt that their contractual risk allocation is unfair. In addition, there is a lack of use of formal risk management methods, and the arbitrary passing down of risks from the client to the contractor has increased in recent years.

3.6.2. Geotechnical baseline report

Each party involved in the projects must understand the risks for which it is responsible, otherwise poor cooperation between the parties involved and/or disputes may occur. To avoid problems and claims, a geotechnical baseline report should be included in the contract, according to van Staveren (2006, 2018). The geotechnical baseline report should present the known geotechnical conditions at a project site and define the range of geotechnical conditions that should be provided for and covered by the contract price. The client is responsible for geotechnical conditions beyond the ranges in the geotechnical baseline report. Van Staveren & Knoeff (2004) discuss the geotechnical baseline report as a risk allocation tool and the development of a geotechnical baseline report. They maintain that the appropriate contractual baseline parameters shall be based on an analysis of the geotechnical risks.

The geotechnical baseline report should include measurable descriptions of the geotechnical conditions to be anticipated during construction. These conditions, the baselines, are sometimes referred to as “reference conditions”, and conditions outside the reference conditions as “differing site conditions” or “abnormal conditions”. The geotechnical baseline report could also include a list of geotechnical hazards to be considered in the tender. Then all the tenderers will have the same basis for their tender and do not need to be speculative and include further contingencies in their price. However, contracts cannot specify all conditions. Therefore, the geotechnical baseline report should preferably incorporate a contractual mechanism to determine how to deal with abnormal or differing site conditions.

Without a differing site condition clause in a design-and-build contract, the geotechnical risks are perceived to be higher among contractors than among the client’s own staff according to a study by the Transportation Research Board (2017). This will result in high contingencies in the contractors’ price proposals and higher overall costs. The suggested solution to this problem is to align the perceptions of geotechnical risks of the client and contractor early in the process. This can be accomplished by early contractor involvement and joint development of the geotechnical risk profile of the project.

Used in an appropriate way, a geotechnical baseline report is an effective tool for allocating the geotechnical risk, to prevent disputes and for settlement of differing site conditions claims. However, it is important to set appropriate baselines. The establishment of baselines is a challenging task due to the, often, limited knowledge of the geotechnical conditions. On a fundamental level, the baselines must be relevant, balanced, and realistic. Conservative baselines can lead to overly conservative and costly bids, as the contractor will probably add a high-risk premium to the bid. The opposite, a non-conservative set baseline, would allocate most of the geotechnical risks to the client. Additionally, a geotechnical baseline report should only include the baselines that are necessary to plan, design, execute, and price the works and not baselines that are irrelevant for the works.

3.7. The contractual framework

3.7.1. General considerations

Construction projects include a client that provides capital for the works and a contractor that is responsible for the execution of the works. The contractual framework decides, among other things, who hires the designer, who controls and manages the risks, the form of compensation, and prediction of the final costs. In a traditional contract agreement, the client's designer often develops the design pf the permanent works, which is put out for tendering. An indication of construction method may also be included. The contractor is often responsible for the construction, method description, and the design of the temporary works.

The general contractual problem in many geotechnical engineering projects is that two or several parties are closing a deal about work that is not completely defined for any party when the work begins. As new information is revealed during the work, the initial conditions change, e.g. regarding resources, construction methods, costs, and time. The responsibility for these changes and the allocation of risk are dependent on many factors, but the most important one is probably the contractual framework, i.e. the type of contract and the form of compensation (payment method).

The greater the risk placed on one actor, the more adversarial that party is likely to become to defend its position and transfer the risk to the other actors. The traditional view that the risk should be placed on the actor that has the best opportunity to handle it will usually not prevent adversarial attitudes developing when the risk becomes real. The idea behind a non-adversarial contract is to attempt to minimize the risk to all parties as far as practical. The fundamental principle is that equitable solutions will be found by agreement at the time, which will save time and cost, and avoid disputes and litigation. However, if there is a true will of the actors involved and a strong agreement exists, the risk issues that might arise should be solvable.

Gordon (1994) describes four main aspects that characterize the contracting method. These are scope, organization, contract, and award. The scope is the portion of the project tasks that is assigned to the contractor, e.g. design, construction, operation and/or finance. The party with whom the client enters a contract is the organization. The contract is the arrangement of compensation between the client and the contractor. The award is the method used to choose the contractor and/or the price, for example by competitive bidding, negotiation, and price proposal. All these aspects must be considered in the procurement process and adapted to the characteristics of the specific project, according to Gordon.

There are several factors other than the allocation of risk that determine the optimal type of contract and compensation (payment method), e.g. the client's long-term objectives and procurement strategy, legal aspects, time, project characteristics and complexity, the client's resources and competence, risk acceptance, degrees of freedom in the execution, possibility for innovation, and the competitive situation (Luu et al. 2003). In geotechnical engineering projects, the choice of contractual framework does not only depend on the factors mentioned above, but also on the geotechnical conditions and the geotechnical risks, as well as geotechnical design methods and construction methods. Thus, the choice of an appropriate type of contract requires knowledge in all these areas.

In some procuring organizations there is a lack of general guidelines regarding the choice of contract type, and the characteristics of the project have little or no influence on the actual choice of contract, according to a study by Kadefors & Bröchner (2015). Instead, the contract is sometimes chosen at project level by the client's project manager or the designer, based on personal preferences and/or experience.

Kadefors (2004) suggests that the trust between the actors involved also influences the preference for different types of contracts on a general level. Additionally, Kadefors discusses different factors behind mistrust in construction projects as a result of the type of contract. It is important that the procurement strategy also includes the designers, and not only the client and the contractor, since the designers also have an important role in the risk management process and the construction process, according to Kadefors & Bröchner (2015).

You et al. (2018) maintain that the presence of uncertainty makes exchanges subject to substantial opportunistic behavior that is generally believed to be controlled by the contract. Under uncertainty, all types of contracts may be used in an opportunistic way and issue for speculation. They claim that how the contract governs the relationship between uncertainty and opportunistic behavior has, however, not been explained. Using data from a large number of clients and contractors, their study revealed that a positive relationship exists between uncertainty and opportunistic behavior. In their study, uncertainty is classified into environmental uncertainty and behavioral uncertainty and the study distinguishes contractual complexity from a functional perspective, with elements including control, coordination and adaptation. They concluded that contractual control and adaptation have effects on weakening the relationship between environmental uncertainty and opportunistic behavior, while contractual coordination can mitigate the opportunistic behavior induced by behavioral uncertainty.

3.7.2. The role of the contract

The need for a contract derives from the view in classic economic theory of humans as rational acting individuals whose primary interest is to maximize their own benefits at the expense of other individuals, so-called opportunism. In addition, geotechnical engineering projects are generally characterized by uncertainty due to incomplete knowledge, which will make cooperation difficult. Therefore, there needs to be a comprehensive framework, e.g. a contract, which will handle this uncertainty and guarantee that all actors will fulfil their obligations.

The general purpose for which the client, contractor, and designer goes into business is the same, irrespectively of the type of contract. The client wants to get maximum value for the invested capital with respect to time and cost. The other actors, i.e. the contractor and the designer, generally want to make a reasonable profit, while at the same time increase their knowledge and experience, and to gain recognition sufficiently enough to attract more work. An ideal contractual framework would accommodate all the expectations involved. However, all types of contracts may be used in an opportunistic way by the actors involved.

The fundamental aim of a contract is to regulate authorities, responsibilities, costs, and risks (Ouchi 1980). The contract has two dimensions: a time dimension, i.e. the project is limited in time, and an insurance dimension, i.e. the allocation of risks. An appropriate contractual framework is an important instrument for assessing the allocation of risk and responsibilities in a clear and unambiguous way. The allocation of risks generally depends on the risk profile of the actors, the complexity of the project, the actors' knowledge, and the uncertainty involved. The role of the contract is dual; it should protect the business agreement while at the same time prevent conflicts. The contract includes a set of rules and regulations for the cooperation between the actors involved. The contract is established based on the information and knowledge at hand. Since complete knowledge of the future does not exist, this will lead to uncertainty, and the contract should be seen as a framework in which the project is realized.

According to Ouchi (1980), there are three main types of contract: spot contract, contingent-claims contract, and sequential-spot contract. The first type is a contract for when the production and payment occur at the same time. A contingent-claims contract specifies the actors' obligations in all imaginable situations. However, due to the assumption of bounded rationality, it is almost impossible to specify all these obligations. Complex contracts should generally be avoided since these tend to complicate the team structure, as well as the internal and external communication. An alternative is an incomplete contingent-claims contract, where not all aspects are specified. This type of contract is dependent on a belief that the opponents in an uncertain future will interpret the contract in a way that is best for both actors. The third type of contract is a series of spot contracts aiming at avoiding the risks and uncertainties in a long-term contract. Ideally, all contracts should be contingent-claims contracts. In reality, many contracts are incomplete contingent-claims contracts, based on incomplete knowledge.

The research on the cooperation between organizations has traditionally focused on the management of relations based on trust, not on formal contracts. The role of trust in business cooperation has been discussed widely in the literature, as well as its related concepts of duty, responsibility, and confidence. Gustafsson (2002) describes trust as social glue, which encourages the cooperation and binds the actors together when the formal means, e.g. a contract, are not complete. In these situations, the cooperation is informal and based on social norms and agreements, which are developed during the process. The contract and trust are regarded as substitutes, and the contract is only needed when there is no, or limited, trust involved. If trust is present, the formal contract may be regarded as unnecessary, or even useless and harmful, as it indicates mistrust and inspires opportunism, according to Malhotra & Murninghan (2002). Then, the contract may induce costs to the project and no significant value to the client. On the other hand, the contract may strengthen the cooperation since it encourages the parties to increase their knowledge of the project and its uncertainties.

Trust influences the cooperation between the actors and successful long-term cooperation is often characterized by trust. The concept of trust includes the personal relations between actors and their confidence in each other. The trust is dependent on the reputation of the actors, their earlier performance and cooperation, and personal values. As mentioned earlier, in the field of classic economic theory, personal relations have generally been seen as something negative when the actors are regarded as rational acting individuals whose primary interest is to maximize their own benefits. However, empirically it has been seen that trust has a positive influence in projects which are characterized by uncertainty, information asymmetry, and incomplete contracts (Ollila 2004). In complex geotechnical engineering projects, a contract, despite its extent, may generally not include all possible scenarios. Trust will then fill the gaps in the contract.

3.7.3. Types of compensation (payment methods)

The two main general types of payment methods in geotechnical engineering projects are lump sum and cost reimbursement. A lump sum may be defined as a fixed price contract where a contractor is responsible for executing the complete contract work for a stated total sum of money that is agreed before the work starts. A lump sum is generally appropriate when the project is well defined and significant changes are unlikely. This means that the contractor is able to accurately plan and price the works. Lump sum contracts generally allocate more risk to the contractor than other forms of contracts, and give the client some certainty about the probable cost of the works.

However, there may be problems and disputes if the project is difficult to define and/or if the tender document is unclear and/or incomplete. In addition, the tender process will tend to be slower than for other forms of contract, and preparing a tender may be more expensive for the contractor. However, a lump sum contract does not automatically allocate all the risks to the contractor and it is even not a fixed price, as the lump sum may be subjected to change, e.g. due to changes in the nature of work.

A cost reimbursable contract, sometimes called a cost-plus contract, is a contract where the contractor is compensated for the actual costs plus an additional fee. A cost reimbursable contract may generally be appropriate where the nature or scope of work cannot be properly defined and the risks associated with the works are high. Tendering may be based on an outline specification, drawings, and an estimate of quantities. This is generally considered to be a high-risk form of contracting for the client. The costs for which the contractor is entitled to be reimbursed must be set out clearly in the contract. A target cost can be used to create incentives for improvements and to increase productivity. The difference between the actual cost and the target cost is usually shared between the client and the contractor on some pre-agreed basis.

There exist several variations of cost reimbursable contracts. For example, a remeasurement contract, sometimes referred to as measurement or admeasurement contract, may be used in situations where the design or type of works can be described in reasonable detail, but the amount cannot. The works should be described in sufficient detail to determine a program and to obtain unit rates from tenderers. Tender rates will normally be based on drawings and approximate quantities, e.g. a bill of quantities. A remeasurement contract might also be appropriate on projects where the design has not been completed in sufficient detail for bills of quantities to be produced. The actual contract sum cannot be determined when the contract is entered into, but is calculated on completion, based on remeasurement of the actual work carried out and the rates specified in the tender.

Measurement contracts may allow an early start on site and generally allow changes to be made to the works relatively easily. However, there is inevitably some risk for the client as the cost of the works is not known before the start of the project. Another disadvantage is that the contractor has no incentives to make innovations or improvements, or to decreasing quantities, as the these include some profit for the contractor (Turner & Sinister 2001). One way of increasing this incentive is to compensate the contractor for the decrease in quantities or to implement a value engineering clause. The concept of value engineering is further discussed in Section 4.7.5. Additionally, there might be speculation regarding the actual quantities when setting the tender rates. This speculation may be reduced by thorough site investigations and detailed bills of quantities.

3.7.4. Types of construction contracts

In general, there are three main types of construction contracts: traditional contracts, design-and-build contracts, and partnering arrangements. However, there are many variations and combinations of these types of contracts. In traditional contracts, sometimes referred to as design-bid-build, the client appoints a designer to perform the design of the permanent works in detail and to prepare tender documents, sometimes including a bill of quantities. Contractors are then invited to submit tenders for the construction of the project, usually on a single-stage, competitive basis. The contractor is responsible for carrying out the specified construction works. In this type of traditional contract, the contractor is usually responsible for the design of the temporary works required to complete the permanent works. Typically, the client retains the design consultants during the construction phase to prepare any additional design information that may be required, to review designs that might be prepared by the contractor, and to inspect the works. This type of contract can be seen to be a somewhat fragmented and adversarial project structure which does not give the contractor the opportunity to contribute to the development of the design that they will be required to construct.

In a design-and-build contract, sometimes referred to as design-build, the client appoints a contractor to complete both the temporary and permanent design and the construction of the project. The design is often based on an outline or scheme design performed by the client or specifications regarding the future function of the facility. The contractor is responsible for the design, planning, organization, control, and construction of the works. Variations of design-and-build contracts are, for example, design-build-finance-operate (DBFO), build-operate-transfer (BOT), build-own-operate-transfer (BOOT), and design-build-operate (DBO), where a contractor is appointed to design and build, and sometimes finance, the project and then to operate it for a period of time, including maintenance, before it is transferred to the client. Engineering, procurement and construction contracts (EPC), sometimes called turnkey contracts, are similar to design-and-build contracts, but generally the client has less influence over the design of the project and the contractor takes more risk than other types of design-and-build contracts.

As discussed by Park et al. (2017), economic theories of contracts may suggest that design-build would be better than other types of contracts in large and technologically challenging projects including a large amount of uncertainty, thereby, requiring better-qualified contractors. However, analyses of comprehensive data on public transportation projects performed by Park et al. revealed some differences between theory and reality. Regardless, they conclude that design-build contracts seem to be advantageous to schedule control, while cost advantages is still questionable.

Chan et al. (2001) conducted a questionnaire survey and identified six project success factors in design-and build projects: project team commitment, contractor's competencies, risk and liability assessment, client's competencies, end-users' needs, and constraints imposed by end-users. Project team commitment, client's competencies, and contractor's competencies were found to be important to bring successful project outcome. Contractor's competencies also contributed to project time performance.

Design-and-build has become one of the favored project delivery methods in the engineering construction industry according to Ibbs et al. (2003). Numerous studies have supported the use of design-and-build over the traditional design-bid-build delivery approach. However, their survey showed that design-and-build projects may not provide all the suggested benefits to project performance. They found that timesaving was a definitive advantage of design-and-build project delivery, but, the positive effects of cost and productivity changes were not convincing. Based on the results of the study, they concluded that project management expertise and experience of the contractor may have a greater impact on project performance outcomes than focusing on project delivery strategy only.

Design-and-build contracts are generally considered to be more innovative than traditional contracts as the contractor has incentives for improvements of the design and execution to lower the costs (van Staveren 2006). A design-and-build contract is often considered to allow a faster delivery schedule than traditional contracts as the detailed design is not completely finished before the start of the bidding process. It may also be easier for the client as the contractor has the responsibility for both the design and execution. A disadvantage is that the client has less control over the detailed design and execution (Munfah 2006). Another problem is that it may be difficult for the contractor to estimate the risks in the tender phase, which may result in a high-risk premium, according to Kadefors & Bröchner (2015). Bröchner et al. (2006) studied three design-and-build projects and found that all projects had both technically unjustified and irrelevant requirement specifications in the tender documents, and that it was difficult to change these when new information became available during the execution. The reasons behind this were the client's unwillingness to make changes, but also the contractor's internal relations, where the designers had no incentive to make changes in the design.

Partnering arrangements is a broad term used to describe a collaborative contractual arrangement that encourages openness and trust between the actors. Although expressed in a formal agreement, partnering identifies a relationship rather than contractual criteria. A partnering contract may be appropriate when it is difficult to define the project before execution, e.g. regarding technical solutions, production issues, and geotechnical conditions. Partnering arrangements are most commonly used on large, long-term or high-risk contracts. If a partnering contract is adopted, team building is crucial and there should be incentives for the contractor to have a high production rate. Partnering became popular largely as a result of Sir Michael Latham's report in 1994 (Latham 1994), which, among other things, criticized the adversarial approach in traditional construction contracts and ineffectiveness in the construction industry. The success of a partnering arrangement depends on the collaboration between the actors and requires a change in culture, attitude, and procedures compared to other types of contracts. Partnering contracts are often arranged on a cost reimbursable, target cost, open-book basis, including both incentives and penalties. A collaborative arrangement can be an alternative to a design-and-build contract to the client if the contractor can be procured in an early phase of the project in order to benefit the contractor's knowledge without losing the influence of the execution, according to Kadefors & Bröchner (2015).

How collaborative contracts and contractual incentives might influence project performance remains ambiguous according to Suprapto et al. (2016). They hypothesized that the effects of collaborative contracts and contractual incentives on project performance are facilitated by owner–contractor collaboration, measured in terms of relational attitudes, i.e. relational norms and senior management commitment, and teamworking quality, i.e. inter-team collaborative processes. By analyzing a large sample of projects, they suggest that through better relational attitudes and teamworking quality, projects with a partnering/alliance contract are likely to perform better than those with lump-sum and cost reimbursable contracts. Also, the projects with incentive contracts are likely to perform better than those without incentives through better relational attitudes and teamworking quality. They concluded, however, that the most important issue is how the contractual framework leads to actual collaborative behavior.

There are several variations of the forementioned types of contracts, e.g. where the client appoints a management contractor, a construction manager, or a project manager to decrease the distance between the designer and contractor. In a management contracting contract, the client employs a designer and a management contractor. The management contractor is paid a fee and employs sub-contractors to each work package. The contractor's contract sum is usually assessed by remeasurement. In a construction management contract, the client appoints a designer and a construction manager but also each sub-contractor directly. The contractor's final contract sum is usually assessed by remeasurement. The client is normally more involved in the project than in a management contracting contract.

Early contractor involvement (ECI) is a non-traditional procurement method that, for example, has been used in some major infrastructure projects in Sweden in recent years. In an early contractor involvement project, the contractor is procured at an early stage of the project in order to take advantage of the contractor's knowledge and experience regarding construction methods and costs in the design stage. Typically, early contractor involvement includes a two-stage tender process, used in the first stage to procure contractor involvement in the design process, and in the second stage to procure construction of the works. Other procurement methods, such as design-and-build, construction management, or management contracting, may also allow a contractor to become involved in the design stage, but these often include a one-stage tender process. Early contractor involvement is general considered to be suitable in large and complex projects. A disadvantage for the client may be that the contractor becomes so involved in the first stage that other tenderers lose their interest in the second stage, i.e. the construction, and the already-engaged contractor will have a significant competitive advantage.

3.7.5. Allocation of risk in different types of contracts

Tengborg (1998) discusses the allocation of the risks due to the type of contract. Two extremes of the distribution of the risk are illustrated in Figure 10: a traditional contract, e.g. design-bid-build contract, and a design-and-build, turnkey, build-operate-transfer (BOT) contract, or similar types of contracts. The total risk is included in the elliptical figure, and the risk to the client and the contractor, respectively, is symbolized by the area that each actor has on their side. The risks that are allocated to the client or the contractor depending on the type of contract are symbolized by the central zone, e.g. risks related to construction methods. Each actor is responsible for some risk, independent of the type of contract. For example, the client should be responsible for the geotechnical conditions and requirements regarding the quality and function of the facility, according to Tengborg (1998). The contractor is generally responsible for risks related to construction methods and safety of the workers (Palmström & Stille 2015).

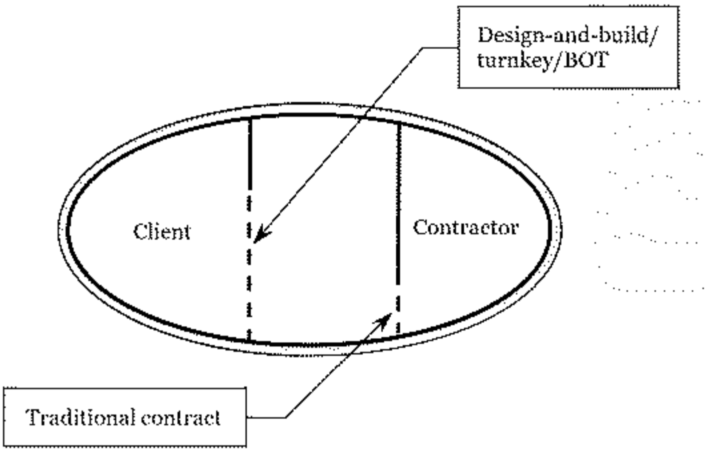


Figure 10: Allocation of risks due to the type of contract.

In a design-and-build contract and similar types of contracts, most of the risks are carried by the contractor or client (or project owner/sponsor) during a specified time interval (Figure 11). In a turnkey project, the client's risk is generally restricted to the requirements regarding the functionality of the project, and the contractor is generally responsible for the design and the execution.

In a traditional contract (design-bid-build contract), the client carries the risks related to most issues, except the risks related to production capacity and production costs and has the initiative to optimize the project performance. The contractor is usually compensated for changes in quantities, as well as changes in production capacity due to unforeseen conditions.

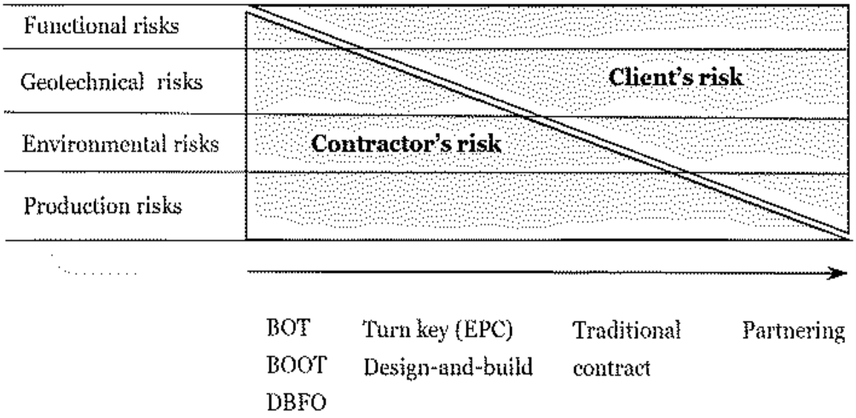


Figure 11: The distribution of risk for some types of contractual arrangement (after Palmström & Stille 2015).

Kleivan (1989) discusses how the project cost is influenced by the risk allocation between the client and the contractor in tunneling projects (Figure 12). According to this study, the minimum project cost is reached by using a target cost or a lump sum with price escalation, i.e. price changes regarding the cost of labor, transport and materials.

Van Staveren (2006) asserts that a collaborative arrangement, e.g. partnering, where the geotechnical risks are shared between the actors, may be the best type of contract for managing geotechnical risks. Malmtorp (2007) claims, however, that a remeasurement contract with fixed rates and varying quantities is generally the best way of regulating the costs when the project includes substantial uncertainty, while Tadelis (2012) recommends negotiated cost remeasurement contracts in these situations.

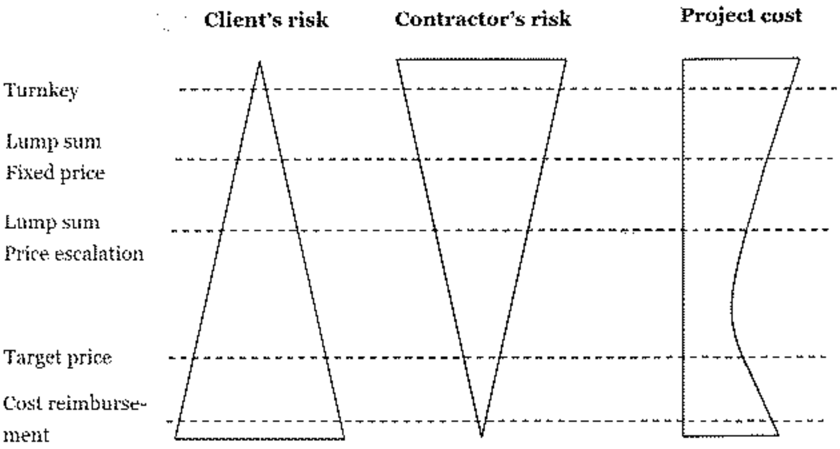


Figure 12: Risk distribution influencing project cost (after Kleivan 1989).

There is a general trend towards more flexible and innovative types of contracts in construction projects, from traditional contracts, via design-and-build contracts, to partnering contracts and other arrangements of collaboration contracts. The traditional arrangement, with a consultant engaged for design and supervision of the work, is used less frequently today. This means that a great part of the design will probably be sub-contracted and that the final design will not be decided until late in the construction process. The following factors are required to provide a more certain outcome in a fragmented construction environment, according to Clayton (2001b):

- High-quality communication.
- A team approach to problem-solving.
- An integrated total project process.
- A risk-based approach to construction management and design.

3.7.6. Dispute resolution

An appropriate and fair allocation of risk between the client and the contractor with respect to economic compensation eliminates many of the conflicts that may occur when there are a number of unknown factors. Ultimately, the client receives the product that is procured, and the contractor is compensated for the work that is done. Any variance from the predicted conditions is an invitation for disputes and claims, particularly in projects where it is difficult to make an accurate description of the geotechnical conditions. If the risks are not fairly distributed in the contract, claims and disputes may be consequences during construction. Furthermore, it is important that the client and the contractor have a mutual understanding of risks, as risk contingencies in a tender generally increase the tender price or extend the time schedule, or both. The contract should aim to foresee and answer the contingencies arising from the original prerequisites, eliminating any future discussion over regulation of construction time or costs.

Traditionally, disputes concerning geotechnical matters have been settled either by litigation or by arbitration. According to Turner & Turner (1999), there are signs that neither these methods, nor those involving adjudication, mediation, or expert determination, are particularly satisfactory. Negotiation is perceived to be the best method of dispute resolution, but it is of course better to avoid disputes at all if possible. Using a mutual and agreed model of the geotechnical conditions and a comprehensive set of parameters to base remeasurements on, may provide a sound basis for negotiation when separate contracts are used for design and for construction. The joint appointment by all actors to a contract of a dispute review board to advise independently on the technical merits of a dispute may also help to speed up dispute resolution, thus saving considerable time and money. An independent geotechnical advisory panel may be used during the execution of the project to address geotechnical matters before they become an issue for disputes and claims.

3.8. Project risk management

As previously stated, geotechnical engineering projects generally involve risks due the geotechnical conditions, high technical levels, long planning and execution times, complex distribution of responsibilities, etc. Furthermore, these projects sometimes involve innovative, but uncertain technologies. Many geotechnical engineering projects face cost overruns and time delays due to the inability to manage these risks (van Staveren 2013 & Tonks et al. 2017).

Project risks may be defined as risks that threaten the viability of a project. The use project risk management methods are based on a common assumption that risk management adds value to the project. However, in a complex and ambiguous environment of a project, value is often subjective. Many organizations perceive that they fail to create value with their project risk management practices, e.g. by executing it as a “tick-the-box” exercise according to Kutsch et al. (2014), Lehtiranta (2014) and Oehmen et al. (2014). Willumsen et al. (2019) have empirically studied the value creation through project risk management based on interviews to explore the subjective value of project risk management. They concluded that what a party perceives to be important, e.g. the future outcome of a project, influences the perceived value of a given project risk management practice. In addition, the empirical findings indicated the need for a contextualized understanding of the value of project risk management, and thereby provide a more nuanced view of the variety of forms through which project risk management can create value.

There are many methods for project risk management that consider the management of risks in a project environment on a fundamental level. However, many of these methods do not explicitly consider the special problems associated with geotechnical risks. Therefore, these are not applicable in geotechnical engineering projects. Practical tools and guidelines for how to implement structured and effective risk management methods in geotechnical engineering projects are few and rarely applied (Spross et al. 2021). The result from a study by Jepson et al. (2020) indicate that there is poor utilization of statistical methods, due to the uniqueness of projects, the lack of data and time pressure on projects. The results from their study were irrespective of project size, type of organization or experience. Consequently, the management of geotechnical risks is based on personal intuition, judgement, and/or experience, more than formal procedures and methodologies. However, the use of a structured project management process with a risk perspective has grown in the construction industry (van Staveren 2006, 2013).

Eriksson et al. (2017) claim that prior project management literature and practice have mostly adopted a traditional control-focused approach, but research suggests that complex projects need more flexible practices to manage inevitable project change. These two project management approaches focus on control and flexibility respectively; see e.g. Geraldi (2009) and Szentes & Eriksson (2016).

The risk management process should be an integrated part of the project and the work activities. It should start in the planning phase of a project and should be performed in all project phases, from feasibility study to design, construction, operation and maintenance, and dismantling (Figure 13). The risk management cycle according to Figure 9 should be completed at least once for each project phase. This allows incorporation of experiences and acquired knowledge into the risk management process and keeps the risk information updated. The flow of information regarding risks from one phase to the next is important so that no information is lost as the project proceeds (SGF 2017).

There are many types of obstacles which can hinder successful risk management in geotechnical engineering projects, e.g. general, organizational, and human obstacles (Stille et al. 2003). Examples of general obstacles are lack of knowledge, contractual blockings, and inadequately defined demands. Unclear organizations and responsibilities, unclear flow of information and decisions, and vague working procedures are examples of organizational obstacles. Human obstacles originate from human shortcomings, e.g. lack of competence and insight, and human errors, such as carelessness and negligence.

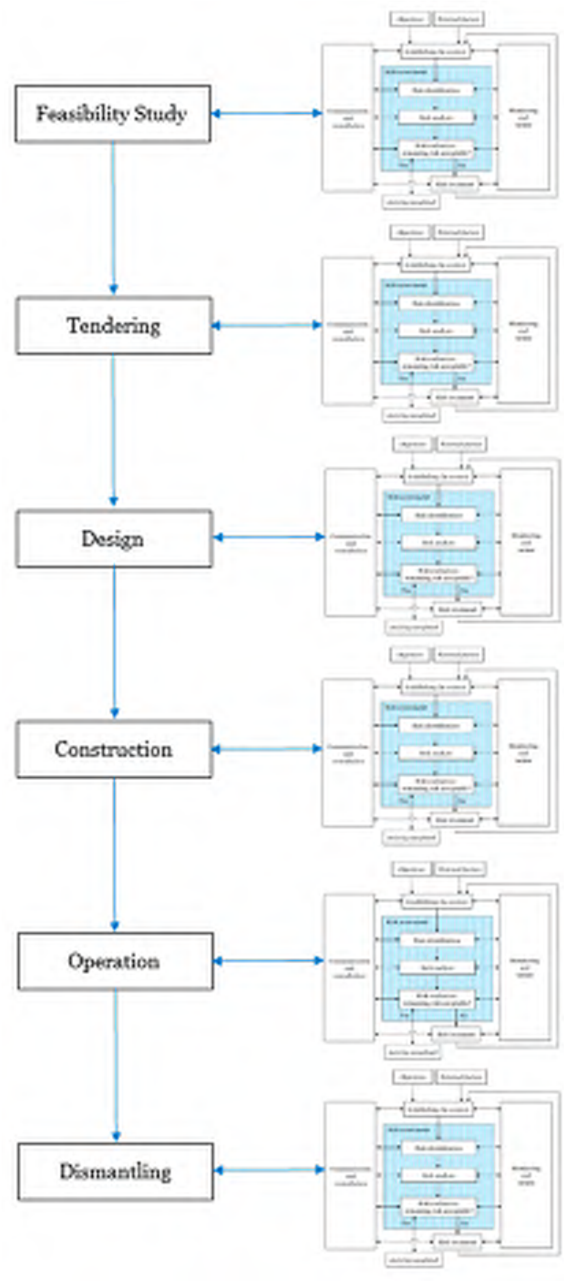


Figure 13: The cyclic risk management process based on ISO 31000 applied to all project phases (after Spross et al. 2015).

For a successful execution of complex high-technological civil engineering projects, Engwall (2002) recommends that these projects should be executed as innovation projects, and not as, traditionally, implementation projects. The traditional idea of project management emphasizes control and is based on a belief that all necessary knowledge can be obtained before the project starts, and that this knowledge can be incorporated into a specification and goal description for the project (Tjäder 2000). This is generally possible in an implementation project, which is defined as a well-known and stable project where the pre-knowledge and the goal description are complete (Obeng 1995). In implementation projects the project goal is exogenous to the project organization and this is equivalent to the view of Verzuh (2003) with project goals defined by the sponsor. In contrast, the definition of the project goal is endogenous for innovation project, i.e. it is a part of the work in the project organization to define the project goal and set the priorities. In an implementation project, the main task is to exploit existing knowledge in an effective way, as all the knowledge of the project content is obtained during the preparations. The extent of the project is, on the other hand, fixed during the execution of the project. The only additional knowledge that is obtained during execution is the knowledge of different methods of production.

An innovation project has a clearly defined objective but the means to reach the objective are not fully known before the start of the project. In an innovation project, the knowledge before the execution of the project is limited. This is also the case in most geotechnical engineering projects. Then, the specification and the goal description of the project only have limited significance for the actors involved. Experience and knowledge obtained during the project execution are required to make the specification and goal description meaningful and complete. In an innovation project, the distinction between the preparations and the execution is not obvious as they are so closely linked that it is difficult to separate them. Instead, the knowledge of the extent of and the conditions for the project gradually increase during execution. Therefore, it is important to have contingency plans to handle the genuine uncertainty that arises due to changing conditions for the project. Additionally, an important issue is to create opportunities for a learning environment, to create appropriate knowledge and experience during the project work (March 1991). This implies that the knowledge about the identified hazards and risks involved also increases during the project. This increased knowledge can be used to reduce the risks, either by reducing the probability or the consequence of the unwanted event, or by transferring them to a party outside the project. The main differences between an innovation project and an implementation project are summarized in Table 5.

Table 5: Characteristics of an implementation and an innovation project (after Engwall 2002).

	Implementation project	**Innovation project**
Pre-knowledge	Complete	Incomplete
Project goal	Exogenous to project work	Endogenous to project work
Acquisition of knowledge	During planning	During planning and execution
Main result	Final product	Final product, knowledge of the goal and the process of reaching the goal
Rationality	Effective project execution	Adequate knowledge for the project

Additionally, Engwall (2002) argues that the characteristics of different types of projects are often not sufficiently acknowledged today due to the traditional rhetoric of projects as implementation projects. In addition, the function of traditional project management tools requires that the goal and scope of the project do not change too much during project execution. However, most projects probably have elements that can be characterized as innovation projects, and elements that can be described as implementation projects. Furthermore, a project can be an innovation project for one individual and an implementation project for another individual, depending on the knowledge and experiences of that individual. Different phases of the project may also be characterized differently.

Nonetheless, it is important that the organization and the construction methods are flexible enough to utilize the new information in the project, in order to handle the uncertainties and the risks. It is also important that the information paths, responsibilities, and authorities are comprehensible, definite, and familiar across the entire project organization.

Recent research sometimes refers to such projects as exploratory projects instead of innovation projects (Wied et al. 2020). Wied et al. (2020) conclude that these projects are a challenge for traditional project management working from known means towards known ends and may explain high rates of project failure. Nonetheless, methods for managing exploratory projects remain situational and fragmented. Wied et al. (2020) present eleven approaches to managing exploratory projects across a range of industries and project types. They explain the repertoire as preparatory, (pre-action), attemptive (during action) and responsive (post outcome) efforts to achieve resistance to and recoverability from unexpected events. Fundamentally, they argue for shifting focus from “what we know” to “how we act” when faced with exploratory projects.

Eriksson et al. (2017) studied 138 construction projects procured and managed by the Swedish Transport Administration and concluded that complex projects require flexibility-focused project management practices. Furthermore, they claim that the complexity level needs to be assessed in early stages to tailor project management practices to project characteristics. Flexibility-focused project management practices include collaboration, explorative learning, and adaptation and these are synergistic and need to be implemented together. The study showed that that complexity and collaboration drive explorative learning, which improves adaptation and, thereby, improves time performance. in complex projects in the infrastructure sector.

Xia et al. (2018) present a study regarding the connection between risk management and stakeholder management. They conducted a systematic literature review and identified four linkage modes between risk management and stakeholder management. They suggest that an integrated risk management and stakeholder management can promote the effectiveness of both areas. These linkages show new ways of thinking about, analyzing, and then managing risks and stakeholders in a holistic and integrated way, but not the traditional way in individual areas. Integrating risk and stakeholder management is challenging but can be a way for improving project performance according to Xia et al.

To make the project work well-planned, structured and clear, a project model could be used, e.g. the PROPS model (Stille 2017). PROPS is a project management model developed by the Ericsson company which has been replaced by a further developed project model called XLPM (Excellence in Project Management). These models divide the project into different phases, and into a general project model and a work model, which are separated from the actual project work. The models are based on milestones and tollgates, which are important reconciliation points and decision points, respectively. The milestones represent a specific result that must be concluded or a specific action that must have been conducted and are a link between the project model and the work model. The toll gates are points that must not be passed until the sponsor, e.g. the decision maker, decides if and how the project shall continue.

The quality work and the risk management should be a part of the project work and not a control function parallel with the construction work. Stille (2017) suggests that a dualistic quality system should be adopted in geotechnical engineering projects that include substantial uncertainties. The dualistic quality system should focus not only on doing things right, but also doing the right things.

3.9. Shortcomings in geotechnical risk management

Earlier studies have exposed several shortcomings with the management of risks in general, as well as geotechnical risks in construction projects. Lewin (1998) discusses general limitations and identifies several weaknesses in common methods of risk management. Some of these are:

- Inadequate follow-up from the analysis phase to the control of risks once the project starts to be implemented.

- Concentration of risks in asset creation rather than on the potentially higher risks in other stages of the investment lifecycle (especially the operating stage).
- Existing methods for risk management fail to manage many risks.
- A tendency to focus on risks which may be most easily quantified.
- Too little attention to changing risk exposures during the investment lifecycle.
- No satisfactory method for combining risks, especially where, as is often the case, the separate risks are interdependent.
- A lack of consistency in analyzing and dealing with risks for different projects.

As a consequence:

- Projects are not consistently analyzed, even for the same sponsoring organization, and different standards of analysis are applied.
- Clients, investors, and other interested parties cannot rely on the result of the risk analysis.
- Risks, which were identified for mitigation, can remain unmitigated.
- There is no reliable basis for auditing risk analysis and management.

Jaafari (2001) discusses the management of risks, uncertainties, and opportunities on projects, and concludes that the risk management process is often regarded as a separate planning and response operation in many projects. Jaafari suggests a shift to strategy-based project management using a lifecycle project management approach to manage risks, uncertainties, and opportunities, and concludes that risk management is a way of thinking and a philosophy that should permeate all project activities.

Clayton (2001a) considers the management of geotechnical risks and discusses several limitations. A shortcoming, according to Clayton, is the fact that the traditional approach of dealing with geotechnical risks is based on a scientific method in a deterministic framework. Desk studies are used to hypothesize about geotechnical conditions, possible problems, and different types of the geotechnical design. Then, geotechnical investigations are planned and executed with the aim of determining the actual conditions at site in order to decide the final design. There are several problems with this approach. First, with an increasing trend of design-and-build arrangements, the geotechnical investigations cannot be adapted to the final design. Second, due to the variability of the properties of the ground, the design alone cannot be based on deterministic values from the geotechnical investigations. Third, since many of the deterministic design methods are, more or less, inaccurate and provide different results, the design alone cannot be based on these methods. In addition, Clayton argues that there has been growing emphasis on numerical modeling, more sophisticated models than before, and less attention to sound design principles, and concludes that sound design principles combined with experience are important for the successful management of geotechnical risks.

Other shortcomings according to Akintoye & MacLeod (1997), Nicholson et al. (1999), Hintze (2001), Clayton (2001b), Spross et al. (2015), Rostami & Oduoza (2017), Stille (2017), van Staveren (2018) and Powderham & O’Brien (2020) are:

- Absence of a structured and well-documented risk management process in many projects.
- Formal risk management techniques are rarely used due to a lack of knowledge and to doubts on the suitability of these techniques for construction industry activities.
- Risk management depends mainly on intuition, judgement, and experience.

- A separation between the risk management and other project management issues.
- There is a belief that all risks may be foreseen, but the risk management process cannot hope to identify them all. Unforeseen risks will exist and processes for managing these risks are often missing today.
- The link between the risk management in the planning, design and construction phase is weak as the risk management is performed by different individuals and not clearly documented.
- Responsibilities for, and authorities of, risk treatment actions are ambiguously described and not clearly explained in the project plan.
- The risks are not considered when developing the contractual framework.
- A systematic management of geotechnical risks is not considered as a part of the everyday work as it is often regarded as a task for experts and for large projects only.
- The different actors perform their own separate risk assessment, therefore a consensus of the risks is difficult to establish.
- The contracts are unclear regarding the allocations of risks.
- Procedures for solving disputes related to geotechnical risks during construction are missing, and dispute negotiation is postponed to after the construction is completed.
- The management of geotechnical risks is performed on different bases in different projects, depending on tradition, culture, individual knowledge and experience, as well as the perceived ability to manage the identified risks.
- Lack of time or effort for the implementation of decided risk treatment actions.

- Many projects identify and assess risks, develop risk treatment plans, and write risk reports, then “file and forget”. Consequently, risk treatment actions are not implemented, and the risk exposure remains the same.
- The risk management is, in some situations, confused with method statements and working procedures. While risk management provides information for decision making to do the right things, the method statements and working procedures focus on doing things right according to the international standards, e.g. SS-EN ISO 9001 and SS-EN ISO 14001.

The presented research suggests that the management of geotechnical risks has not improved significantly during the last decades. The problems that existed twenty years ago (e.g. Nicholson et al. 1999, Jaafari 2001 and Clayton 2001) still remain (e.g. Rostami & Oduoza 2017, van Staveren 2018 and Powderham & O’Brien 2020). The most serious problem is, of course, the lack of some form of risk management in many projects. The absence of a structured risk management process can have severe consequences for the project performance in terms of cost, time and quality.

3.10. Conclusions

3.10.1. Risks and uncertainties in geotechnical engineering

Geotechnical risks can be defined as the effect of geotechnical uncertainty on objectives. An objective in a geotechnical engineering project may be to complete a specific structure that satisfies both the client’s requirements on costs, time, and quality. and society’s requirements on structural safety and environmental sustainability. Geotechnical risks have influence on, for example, the technical, economic, and contractual parts of a project, as well as the project management.

There are several reasons why geotechnical risks often affect the outcome of a geotechnical engineering project in a severe way. These are both due to the special nature of the ground, e.g. pre-determined properties with large variability, and the characteristics of many geotechnical works, e.g. work activities connected as series systems.

In geotechnical engineering, uncertainty is mainly caused by the lack of knowledge regarding the geotechnical conditions at a site. This kind of uncertainty is known as epistemic uncertainty and can be reduced by gaining additional information about the geotechnical conditions before or during construction. There is also uncertainty that is caused by randomness, known as aleatory uncertainty, which cannot be reduced.

3.10.2. The allocation of risk

The allocation of risks is governed by the contractual arrangement, i.e. the type of contract and the form of compensation (payment method). The choice of type of contractual framework depends on several factors, e.g. the client's long-term objectives and procurement strategy, legal aspects, time, project characteristics and complexity, client's resources and competence, risk acceptance, degrees of freedom in the execution, possibility to innovate, and the competitive situation.

In an optimal situation, the contract should allocate the risks, responsibilities, and authorities in a fair way and with a direct connection between risk taking, work, and compensation. The general idea of risk allocation is that the party that has the ability and capacity to manage a risk shall be responsible for it. The party that carries a risk should be given reasonable compensation for it.

To choose an appropriate contractual framework, it is important to perform a comprehensive risk assessment before the contract is signed. The contract should try to describe and regulate all imaginable deviations and changes which may arise during the project execution, especially deviations arising from the geotechnical conditions, which often are disputable.

3.10.3. Geotechnical baselines

It is important that all actors understand the risks that each actor is responsible for, otherwise poor cooperation between the actors involved and/or disputes may occur. To describe the responsibility for geotechnical risks, a geotechnical baseline report should be included in the contract. The geotechnical baseline report should present the known geotechnical conditions and set the range of geotechnical conditions that should be provided for and included in the contract price. The geotechnical baseline report should include measurable contractual descriptions of the geotechnical conditions. A list of geotechnical hazards to be considered in the tender could also be included.

The geotechnical baseline report should preferably also incorporate a contractual mechanism to determine how to deal with conditions outside the baselines, so-called abnormal or differing site conditions. The baselines must be relevant, balanced, and realistic. Conservative baselines can lead to overly conservative and costly bids as the contractor probably will add a high-risk premium to the bid. The opposite, non-conservative set baselines, would allocate most of the geotechnical risks to the client.

3.10.4. Dispute resolution

If the risks are not adequately allocated in the contract, claims and disputes may be some of the consequences. Using a mutually agreed model of the geotechnical conditions, e.g. presented in a geotechnical baseline report, and a comprehensive set of parameters to base remeasurements on may provide a sound basis for negotiation. The joint appointment by all actors to a contract of a dispute review board to advise independently on the technical merits of a dispute may also help to speed up dispute resolution, thus saving considerable time and money. An independent geotechnical advisory panel can be used during the execution of the project to address geotechnical matters before they become an issue for disputes and claim.

3.10.5. Contractual considerations

Methods of procurement in the construction industry have changed during the last decades. Today, the traditional arrangement, e.g. design-bid-build contracts, with a single consultant engaged for design and supervision of the work, is used less frequently. Instead, more competitive, and time-restricted conditions have led to new requirements and demands for construction clients, designers, and contractors. Traditional contracts have been replaced by methods such as design-and-build and other similar arrangements. Collaborative arrangements, such as partnering, have been found to be appropriate when it is difficult to define the project before execution, e.g. regarding technical solutions, production methods, and geotechnical conditions.

3.10.6. Management of geotechnical risks

Due to the risks and uncertainties involved in many geotechnical engineering projects, the use of project management with a risk perspective, i.e. project risk management, has grown in the construction industry in recent decades. The fundamental objective of these methods is to gain insight into the principal sources of uncertainty and to create opportunities to manage the risk in a systematic and effective way to ensure a cost-effective product with a desired quality. A successful geotechnical risk management needs to be structured, adapted to the characteristics of the project, integrated into the other project activities and part of the everyday work. The risk management procedures should be introduced in the planning phase and updated throughout the lifetime of the project. This gives an updated risk profile which allows the incorporation of experience into the project, new opinions of experts, and new technical developments. In complex projects with substantial geotechnical uncertainties present, the observational method has proven to be effective for managing geotechnical risks in the execution phase.

Geotechnical risks are unavoidable and will always be present in geotechnical engineering projects. Additionally, all risks may not be foreseen and managed before the start of the construction phase. Therefore, the management of risks and uncertainties is a central feature of the design and construction process in geotechnical engineering and should be a part of the geotechnical engineer's everyday work.

Central concepts in the process from hazard to damage are risk object, hazard, initiating event, warning bell, damage event, and damage object. These concepts and their meanings are often used with differently in different situations, but it is recommended that a stringent nomenclature is used in the context of risk management in order to avoid misunderstandings and to ensure effective risk management. Warning bells, or "damage indicators", exist for almost all types of hazards in geotechnical engineering, and they are crucial to identifying and noticing the hazards in due time.

The performance and quality in construction projects depend on an understanding and management of the geotechnical risks and uncertainties involved. The cooperation between the parties involved and the allocation of the risks between the actors involved in the construction process also influences the result of the project.

Regardless of the type of contract and the payment method, risks will be best managed when the risk management process is started in the planning phase, and key individuals representing all the actors involved are brought together as early as possible in the project. It is in all actors' best interest to assess the risks involved as well as possible before the contract is signed. However, there is always a conflict of interests involved in a project, which makes the allocation of risks difficult. Additionally, all types of contracts can be used in an opportunistic and speculative way.

The success of the risk management process in geotechnical engineering projects depends, for example, on:

- An understanding that geotechnical risks are unavoidable and always will be present in geotechnical engineering projects.
- An understanding of the different types of uncertainty, i.e. epistemic and aleatory uncertainty, and how additional information can be used to decrease the uncertainty.
- An understanding of the geotechnical hazards and the process from the initiating event to the damage.

- The use of a risk management framework that enables a structured and effective management of geotechnical risks, e.g. the framework described in SGF (2017) and Spross et al. (2020).
- An understanding of the obstacles which can hinder a successful project risk management, e.g. human and organizational obstacles.
- An appropriate and clear allocation of the geotechnical risks between the actors involved based on the characteristics of the project, the geotechnical risks involved, and the actors' ability to manage the risks.
- Inclusion of a geotechnical baseline report in the contract.
- The use of a geotechnical advisory board and a dispute review board in projects with complex geotechnical conditions.
- The execution of geotechnical projects as innovation projects (or exploratory projects) rather than implementation projects.
- The use of a project model that incorporates the risk management process and quality work into the daily project work.
- The use of a dualistic quality system that focuses on both doing things right and doing the right things.

4. The observational method in geotechnical engineering

4.1. Introduction

Observations have been used by engineers to deal with uncertainties and to observe the performance of structures since the early days of civil engineering. In those days, modifications of the design based on observations were often made using a “trial-and-error” and “ad hoc” process. With the development of modern soil mechanics, an integrated process, pioneered by Terzaghi, of predicting, monitoring, reviewing, and modifying the design gradually evolved.

Terzaghi & Peck (1948) discussed the first thoughts and ideas behind this process in geotechnical engineering as they drew attention to the fact that geotechnical conditions often differ to the predictions made from the site investigations. They considered problems and risks that arise when the actual conditions are different from those predicted and emphasized that the design should be modified in accordance with these conditions to maintain an acceptable safety level. In addition, they also concluded that a design based on the most unfavorable condition is non-economic. Therefore, they suggested a new design procedure, called the observational procedure, where information obtained during the construction phase is used to optimize the design (Terzaghi & Peck 1967).

This procedure was eventually named the “observational method” by Peck (1969a), who provided the basis to understand the overall philosophy and the essential requirements and limitations of the observational method. Later, Peck (1985) raised his concerns about the potential misuse of the method, but still recognized it as an appropriate method if it is used in its intended way.

In Sweden, the term “active design” has been used to describe a broader methodology for the design and execution of complex underground structures, similar to the observational method described by Peck (Stille 1986). This methodology was introduced for emphasizing that the design should be an active element subjected to modifications as additional information is obtained during the construction process.

The interest for the application of the observational method has increased in Europe during the last couple of decades, mainly due to the drive for competitiveness in the construction industry, as well as an increasing demand on reducing time and costs. In the UK, there was a notable increase in interest of the observational method in the early 1990s due to concerns of reducing construction time and costs, improving safety, and improving cooperation in the industry.

In the report by Latham (1994), the procurement and contractual arrangements in the UK construction industry were reviewed. The report gave recommendations on how to reduce the construction costs by 30% by the year 2000. Of this 30%, a saving of 20% was assumed to be achieved in the design process by better collaboration between the designer and contractor. Used in its intended manner, the observational method will improve these issues (Nicholson et al. 1999). The establishment of the Eurocode part 7 (EN 1997-1), that considers the observational method as one of the designated methods for verifying limit states in geotechnical engineering, has probably increased the interest in and use of the method further.

The demands for reducing the use of resources, costs and completion times, increasing safety, and improving cooperation in the construction industry will increase the demand for new design and construction methods, as well as improved methods for management of geotechnical risks, according to Nicholson et al. (1999). The observational method is a design method that has the potential to satisfy these demands as long as it is used in an appropriate way together with adequate risk management, even if it may lead to increased initial costs for design and observations in the construction phase (Powderham 2002b).

The observational method has been proposed as a cost-effective and safe working practice in construction projects, especially in complex projects including geotechnical risks and uncertainties by, for example, Baecher (1981), Ladd (1991), Nicholson et al. (1999), Powderham (2002a & 2002b), GeoTechNet (2005), Spross et al. (2014), Chen et al (2015), Spross (2016), and Stille (2017). The theoretical background to the observational method has been discussed by, for example, Spross (2016) and Bjureland et al. (2017).

However, the observational method has not been used to its full potential for several reasons. Powderham & O'Brien (2020) assert that one reason is that there are no guidelines regarding the implementation of the method in a project environment, e.g. regarding contractual arrangements. If these issues are not handled appropriately, the adoption of the observational method may lead to disputes regarding decisions and contingency measures, as well as time and cost. A second reason, according to Powderham (1998), is that the observational method, for the wrong reasons, has been associated with low safety margins and potential time and cost overruns. The reasons for this are initial designs that are too optimistic, based on most probable conditions of the geotechnical parameters, as well as the demand for alternative design solutions and predefined actions if the actual conditions differ from those anticipated in the initial design. Spross & Johansson (2017) suggest that a third reason may be the unclear safety definition and the lack of guidelines on how to establish whether the observational method is more favorable than traditional design methods.

The present chapter includes the concept of the observational method, differences from the traditional design methods, benefits and limitations of the observational method, experiences from case histories of the observational method presented in the literature, the relation to some design codes and risk management, and contractual considerations, as well as some management considerations with respect to the observational method. The chapter ends with conclusions from these sections and recommendations for successful implementation of the observational method in geotechnical engineering.

4.2. The concept of the observational method

4.2.1. Definition by Peck

The concept of the observational method has its origin in a procedure for a cost-effective and safe execution of geotechnical works, which was introduced for the first time by Peck (1969a). This procedure divides the design process into eight parts:

1. “Exploration sufficient to establish at least the geotechnical nature, pattern and properties of the deposits, but not necessarily in detail.
2. Assessment of the most probable conditions and the most unfavorable conceivable deviations from these conditions. In this assessment, geology often plays a major role.
3. Establishment of the design based on a working hypothesis of behavior anticipated under the most probable conditions.
4. Selection of quantities to be observed as construction proceeds, and calculation of their anticipated values on the basis of the working hypothesis.
5. Calculation of values of the same quantities under the most unfavorable conditions compatible with the available data concerning the subsurface conditions.
6. Selection in advance of a course of action or modification of design for every foreseeable significant deviation from the observational findings from those predicted on the basis of the working hypothesis.
7. Measurement of quantities to be observed and evaluation of actual conditions.
8. Modification of the design to suit actual conditions.”

These principles provided a basis for the understanding of the fundamental requirements of the observational method. According to this procedure, the observational method has a specific and restricted meaning, and Peck was categorical about the possibility to modify the design during construction. If this is not possible, then the method is not applicable. The nature and complexity of the work generally determine the extent of the program, and all these parts may not be applicable to their full extent in all projects.

Peck identified two typical situations where the observational method can be applied. First, is a situation where a failure or accident threatens or has occurred, i.e. a “best-way-out” situation. In these situations, the observational method may be the only way to success. Under these circumstances, most engineers will probably instinctively adopt such a procedure to try to “rescue” the project, i.e. to modify the design to meet actual conditions. Second, is a situation in which the method has been adopted from the inception of the work. In this situation, “ab initio”, the observational method offers more benefits regarding safety, economy, and time than traditional design methods, since it may lead to the best possible design with respect to the actual geotechnical conditions. It is generally the “ab initio” application that is intended when referring to the observational method nowadays, and the application that has the greatest potential.

In the definition of the observational method by Peck, the design starts with the “most probable” conditions according to part 3 in the procedure above. The “most probable” conditions relate to the nature, pattern, and properties of the ground and should be based on the most reasonable interpretation of the geotechnical conditions at hand. This process will involve the selection of less conservative design parameters than in traditional design methods, but also requires judgement of unquantifiable factors. In geotechnical engineering, these factors will typically include non-linear, three-dimensional, and time-dependent effects. Possible modes of failure must be addressed carefully, especially those including brittle or progressive failure. Thus, some conservatism is necessary and careful judgement is essential to balance the measures to assure safety with the potential savings in time and/or cost.

According to the definition by Peck, the site investigations should at least establish the geotechnical nature, pattern, and properties of the ground, but not necessarily in detail (part 1). In addition, the design should start with "most probable" conditions and be modified if the actual conditions differ from the "most probable conditions" (parts 3, 6 and 8). Starting the design with most probable conditions based on a general site investigation would probably result in many situations where the actual geotechnical conditions differ from those anticipated in the design and, consequently, modifications must be made.

Powderham (1994) discussed the difficulties in implementing a design based on the "most probable" conditions according to Peck (1969a) and noted that a fundamental element when applying the observational method is to overcome the limitations of analysis by addressing actual or "most probable" conditions. A design based on "most probable" conditions may create concerns about the safety, which could inappropriately be associated with low safety margins. In addition, contingency measures must be introduced more often with a design based on "most probable" conditions, which may lead to cost and time overruns, while in the meantime the safety margin may decrease and the risk increase.

Powderham (1994) considered it to be more suitable to base the design on "more probable" conditions rather than "most probable" conditions. Here, "more probable" conditions are those considered to be between the "most probable" conditions and "moderately conservative" conditions (Figure 14). A design made under these conditions is less conservative than a traditional design, but more conservative than one based on the "most probable" conditions.

The "moderately conservative" parameter values were introduced in CIRIA report 104 (CIRIA 1984). The "moderately conservative" parameter is a cautious estimate of a parameter, worse than the probabilistic mean but not as severe as the most unfavorable. The "moderately conservative" value is defined as a range, and the specific value depends on the structural properties and soil properties, e.g. type of foundation and the ability of the soil to redistribute the load.

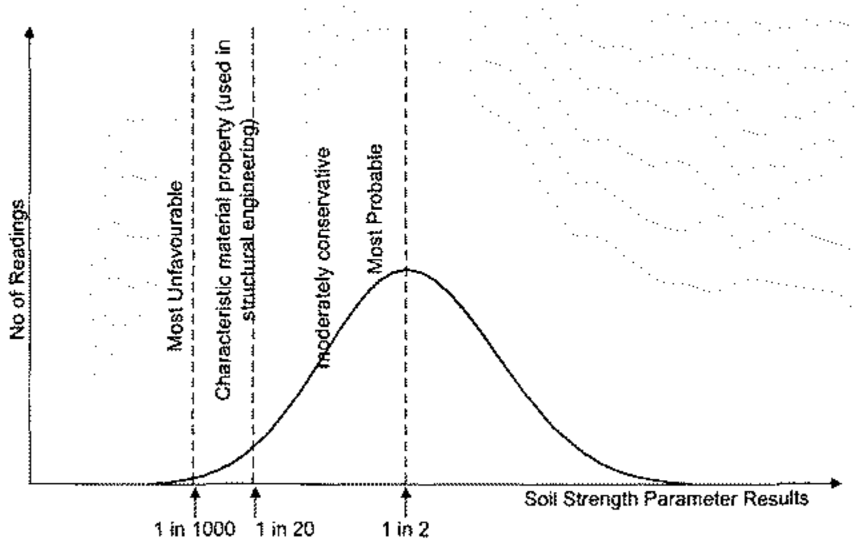


Figure 14: Concepts of soil strength parameters in the design process (Nicholson et al. 1999).

Hardy et al. (2017) suggest that the uncertainty in which design parameters to use, may partially explain why the observational method has not been exploited to its full extent in the construction industry.

4.2.2. Definition according to CIRIA report 185,

In CIRIA report 185 (Nicholson et al. 1999), the observational method is described as:

> “A continuous, managed, integrated, process of design, construction control, monitoring and review which enables previously defined modifications to be incorporated during or after construction as appropriate. All these aspects have to be demonstrably robust. The objective is to achieve greater overall economy without compromising the safety.”

This process is presented in Figure 15. The different steps in this process are described below based on Nicholson et al. (1999).

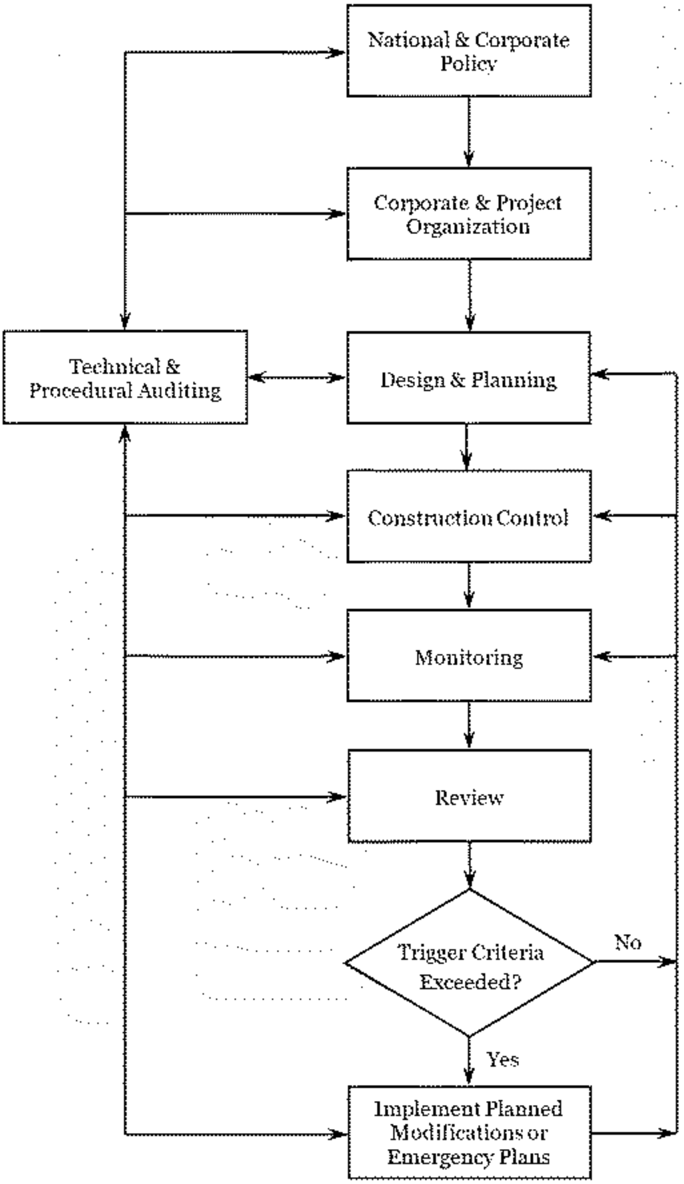


Figure 15: The observational method (after Nicholson et al. 1999).

National and corporate policy

Nicholson et al. (1999) state that the observational method must be carried out within the framework of any national and corporate policy. These are the values and objectives of an organization and the criteria and principles on which actions and responses are based, e.g. laws, design codes, quality management systems, works specifications, safety regulations and conditions of contracts. Experience has demonstrated that a suitable corporate and project operating environment, e.g. where the definition and limitations of the observational method are understood and suitable specifications and contracts arrangement are adopted, is important.

Corporate and project organization

The corporate and project organization should be established before the observational method is implemented, according to Nicholson et al. (1999). This includes key actors, i.e. the client, designer, contractor, and reviewers, involved in design, construction and monitoring, and their roles, responsibilities, relationships and authorities. The key actors need to have an understanding of the key aspects of the observational method, and the technical and commercial risks and should plan contingency measures to be used if program or cost is influenced. Procedures for communication should be established.

Design and planning

The design and planning phase involves collection of data, interpretation of data, initial and final design, establishment of contingency measures, procedures for risk management, allocation of resources to achieve the objectives, as well as decisions regarding priorities. According to Nicholson et al. (1999), this phase should start with a desk study, in which the type of problem to be encountered is defined. The main source of information is usually previous case histories in similar geotechnical conditions and earlier site investigations in the surroundings. Back-analysis may be used to determine the most probable design parameters. Hardy et al. (2017, 2018) maintain that maximum benefit of the method is achieved by back analyzing case histories in similar ground conditions to derive the design parameters. Duncan e& Brandon (2019) discuss the use of the method as the only basis for design where the design parameters are derived by back-analysis of the stability of existing slopes.

A desk study has eight primary objectives in the context of the observational method (Nicholson et al. 1999):

1. To determine what is known about the site and to help to decide to what extent and by what method it should be further investigated.
2. To identify the type of construction problems that might occur and to consider the range of construction options available.
3. To establish the acceptable limits of behavior, e.g. regarding permissible deformation of adjacent buildings.
4. To identify geotechnical hazards and define design parameters, e.g. most probable, moderately conservative, and most unfavorable parameters, to assess the potential risks associated with each of the conditions and to define the acceptable level of risk.
5. To assess the feasibility of using the observational method based on the geotechnical conditions.
6. On the basis of the available information, to assess if the degree of uncertainty is large enough to merit the use of the observational method.
7. On the basis of the desk study, to assess the feasibility of different engineering schemes.
8. To assess the cost and benefits of implementing the observational method.

The desk study is generally followed by a site investigation which should, at least, establish a general view of the geotechnical conditions and the potential geotechnical behavior. Nicholson et al. (1999) suggest that a phased approach to site investigations is often appropriate. During the initial phases of the site investigation, the site should be investigated sufficiently enough to establish the range of geotechnical conditions and parameters to meet the requirements identified in the desk study. An initial site investigation for a project using the observational method should, besides the essential geotechnical and hydrological conditions, obtain information of the most probable and most unfavorable design conditions. The final phases of the site investigations could be undertaken during construction, e.g. using traditional site investigation methods or observations made during the actual work.

The interpretation of data includes assessment of the information from the site investigation, the range of design conditions likely to be encountered, and the corresponding design parameters to be considered. The objective of the data interpretation is to assess the design conditions, identify geotechnical hazards and uncertainties, and decide whether it is appropriate to implement the observational method. The data should be kept under constant review and re-evaluation as additional information becomes available.

Nicholson et al. (1999) divide the design process into an initial design and a final design. The initial design, also known as the scheme design stage, includes calculations, method statements, construction plans, program, allocation of resources, monitoring plans, and procedures for implementing the contingency measures. Both designer and constructor should be involved, if possible. In the final design, the steps in the initial design are re-evaluated in the light of any new information, further interpretation of data, and new requirements from the client. In other references to the observational method, final design is often referred to as the design after modifications, i.e. the design of what was built.

The initial design should be regarded as a temporary design, which is subjected to modifications during the construction phase. Terzaghi (1945) wrote:

> "[...] a vast amount of effort and labor goes into securing only rough approximate values for the physical constants that appear in the equations. Many variables, [...], remain unknown. Therefore, the results of computations are not more than working hypotheses, subject to confirmation or modification during construction."

The objectives of the initial design phase are to (Nicholson et al. 1999):

- Reconfirm the client's requirements and expectations.
- Assess options through value engineering (see e.g. Guthrie & Mallet 1995, ICE 1996, Connaughton & Green 1996, and Section 4.7.5).
- Carry out initial design covering all likely scenarios for at least two sets of design parameters, e.g. most probable and most unfavorable or moderately conservative and most unfavorable.
- Decide the procedures and resources for implementing the planned contingency measures.
- Identify the observations to be monitored and consider options for monitoring schemes.
- Make a value engineering assessment of the designs, the corresponding modifications, and the associated monitoring.
- Assess buildability of the design, i.e. ensure that the design is uncomplicated to construct.
- Decide on either progressing with a traditional design method based on moderately conservative conditions or continuing to develop the observational method.
- Interact with the contractor concerning the above requirements and to develop the associated preliminary method statements.
- Take full account of matters affecting health and safety.
- Review the hazards and carry out risk assessment.

Powderham (1998) and Nicholson et al. (1999) recommend the use of the “progressive modification” approach starting with more conservative design parameters instead of a design that starts with “most probable” conditions. They considered this approach to be a safer method than the original approach of the observational method presented by Peck (1969a). They recommend using Peck’s approach starting with “most probable” conditions only in projects where there are previous case history data available on similar geotechnical conditions, a multi-stage construction sequence is planned, or experience of the observational method is extensive.

In the “progressive modification” approach, the design starts with predefined design parameters, see e.g. Powderham (1994, 1998 & 2002) and Ikuta et al. (1994). An initial step in the progressive modification is to establish an acceptable basis on which to implement the method. This assessment must identify adequate savings while maintaining safety. During construction, the performance should be reviewed, and back-analysis should be used to re-evaluate the parameters. All relevant information should be progressively synthesized through a feedback loop, and the overall performance should be measured and evaluated, e.g. soil-structure interaction, construction methods, communication, and teamwork.

The objective of the “progressive modification” approach is the same as in the original definition of the observational method by Peck (1969a), to sequentially make design changes during construction that maximize overall project benefits, i.e. that result in cost or time savings while maintaining a risk level that complies with existing laws and design codes, and that is acceptable to the actors involved in the project. In “best-way-out” projects, the overall benefit from the progressive modification approach is to avoid implementing the design changes too early when sufficient knowledge is not present. Impulsive design changes may adversely affect safety or at best lead to unnecessary cost or delay.

Powderham & Nicholson (1996) considered that it might be appropriate to start with “moderately conservative” parameters when applying progressive modification. The design is then “relaxed” to a likely real situation and “more probable” or “most probably” condition during construction if the observed behavior permits it. Nicholson et al. (1999) recommend that the design in the observational method uses “most probable” and “moderately conservative” conditions in serviceability limit design, e.g. for deformations and load predictions, and “most unfavorable” conditions in ultimate limit designs and robustness checks during risk management.

The process in the observational method operates on the basis that monitoring and reviewing of data will reveal the appropriate time for introduction of the contingency measures. Therefore, the method will operate most effectively when conditions deteriorate gradually to the design limit state. This ensures that there is sufficient time to review and analyze the monitoring results, and to implement contingency measures if necessary. A fast deterioration rate requires continuous monitoring, with immediate review of the observations and implementation of contingency measures.

The limit states can either develop through gradual ductile behavior or in a rapid brittle manner, similar to the progressive failure mechanism referred to by Peck (1969a). The main differences between ductile and brittle geotechnical behavior are presented in Table 6. Brittle behavior may lead to progressive failure as the stress is transferred to the surrounding soil/rock, which may become overstressed. Consequently, the possibility of progressive failure may introduce a serious element of uncertainty. If the behavior is brittle, there is usually not sufficient time to implement appropriate contingency measures as soon as the failure mechanism has been initiated. Thus, the presence of brittle elements may, if not acknowledged, lead to failure despite the use of the observational method, due to its rapid nature of failure.

Besides quality control measures, material quality and workmanship, the rate of deterioration depends on (Nicholson et al. 1999):

- Geotechnical conditions (e.g. ductile/brittle soil behavior).
- Hydrological conditions (e.g. rainfall, high pore water pressures and liquefaction).

- Temporary surcharges (e.g. unexpected loads to structures).
- Construction sequence and program (e.g. multi-stage or incremental construction process).

Table 6: Comparison between ductile and brittle geotechnical behavior (after Nicholson 1994).

Feature	**Ductile**	**Brittle**
Nature of failure	Gradual developments of movements	Abrupt with progressive failure
Governing limit state	Serviceability	Ultimate
Prediction ability	Numerical models provide reasonable deformation predictions Many case histories for extrapolation	Modeling complex because of rapture and stain softening Few case histories to back-analyses
Monitoring systems	Simple monitoring can be used Time to implement contingency plans	Simple monitoring cannot detect pre-failure movement Progressive failure so rapid that contingency plans cannot be implemented
Influence on the observational method	Good Gradual deformation enables people to be evacuated Damage to structures can be avoided or controlled to acceptable levels while still operating close to most probable conditions Good opportunities for savings	Bad Work in small stages to minimize risk to people and structures Need to work conservatively with comfortable factors of safety In soil/structure applications the structural failure should be ductile even if the local soil mode is brittle Poor opportunities for savings

The steps in the initial design should be re-evaluated in order to complete the design in the light of any new information, further interpretation of data, and new requirements from the client during the final design phase. The objectives of the final design phase are to (Nicholson et al. 1999):

- Define trigger criteria for the project structure and adjacent buildings.
- Produce final designs for the most probable, moderately conservative, and most unfavorable design conditions.
- Confirm the method of dealing with planned modifications and emergency procedures, and the strategy for mobilizing the resources.
- Confirm that all hazards are identified, and mitigation measures are put in place.
- Produce a final set of designs which may be tendered and built.

A plan of contingency measures should be prepared for every foreseeable significant deviation from the initial design conditions. It should be possible to implement the contingency measures in time to prevent safety from being reduced to unacceptable levels and/or to reach an unwanted geotechnical condition. The contingency measures should be defined in advance of the construction works and should include change of design, construction sequence, construction method etc. Contingency measures could include measures to be applied during unwanted conditions and a plan to achieve potential benefits. Planning is important to ensure that the contingency measures may be implemented with the right speed in due time to avoid a failure condition. In addition, health and safety issues should be assessed together with the risks associated with the construction method and planned modifications, according to Nicholson et al. (1999).

Trigger criteria

A trigger criterion, sometimes called an alarm threshold, defines the limit for implementing the contingency measures. Olsson & Stille (2002) define an alarm threshold as “a predetermined value of one or a combination of several monitor parameters which, if exceeded, will trigger predetermined measures in order to prevent damage". According to Spross & Gasch (2019), the establishment of the alarm threshold is a crucial aspect. The alarm threshold should neither be too conservative, to avoid false alarms, nor too tolerant to avoid failures.

According to Nicholson et al. (1999), the trigger value should be assessed with respect to the time for performing and reviewing the observations, decision making, and implementing the contingency measures. A trigger criterion may be based on the time necessary for implementing the contingency measures and the time for the measures to prevent the critical limit, or an unwanted condition, from being exceeded (Paté-Cornell & Benito-Claudio 1987). The contingency measures generally require some time to be effective. Therefore, it is necessary that some time, "lead time", elapses between the time when the trigger criteria and the critical limit state is reached (Figure 16). If the consequence of failure is serious, conservative estimates should be made of the time required to identify the need for, and implementation of, the contingency plans.

A trigger criterion should be based on a prognosis of the geotechnical behavior and reflect the expected value of the measured quantity. The trigger criteria depend on the physical quantity that is considered, and an important issue in the initial design phase is to carefully decide which quantities, i.e. control parameters, are to be observed in the construction phase. These robust parameters should reflect the present uncertainties and expose the significant events that influence the geotechnical behavior in a relevant way. The control parameters may be physical or chemical properties, e.g. forces, deformations, temperature, and chemical substances, which may be assessed either by calculation or empirical procedures for the range of conditions considered in the design.

Besides the trigger criteria, it can be useful to define a target value and critical limit (Stille et al. 2003). Here, a target value is a guide to efficient and safe work. For example, a value of vibration during blasting which is set so that the blasting can be carried out with as large rounds as possible, but at the same time with sufficiently low probability of exceeding the alarm threshold. Stille et al. (2003) define the critical limit as the limit where damage is expected to occur with an unacceptable probability. Spross & Gasch (2019) define the critical limit as the limit where unacceptable behavior occurs with too high probability. It is important that the trigger criteria, target value, and the critical limit are set under careful considerations and are clearly distinguished between. Arbitrarily set values tend to undermine the importance of the observations and the perception of the risk.

To determine trigger criteria and lead times, a model of the geotechnical behavior should be established (Olsson & Stille 2002). Different types of systems, e.g. series systems (weakest link systems) and parallel systems, loading situations, and stress-strain relationships result in different geotechnical behavior as well as different trigger criteria and lead times. The efficiency of the project organization should also be considered.

Construction control and monitoring

Construction control and monitoring constitute of, in the context of the observational method, a planned process of collecting information about the construction process and the monitoring. This process includes the establishment of a monitoring plan, monitoring specifications, and a construction control plan setting out procedures and reporting methods.

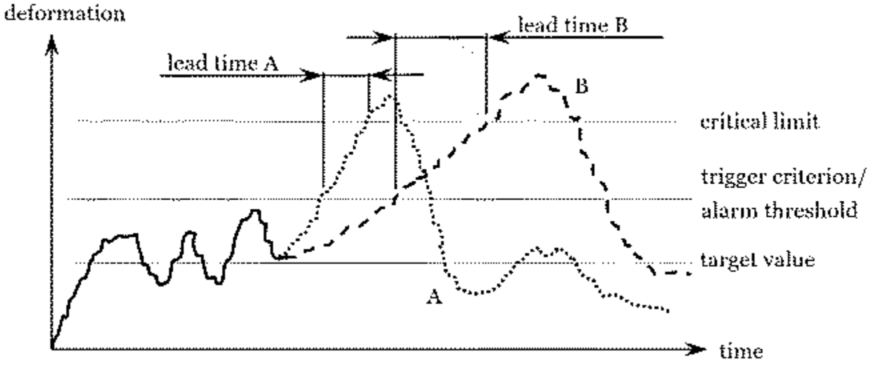


Figure 16: Alarm thresholds and lead times for two different stress-strain relationships A and B.

The duties and responsibilities of different actors regarding these issues should also be defined. In addition, the construction control may also include processes of dualistic quality assurance, observations of actual geotechnical and mechanical behavior, and check-ups on the established requirements.

The objective of site monitoring in the context of the observational method is to gather relevant data to be compared with trigger criteria. The monitoring scheme should be based on a thorough hazard identification and hazard analysis. The construction control and the monitoring should be based on a monitoring plan established before the construction starts. The extent of a monitoring system ought to be based on several factors, e.g. geotechnical conditions, design situation, construction sequence, the probability and consequence of the potential damage events, as well as the cost of the system components and measurements. The strategy behind the monitoring plan should be to provide the designer with sufficient information to verify the initial design or to implement planned contingency measures when necessary. The monitoring must give an indication of unforeseen behavior and a confirmation that appropriate quality standards have been met.

Peck (1969a) emphasized the importance of asking the right questions when designing the monitoring system. The planning of a complex monitoring system requires adequate knowledge and experience of measurements under similar conditions, i.e. geotechnical conditions and type of structure and instruments. However, not all applications will require specialists and sophisticated instruments. Instruments that are well documented and tested under the circumstances at hand should generally be preferred. The key is to combine comprehensiveness with reliability, repeatability, and simplicity.

The observations should be made at an appropriate time and interval during a construction sequence. The results of the field observations are only useful if they reported promptly and clearly show the essential features. The feedback and assessment from the observations must be timely in order to confirm the predictions or to provide adequate warning of unexpected trends, and there must be sufficient time to effectively implement the planned contingency measures. The reports, including the results, should be regarded as working documents, issued whenever the information needs to be brought up to date.

Review

The objective of the review phase is to review the monitoring results against pre-determined criteria and the decision on, and execution of, contingency measures. The review will be based on information gathered during the construction, e.g. regarding construction progress, observed geotechnical conditions, and results from the monitoring. The decision process requires proactive monitoring where timely, reliable, and easily interpreted data are collected and critically examined. In addition, there needs to be clear instructions to all involved regarding the planned contingency measures. The frequency of the review should be based on the potential failure and recovery patterns in order to identify adverse trends and events before a failure condition is reached. Procedures for review and interpretation of the information should be established before the start of the construction so that delays in reaching critical safety decisions can be avoided.

It must be acknowledged that there may be errors and/or bias in the measurements or the interpretation of the measurements. Additionally, it is important not only to focus on the absolute values of the observations but also on the trend or pattern, as well as the rate of change of observed parameters with time.

Technical and procedural auditing

The technical and procedural auditing is, according to Nicholson et al. (1999), a structured process of collecting information on the efficiency, effectiveness, and reliability of the management system, and making plans for the contingency measures. The objective of the technical and procedural auditing is generally to provide an independent assessment of the validity and consistency of all components of the application of the observational method. The process of the observational method should be audited at a frequency that is agreed by all key actors involved in the process.

The technical auditing concerns the technical aspects of the observational method, e.g. design, workmanship, and quality of monitoring. The procedural auditing concerns the procedural aspects, e.g. how the design and the construction works are carried out. The auditing supports the monitoring by providing the project team with information on the implementation and effectiveness of the performance. It also provides a control mechanism on the reliability, efficiency, and effectiveness of the system and process, and provides information for improving the application of the observational method. The auditing and monitoring should be a part of the quality control and quality assurance. Ideally, auditing should be carried out by a team of engineers independent of the process.

4.3. The observational method in Eurocode 7

According to Clause 2.1 in Eurocode 7 (CEN 2004) “Basis of geotechnical design”, the limit states in geotechnical engineering may be verified by one or a combination of the following methods:

- Calculations (analytical, semi-empirical, or numerical).
- Adoption of prescriptive measures (i.e. comparable projects or comparable experience).
- Load tests and tests on experimental models (tests on large or small-scale models).
- The observational method.

The first three verification methods are primarily methods for validating the proposed design. The use of calculations may be based on partial coefficients and/or probabilistic methods. Design by prescriptive measures is an empirical method that has a lot in common with semi-empirical principles which originate from case histories. The observational method generally allows the combination of the first three methods with flexible construction methods in situations where there is a wide range of geotechnical uncertainties. This flexibility is provided by an integrated process of planning, monitoring, reviewing, and implementation of planned modifications.

The definition of the observational method in Eurocode 7 is general and includes a rather short list of requirements regarding the method. This definition is slightly different from that of Peck (1969a). In Eurocode 7, the observational method process is primarily aimed at the "ab initio" application but does not exclude the "best-way-out" application. According to Subclause (1) in the definition in Eurocode 7, it may be appropriate to apply the observational method when it is difficult to predict the geotechnical behavior. In geotechnical engineering, predicting the geotechnical behavior may be synonymous with the difficulty of achieving a sufficiently accurate assessment of the in-situ geotechnical conditions. Therefore, the uncertainties are linked to the acceptable level of accuracy in the assessment of the properties and/or behavior of the soil/rock, boundaries of soil/rock layers and structural elements, and the result and quality of the planned contingency measures.

When adopting the observational method, the following five requirements shall all be fulfilled before construction starts, according to Subclause (2)P in Clause 2.7 (where P stands for principle and implies a mandatory part):

(i) "Acceptable limits of behavior shall be established.

(ii) The range of possible behavior shall be assessed, and it shall be shown that there is an acceptable probability that the actual behavior will be within the acceptable limits.

(iii) A plan of monitoring shall be devised, which will reveal whether the actual behavior lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage and with sufficiently short intervals to allow contingency measures to be undertaken successfully.

(iv) The response time of the instruments and the procedures for analyzing the results shall be sufficiently rapid in relation to the possible evolution of the system.

(v) A plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behavior outside acceptable limits."

Additionally, three more principles are stated:

- "(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 behavior 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 quality."

The phrases "acceptable limits of behavior" and "acceptable probability that the actual behavior will be within the acceptable limits" are not explained explicitly in Eurocode 7. The "acceptable limits of behavior" may be seen as threshold values when the design needs to be modified. The "acceptable probability that the actual behavior will be within the acceptable limits" is related to the probability that any contingency measures must be put into action. According to Spross & Johansson (2017), the initial design should be chosen so there is an acceptable probability that costly and/or time-consuming contingency measures must be executed.

In Eurocode 7 and available design guidelines, e.g. Frank (2004), there is no guidance regarding the fulfillment of the requirements in Subclause (2)P or the society's requirements on structural safety of the final design. These issues have been discussed by, for example, Spross et al. (2014). In addition, there are no guidelines regarding how the observational method should be managed and integrated during construction. Furthermore, it is unclear how the trigger limits are selected to establish an appropriate plan of contingency actions. Practical application of the definition of the observational method in Eurocode 7 is discussed in Spross & Larsson (2014) and Spross (2016).

4.4. Suitability of the observational method

The most appropriate design method is that which results in the lowest costs while fulfilling the formal requirements, e.g. regarding resistance, serviceability, durability, environmental impact, and working environment, at an acceptable level of safety. The decision on whether to use the observational method should be based on a judgement of whether the benefits of reducing the identified uncertainties of the geotechnical behavior by observations outweigh the disadvantages with the method. The decision should be made based on critical design issues, geotechnical uncertainties, analysis of the design problems, and the prediction of the geotechnical behavior.

The observational method is associated with extra costs compared to traditional design methods due to extra design work and extended monitoring. Therefore, the observational method will only be appropriate if these extra costs are balanced against savings through a modification of the design based on the observations, or if the safety is improved to an acceptable level. In addition, the probability of modifications of the design should not be too large (depending on the cost for the modifications). The most appropriate design method may be determined using decision tree analysis where the final cost for different scenarios using traditional design methods and the observational method is estimated; see Spross & Johansson (2017).

The observational method may be a suitable design method when there is considerable inherent geotechnical uncertainty. In fact, the observational method may be the only appropriate design method in situations including substantial geotechnical uncertainty, as other design methods will either lead to conservative (and costly) designs or to designs with unpredictable (and low) safety. However, if the possible geotechnical behavior lies well within the limits for acceptable behavior there is no need to use the observational method. The method can be used to reduce the uncertainties by collecting and analyzing observations during the construction. The geotechnical uncertainty arises because of epistemic and aleatory uncertainty regarding the geotechnical conditions as discussed in Section 3.3. Furthermore, geotechnical engineering involves different and complex materials and different mechanisms of behavior, and the interaction between theory and practice is complex, e.g. for soil-structure interaction problems. The possibility of making exact deterministic theoretical predictions, even by the most advanced methods, is questionable in some situations. There are many areas where analysis and deterministic calculations may help to explain a problem, but not solve it in a predictive way.

Often, if problems are understood, uncomplicated calculation methods may provide sufficiently accurate solutions which can be checked during the construction. Numerical analysis provides great opportunities in predictions of mechanisms of behavior. However, there are situations where mechanisms are too complex for predictive analysis. Then, predictions must be based on experience applied with an understanding of the mechanisms involved, and observations during execution. An understanding of geotechnical behavior provides a framework within which unavoidable uncertainties can be defined and managed. Palmström & Stille (2007) present some rock engineering tools that are applicable in different types of geotechnical behavior.

Design based on the most unfavorable assumptions is generally uneconomical. It is also impossible, or not economically feasible, to investigate the geotechnical conditions completely. The gaps in the available information may be filled by observations during construction and the design can be modified in accordance with the observations. Since the design is often based on limited information, it needs to be re-evaluated based on additional information obtained during construction. Due to the inherent geotechnical uncertainty, it is unavoidable that some actions, which are unknown before the construction phase, must be taken during the construction.

The use of the observational method requires that the geotechnical behavior can be observed reliably and that the planned contingency measures may be implemented in due time before an unwanted condition is reached. Potentially the most serious mistake in applying the observational method is the failure to identify and select the appropriate contingency measures for all foreseeable deviations of the real conditions, as disclosed by the observations, from those assumed in the design (Peck 1969a). If the situation is unfortunate, there are no adequate contingency measures at all. In these situations, a robust design based on most unfavorable conditions may be preferable.

The observational method rests on the fact that the design and construction scheme can be modified during construction, and Peck (1969a) noted that the observational method is not applicable if the design cannot be changed during construction. In addition, the possibility of having to slow down construction, before the contingency measures are effective, is a drawback inherent in the method. This disadvantage must be balanced against the benefits of the method. If the probability of being faced with the most unfavorable condition is high, the use of the observational method may not be worth the cost for the modification of the design.

Korff et al. (2013) analyze the strengths, weaknesses, opportunities, and threats for the application of the observational method in civil engineering practice by studying several projects where the observational method had been applied. They conclude, for example, that observations of a sudden brittle, ultimate failure are challenging, as the time for implementing contingency measures may be limited or even non-existent. Therefore, a ductile behaviour is often preferable. Additionally, they conclude that the observational method generally is advantageous in projects with a multistage construction process because observations conducted in one stage can be utilized in subsequent phases of construction.

Scavitz-Nossan (2006) concludes that the observational method is best suited for designs that are governed by the serviceability limit states. Furthermore, Scavitz-Nossan (2006) asserts that the method is applicable, but less suited, for designs governed by the ultimate limit states with ductile behavior, and it is not suitable for the ultimate limit states with brittle behavior.

If the observational method is implemented in an appropriate manner, it offers potential for saving both time and costs without compromising the safety by decreasing the epistemic uncertainty through observations during the design. The most potential for savings probably occur during construction related to temporary works or sequencing, although substantial savings may also be relevant to permanent works, particularly by avoidance of major protective works, according to Nicholson et al. (1999).

4.5. Differences from traditional design methods

Peck (1969a) cited Terzaghi when stating:

> "In the past, only two methods have been used for coping with the inevitable uncertainties: either to adopt an excessive factor of safety, or else to make assumptions in accordance with general, average knowledge. The designer who has used the latter procedure has usually not suspected that he was actually taking a chance. Yet, on account of the widespread use of the method, no year has passed without several major accidents. [...] The first approach is wasteful, the second is dangerous. [...] Soil mechanics as we understand it today, provides a third method which could be called the experimental method. [...] On the basis of the results of such measurements, gradually close the gap in knowledge and, if necessary, modify the design during construction."

The fundamental difference between the observational and traditional design methods is that, in the observational method, the initial design is considered to be temporary, and the formal possibility to modify the design on the basis of observations of actual conditions made during construction is actively used. In the traditional design method, a single robust design is established before the construction is started. Due to the uncertainties generally present in geotechnical engineering, the presence of epistemic and aleatory uncertainty may be high. This results in a conservative design if the design has to be defined completely in advance of the construction work. If monitoring is used at all, it often has a passive role and is used as a check-up on whether the design predictions are exceeded as a verification of the design, and not to improve the design. The use of the observational method results in a link between the design process and construction process as the observational method integrates them. Other differences between the observational method implemented “ab initio”, i.e. before construction, and traditional design methods are presented in Table 7.

Nicholson et al. (1999) include the preparation of emergency plans in the observational method since making arrangements for dealing with emergencies at construction sites is a legal requirement in the UK under the Construction (Health, Safety and Welfare) Regulations 1996 (HMSO 1996). A modification plan can include a plan with contingency measures to be applied during adverse conditions, and a plan to achieve identified benefits.

The observational method is most advantageous in situations including substantial geotechnical uncertainties since it has the potential to decrease the uncertainties by utilizing the observations. In fact, the observational method may be the only appropriate design method in these situations, as it overcomes the limitations of the traditional design methods by evaluating feedback from the actual conditions discovered during construction. In projects where there is minor geotechnical uncertainty, there may be no benefit to implementing the observational method. In these situations, the traditional design method is probably the most appropriate since it involves lower costs for design, monitoring, and monitoring review. However, if there is substantial uncertainty, the traditional design method may lead to a design with an unsatisfactory safety margin or unnecessary costs and completion times.

Table 7: Differences between the observational method “ab initio” and traditional design methods (after Nicholson et al. 1999).

Traditional Design Methods	**Observational Method**
Normally one set of soil parameters, e.g. moderately conservative or characteristic values (EC7) – but may do parametric study.	The range of foreseeable soil parameters is considered, e.g. most probable and most unfavorable.
One design and one set of predictions based on limited construction method considerations.	Two or more designs and construction methods are sufficiently developed to include predictions for trigger criteria.
A construction method option may be outlined sufficiently for the design to be progressed. This is subsequently developed by the contractor in the method statement.	A flexible construction method statement is developed that can incorporate design changes and modification strategies. It is often developed jointly between the contractor and the designer.
Monitoring limited to checking that predictions are not exceeded.	Comprehensive and robust monitoring that is regularly reviewed as the basis for management and design decisions.
Prediction unlikely to be exceeded. Therefore, construction programme is not constrained by monitoring results. If predictions are exceeded, then unforeseen conditions have developed, and the work may need to stop while the problem is resolved.	The design, construction method, and construction programme may be changed depending on the review of monitoring results.
	Management of construction, monitoring, interpretation, and implementation of modification plan or emergency plan are required.
	The monitoring system must be sensitive enough to allow early discovery of a rapidly deteriorating condition. The modification plan must be rapidly implemented to ensure that the limiting trigger criteria are not exceeded.
Emergency plans are needed to control failure.	Emergency plans must be introduced. This can be achieved as an extension of the observational method trigger criteria beyond the serviceability limit state to ensure that failure does not cause injuries.

The observational may be initiated at this stage in its “best-way-out” format.	It may be that the “best-way-out” observational method can be introduced to overcome unforeseen geotechnical conditions.

4.6. Case studies presented in the literature

There are several case studies of the implementation of the observational method presented in the literature. Some of these are presented in this chapter. Other case histories including the observational method are presented by, for example, Muir Wood (1990), Card & Carder (1996), Nicholson et al. (1999), Hartlén et al. (2012), Chen et al. (2015) and Lacasse & DiBaigio (2019). Stille (1986) presents a number of successful cases using the “active design” methodology in Sweden.

4.6.1. The Ninth Géotechnique Symposium (1994)

In 1994, 25 years after Peck’s definition of the observational method, Géotechnique called for papers on the observational method in geotechnical engineering for a special issue that was published in December 1994. A symposium was held at the beginning of 1995, where the authors discussed experiences from the case studies and future developments. The case studies were published together with the symposium discussions in a book edited by Nicholson (1996).

Eleven papers considering the observational method were presented. These papers include case studies of the application of the observational method in different types of geotechnical works. Three papers (Young & Ho, Ikuta et al., and Glass & Powderham) discuss the application of the observational method to excavations in projects where the main contractor was involved in the development of the method during the construction of both temporary and permanent works, with the aim of increasing safety and saving costs and program time. Another three papers (Powderham, Iwasaki et al., and Harris et al.) present the implementation of the observational method to deal with tunneling works. In these projects, the application of the observational method was mainly developed by the consultant rather than the contractor. The remaining five papers consider the application of the observational method to investigation and treatment of strata affected by gold mining in Johannesburg (Hammond & Thorn), the design of groundwater control systems (Roberts & Preene), hydraulic fill reclamation (Choa), earth structures constructed on soft ground (Wakita & Matsou), and performance of a bridge abutment (Nicholson & Low).

The observational method was adopted to various extents and in different ways in the case studies presented. The authors of the papers were generally positive about the use of the observational method in projects including geotechnical uncertainty, and about the future of the method. However, there were disagreements regarding the definition, content, and implementation of the method. A conclusion from the symposium was that the method needs to be clarified together with other key issues, e.g. monitoring techniques, interpretation of data, and contractual restrictions. Based on the discussions during the symposium, Powderham & Nicholson (1996) proposed the following objectives for future work:

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."

4.6.2. Powderham (1998 & 2002)

Powderham (1998, 2002) presents four case studies where the observational method has been applied successfully in projects including design and construction of retaining walls ("ab initio" applications), as well as minimizing risk to damage on buildings due to tunneling ("best-way-out" application).

The case studies where the observational method was implemented "ab initio" presented significant savings in time and cost by a reduction of the material used, and the scope of the works, by removing a substantial temporary steel strutting system to the retaining walls. Besides this, the removal of the temporary strutting led to an increased speed of construction and safer working conditions due to less handling of the heavy steel section in a limited working space.

In the project where the observational method was implemented as a "best-way-out" application, the observational method was used to prevent unacceptable damage to a building due to adjacent tunneling, by implementing the observational method in the design and construction of the tunnel. Through the application of the observational method on a progressive basis, it could be shown that the risk of damage was maintained below acceptable limits and that the safety of the building was assured.

4.6.3. Innovative Design Tools in Geotechnics, Part 1: The Observational Methods in Geotechnics (2005)

In the report "Innovative Design Tools in Geotechnics, Part 1: The Observational Methods in Geotechnics", seven European case studies of the observational method are presented (GeoTechNet 2005). The overall purpose of this report was to increase the awareness of the benefits of the observational method among designers, contractors, and clients. The case studies were selected to illustrate the application of the observational method, and the potential benefits that were achieved through its adoption. The case studies have been selected to show the benefits in terms of time and cost, and to include three studies of deep excavations in clay (two with secant pile walls and one with a diaphragm wall), road embankment, grouting to reduce settlement, dewatering due to tunneling, and re-use of existing piles for foundation. Five of the presented case studies are “ab initio” applications and the other two are “best-way-out” applications (grouting and dewatering).

In these case studies, the observational method was generally used to improve the design and/or the construction scheme. In some of the case studies, the contractor proposed an alternative construction sequence. Analysis using “moderately conservative” design parameters, which was used in the adoption of traditional design process, showed that the specified limits of permissible behavior were exceeded. However, analysis of the alternative sequence using “most probable” design parameters in the adoption of the observational method showed that the specified limits were not exceeded. The alternative sequence could be adopted with the support of a strategy with “trigger driven” contingency plans. Both design-and-build contracts and traditional contracts were adopted in the case studies. A construction manager was used in one project to be the link between the designer and contractor.

4.6.4. Powderham & O’Brien (2020)

Powderham & O’Brien (2020) present 12 case studies of the application of the observational method in major infrastructure projects executed between 1998 and 2006. The case studies include retaining walls, embankments, deep foundations, protection of adjacent structures including buildings and railway systems, bored and jacked tunnels, shafts and cofferdams, and ground improvement and groundwater control.

The case studies illustrate how the observational method may achieve more effective collaboration between the actors involved in the construction process, and how the method may enhance future practice and innovation. The authors conclude that “the observational method is a natural and powerful technique that maximises economy while assuring safety”. They also conclude that the method is still underused, despite its many benefits.

4.6.5. Summary of the case studies

Some of the benefits of the implementation of the observational method in the case studies were:

- Design using less conservative design parameters than traditional design methods.
- Cost savings, e.g. due to the use of alternative designs and construction sequences, which could only be used within the framework of the observational method.
- Time savings due to changes in design and construction.
- Increased safety, e.g. due to increased knowledge of geotechnical behavior obtained during construction, and elimination of constricting temporary structures.
- Increased team spirit, and cooperation e.g. due to mutual goals and objectives.
- Feedback from the monitoring for future work.

Key ingredients for a successful implementation of the observational method were, for example:

- An unambiguous understanding of the method role and responsibilities of all actors involved.
- A coordinated team, implementing and fully integrating the method within the project team.
- Clear responsibilities and authorities within the project organization.
- Committed, competent, and experienced staff who was thoroughly familiar with the problems involved and were able to make modifications and respond quickly to any unexpected observations during construction.

- A dedicated owner of each process in the method who has the responsibility for that process.
- Successful construction control, e.g. via a construction control chart, which includes all details of construction operations, instrumentation, predictions, trigger values, alarm thresholds, etc.
- Continuous and high-quality communication between the client, designer, and contractor.
- Well-planned and clear monitoring plan and observation strategy.
- A ductile mode of failure and a design that can be modified in a timely way.
- Training and regular review meetings, providing a basis for modification to optimize construction efficiency.
- Integration of the method into the project risk management system.
- Carefully designed contractual framework with an incentive to use the method.
- Procedures including planned contingency measures were built into specifications and contract documents.
- Accurate and reliable measurements.
- A phased approach to the site investigation, adapted to the use of the observational method.

4.7. Contractual considerations

The observational method may be regarded as a procedural framework for managing risks. The management of risks and changes in risk allocation generally have contractual implications. Therefore, contractual conditions have an important, often critical, influence on the implementation and the result of the observational method. When the implementation of the observational method is considered, concerns about increased risks are sometimes expressed, according to Powderham (1998). However, an adequate implementation of the method by following the formal procedures within a stringent risk management framework will decrease the risks.

The contractual framework, e.g. the procurement method, the payment method, and the type of contract, should be adapted to the nature of the observational method. Such a framework will probably not be put in place unless the actors involved in the project are aware of the possible benefits with the application of the observational method. According to Nicholson et al. (1999), it is, however, unlikely that the type of contract will be adopted to the implementation of the observational method. If the contractual framework is already decided when it is decided to implement the observational method, the result of the observational method will depend on how well the method can function within the existing contractual framework. A key aspect is that the contractual framework must enable the possibility to change the design during construction. In "best-way-out" applications of the observational method, this situation has to be, and usually is, enabled regardless of the contractual framework, especially if the method offers the only acceptable solution to the problems encountered. In "ab initio" applications, the appropriate contractual framework should be developed before the start of the construction. If the actors involved are not confident in implementing the observational method, constraints can be imposed by contractual conditions.

The case studies presented in the literature show that the observational method has been used in both traditional contracts and design-and-build contracts, see e.g. Powderham (1998 & 2002a), Nicholson et al. (1999), GeoTechNet (2005), Hartlén et al. (2012), and Powderham & O'Brien (2020). An important condition when adopting the observational method is that the actors involved, i.e. the client, designer, and contractor in particular, have to understand that the design may change during construction. This may result in changes to both the project costs and the completion time. Some construction contracts provide possibilities for variations and remeasurements, but the procedures for this are rarely described thoroughly enough and are left for interpretation, according to Nicholson et al. (1999). As a result, the cost and time outcomes in many contracts are left to be solved after the project is finished. This is not an ideal situation and it is better if mutually decided methods for regulations are set before the start of the project. Nicholson et al. (1999) conclude that a fundamental change in design, which can be the situation when the observational method is used, can only be successful in a non-adversarial contract environment, and that the observational method can only function effectively within an agreement, and with the understanding of all actors involved in the construction process.

The success of the implementation of the observational method is influenced by the contractual framework and the tender strategy, i.e. procurement method, payment method, and operating environment. Despite the importance of these issues, there is a lack of guidelines regarding an appropriate contractual framework for the observational method. Holmberg & Stille (2007) consider the development of contractual arrangements that can regulate changes in cost and time, due to modifications of the design in the execution phase, to be a necessity for the adoption of the observational method in the future. The contractual framework in the context of the observational method has been considered by, for example, Nicholson et al. (1999), Kadefors & Bröchner (2008), Korff et al. (2013), and Powderham & O'Brien (2020). Kadefors & Bröchner (2015) discuss organizational and contracting issues in rock tunnel projects on a general level.

According to Eurocode 7, the observational method could be appropriate when it is difficult to predict the geotechnical behavior. In these situations, a fundamental issue regarding the contractual framework is that a work operation that, by definition, is difficult to define, should be time scheduled, cost estimated, and compensated fairly. Thus, it is important to find adjustable quantities on which to base the compensation regarding both time and cost. These quantities should be measurable, unambiguous, and fair. To adopt a suitable contractual framework related to the use of the observational method, it is necessary to know the features and the nature of work involved.

In the literature, there are different opinions about which type of contractual arrangement is appropriate in the framework of the observational method. According to Nicholson et al. (1999), it is unlikely that the adoption of the observational method will determine the contractual arrangement. Regardless of the type of contracts, Nicholson et al. (1999), Hartlén et al. (2012) and Korff et al. (2013) claim that a successful implementation of the observational method requires good cooperation among the actors involved in the process.

The following sections consider the implementation of the observational method in projects with different types of contracts, and the concept of value engineering in a contractual context. Advantages and disadvantages of the main types of construction contracts when adopting the observational method are summarized in Table 8 and discussed in the following sections.

Table 8: Advantages and disadvantages of the main types of construction contracts when adopting the observational method.

Type of contract	**Advantages and disadvantages**
Traditional contract (design-bid-build, design-build)	+ The client can initiate the method from the inception of the project. + The client can hire a designer who is familiar with the method. – Separation between the client, designer and contractor. – The designer may be unwilling to use the method. – The contractor may be unwilling to use the method. – The contractor may be unable to use the method.

Design-and-build contract (BOT, BOOT, EPC, etc.)	+ The contractor has the responsibility for both design and construction. + A single party is responsible for the method, i.e. the contractor. + Close cooperation between the designer and contractor. + The contractor can hire a designer who is familiar with the method. – The client may be unwilling to use the method if the method is initiated by the contractor after the contract is awarded. – The client may be unwilling to approve modifications of the design. – The designer may be unwilling to use the method. – Internal blockings.
Collaborative arrangement (partnering, ECI, etc.)	+ The method can be initiated from the inception of the project. + The client can “choose” a designer and contractor who is familiar with the method. + All parties benefit from adopting the method. + Encourages cooperation between the parties. – Difficulties to include all parties involved in the method (sub-contractors, reviewers, etc.).

4.7.1. Traditional contracts (design-bid-build or design-build)

In a traditional contract, the client hires a designer directly, and the contractor by a separate contract. The designer is often engaged to verify that the construction process complies with the specifications set up by the client. Changes in design and execution are normally regulated by remeasurement of the contract sum. The potential savings obtained from the use of the observational method will generally benefit the client through reduced quantities.

If the observational method is to be successfully adopted under a traditional contract, some difficulties must be overcome (Nicholson et al. 1999). First, this type of contract does not encourage cooperation between the designer and contractor. The designer may intend to use the observational method but finds the contractor to be either unwilling or unable to use a method that directly controls the program and methods of working. Second, historically there have been no incentives for the designer and contractor to participate in a method that mostly benefits the client. The designer may be reluctant to change the design based on the observations if the designer is not compensated for it. As the observational method requires flexibility in the work and use of resources, it involves operational risks and, thereby, risks regarding time and costs. It is not likely that the contractor will take these risks without being compensated for them. Third, if the observational method is to be used "ab initio", problems may arise if the contractor is unknown at the time of tender preparation or if the appointed contractor is insufficiently skilled to execute the works in the framework of the observational method. Some possible obstacles and solutions in design-bid-build contracts are shown in Table 9. Nicholson et al. (1999) claim that this type of contract is the least favorable for a successful execution of the observational method. Nevertheless, this type of contract may be successful if the actors involved have the appropriate knowledge, are truly committed to the use of the method, and the contract includes incentives for the designer and contractor. If a design-build contract is used, it should preferably be complemented with a value engineering clause (see Section 4.7.5).

Table 9: Obstacles and solutions when implementing the observational method in a traditional contract (after Nicholson et al. 1999).

Obstacle	**Solution**
Contractor is not willing to use the observational method	▪ Introduce value engineering clause ▪ Describe the importance of cooperation in tender documents ▪ Introduce collaboration arrangements or partnering ▪ Information and education
Designer is not willing to use the observational method	▪ Introduce value engineering clause ▪ Define the process of submission and approval ▪ Enable designer to initiate a change ▪ Clarify the authorities and responsibilities

4.7.2. Design-and-build contracts

In a design-and-build contract, the client generally sets up a number of requirements regarding the function of the final product, and the contractor tenders and hires a designer. The contractor is usually engaged on a lump sum contract basis and the contract sum can only be adjusted by agreement between the client and contractor.

In the context of the observational method, many authors, e.g. Powderham (1998), Nicholson et al. (1999), and Powderham & O’Brien (2020), recommend a design-and-build contract to the inclusion of the observational method since traditional contracts may result in complex distribution of responsibilities and an opposition between the designer and contractor. A design-and-build contract allows the contractor to cooperate with a designer at the time of tendering and to offer the client a more safe and cost-effective solution when adopting the observational method. If the work is compensated with a lump sum, the contractor will retain the potential saving. The client will benefit through a lower tender price without compromising safety, as the contractor will reduce the tender price if the contractor realizes that the use of observational method will lead to savings by comparison with traditional design methods. When adopting the observational method and a design-and-build contract, the contractor has to employ a designer who not only understands the observational method but can also use it effectively and has the will and confidence to support the resulting design solution.

Other factors that facilitate an effective execution of the observational method within a design-and-build contract environment are (Nicholson et al. 1999):

- “The freedom of the design-and-build contractor to incorporate the observational method in the design solution.
- The ability to undertake value engineering without contractual restraints.
- An improved contract interface between designer and constructor.
- Co-ordinated design and construction teamwork, in which team members share the same primary project objectives.
- The clear lines of communications between the workforce at the site where the observational method is being applied and the design office.
- A single party taking responsibility for the observational method.
- The flexibility to optimize between buildability and design security.”

However, the single most important factor is probably that the design-and-build contract promotes close cooperation between the designer and contractor. Close cooperation between the actors is necessary for a successful implementation of the observational method since the method sometimes requires a short reaction time between observations and implementation of contingency measures in order to manage the risks.

Nevertheless, design-and-build contracts are not without problems. Nicholson et al. (1999) mention that if a lump sum payment is used, there is a possibility that the client is unwilling to approve the modifications suggested by the contractor, since the client will not receive any economic benefit from the modifications as soon as the contract has been signed. The client's advisors and external auditors have even less interest in assisting the contractor. To overcome this, there must be clear rules and procedures regarding the modification process, which should be agreed before the execution starts. Different views of, for example, safety and functionality as well as prestige, can also represent obstacles to the application of the method. Additionally, the client or the client's advisor may not have the knowledge or experience to objectively assess a tender that includes the method. Consequently, the tender may be rejected. The advisor could also have an auditing role and, therefore, possibly restrict the use of the observational method.

The aforementioned study performed by Bröchner et al. (2006) expose some potential problems with design-and-build contracts. They conclude that there is a tendency that clients stick to the original requirements in the contract documents, even if they are irrelevant. Therefore, it may be difficult to get acceptance for the suggested modifications of the design. The contractor's internal organization, e.g. relationship with the designer, also has a great importance for the execution of the observational method. Bröchner et al. emphasize the importance of the project management since it is vital to work out the, sometimes, conflicting interests of the designer and contractor. However, the use of a design interface manager or construction manager with adequate knowledge, experience, and strong integrity acting as the link between the designer and contractor may solve these problems. Some possible obstacles and solutions in design-and-build contracts are shown in Table 10.

Table 10: Obstacles and solutions when implementing the observational method in a design-and-build contract (after Nicholson et al. 1999).

Obstacle	**Solution**
Client is not willing to use the observational method	▪ Introduce value engineering clause ▪ Persuade client to accept non-fixed price and programme ▪ Define procedures for approval of changes ▪ Use an interface manager
Designer is not willing to use the observational method	▪ Introduce value engineering clause ▪ Use a design manager
Internal blockings	▪ Information and education ▪ Ensure flexibility

4.7.3. Collaborative arrangements

Partnering and other collaborative arrangements, e.g. early contractor involvement, encourage openness and trust between the actors involved in the design and construction process, as has been discussed earlier. Cooperation and team building are crucial in both partnering and in the implementation of the observational method. Partnering requires a change in culture, attitude, and procedures compared to other types of contracts including mutual problem solving and procedures to ensure improvements and innovations.

Nicholson et al. (1999) stress that the adoption of a partnering agreement including all actors involved in the observational method can only have a positive effect. In a partnering environment, where the actors are working together to deliver an optimal project in terms of, for example, cost, time, and risk allocation in which the gains and the losses are shared, the observational method can deliver its maximum potential.

4.7.4. Other types of contracts

As mentioned before, there are several variations of these types of contracts, e.g. where the client appoints a management contractor, a construction manager, or a project manager to decrease the distance between the designer and contractor. In a management contracting contract, the client hires a designer and a management contractor. The management contractor is paid a fee and hires sub-contractors to each work package. If the observational method is used in management contracting contract, it can be difficult to obtain the agreement of all actors to use the observational method instead of the normal working arrangements, since there are no obvious incentives for the designer and sub-contractor (Nicholson et al. 1999).

In a construction management contract, the client appoints a designer and a construction manager but also each sub-contractor directly. Nicholson et al. (1999) point out that this type of contract has the same difficulties when adopting the observational method as the management contracting contract. However, the client is more directly involved in the project, which could make it easier to emphasize the benefits of the observational method to the other actors involved.

4.7.5. Value management

In all types of contracts, it seems important to include a value management clause to provide possibilities for successful implementation of the observational method. As the name indicates, value management is directed at the enhancement of value (Dell'Isola 1982 & ICE 1996). Historically, the concept of value engineering was introduced by L D Miles at General Electric after World War II (Miles 1947).

The value management approach can be described as a creative, organized approach whose objective is to optimize cost and/or performance of a facility or system. Osterberg (1999) maintains that value management is an important concept with a potential to lower the construction costs and, in many situations, to provide improved and safer designs. Value management is the management of the value process throughout a project, aiming to ensure that maximum value is derived, and may be defined as (BS EN 12973: 2000):

> “A style of management, particularly dedicated to mobilize people, develop skills and promote synergies and innovation, with the aim of maximizing the overall performance of an organization.”

SAVE International describes value engineering as a systematic application of recognized techniques that identify the function of a system at the lowest overall cost. Value management is a systematic and structured process of team-based decision making. It aims to achieve best value for a project or process by defining those functions required to achieve the value objectives, and delivering those functions at least cost (whole-life cost or resource use), consistent with the required quality and performance (Hamersley 2002). The value process is the process of creating value, i.e. the design or construction process. Here, value can be defined as the relation between function and cost (Miles 1947) or between function performance and resources (SAVE International).

Both the observational method and value management have as their primary objective the elimination of unnecessary costs without compromising other objectives, such as time and safety. The concept of value management has been criticized since there has been too much focus on saving costs and not on adding value in some projects (Perera et al. 2011). As a result, the quality has reduced. Simply reducing cost at the expense of quality is not value engineering but merely cost cutting. Thus, it is important to ensure that actions taken do not affect quality and function.

Value management consists of two elements: value planning and value engineering. Value planning is the process of establishing to whom value shall be delivered and what that actor perceives value to be. This relates to the client’s perception of value. The identified values can be listed hierarchically, as value criteria in a value tree. After a speculation phase, e.g. brainstorming, and an evaluation phase of the scheme giving best overall value, i.e. satisfying the most value criteria, a design based on this scheme is developed. Examples of general value criteria of the actors involved in a construction project are presented in Chen et al. (2010). Nicholson et al. (1999) present examples of value criteria in construction projects adopting the observational method.

The aim of value engineering is to increase the value of products without compromising the product's performance requirements. Value engineering is about taking a wider view, and it is used to solve problems and identify and eliminate unwanted costs while improving function and/or quality. In construction, this involves considering the availability of materials, construction methods, transportation issues, site limitations or restrictions, planning and organization, costs, profits, etc.

Both the observational method and value management may be operated separately, but the observational method operates well with an effective value engineering clause in the contract. Nicholson et al. (1999) claim that, in current practice, clients often do not consider the value issues at the concept stage and, thus, do not initiate a value strategy which could lead to the use of the observational method where appropriate. The complementary nature of these concepts makes a powerful combination, as both (Powderham 1994 and Nicholson et al. 1999):

- Require a reasonably knowledgeable client able to realize the potential gains and willing to introduce and support these processes to a successful conclusion.
- Involve circumstances that provide less certainty of cost outcome at the time of construction award, i.e. projects including substantial uncertainty, than traditional lump sum contracts including little uncertainty.
- Encourage good teamwork during the construction phase.
- Have the potential to provide significant cost savings to the client.
- Require effective conditions to be incorporated into the contract to ensure successful results.
- Require monitoring and audit.

- Need experienced and capable management of the process.

The value planning should identify and initiate the potential benefits in using the observational method. Its powerful synergy with the observational method has been confirmed in many projects; see Glass & Powderham (1994) and Powderham & Rutty (1994). The value engineering clause will enable the benefits to be achieved and enable the savings to be shared in an agreed way between the actors. The elements of the proposed design should be analyzed, as well as possible alternatives to these that can provide the required functions at a lower cost without jeopardizing quality or safety. The alternatives should be priced and compared with the value criteria to determine the most acceptable design solution for each element. By evaluating key functions, it is directed at the enhancement of value, and focuses on the elimination of unnecessary costs.

The value management clause should include all actors involved in the execution of the project, e.g. client, contractor, designer, reviewers, and advisors appointed by the client. Nicholson et al. (1999) present some key features of a value management clause to enable a successful implementation of the observational method, which are:

- The right of any party to raise a cost-saving or a time-saving proposal, e.g. a solution related to the observational method.
- Demonstrable net benefit to the client.
- Contract program, e.g. the sequence in which a series of tasks must be carried out to complete a part of the project, not being unacceptably compromised.
- The parties having a share of the net saving.
- The level of contractual risk taken by each party being reflected in the percentage split of the savings.
- Fixed submission and approval periods, e.g. proposals to modify the design.
- The client being able to reject any proposal.

- Reasons being given for the rejection of any proposals.
- A resubmission of proposals being permitted provided it adequately addresses the reasons for any previous rejection.

Powderham (1998) discusses the contractual conditions briefly and recommends the use of a design-and-build contract complemented with a value engineering clause when adopting the observational method. This type of contract is supposed to remove the barrier between the designer and contractor. It is important that the designer also has incentives to be part of the observational method and should therefore also be part of the value engineering process. If the designer is hired on a fixed price, there are no incentives to modify the design. If the client chooses to initiate the observational method process from inception of the project and take the risk of uncertainty of cost outcome in order to obtain all the benefits, it is important to use a remeasured contract sum rather than a lump sum contract. If a lump sum contract is used, the client must pay the cost of the risks taken by the contractor in the tender price as a risk premium. With the use of a remeasurable form of contract, the client will pay the actual price for the risks.

4.8. Management considerations

Poor management has been a contributing factor in many unsuccessful projects, see e.g. HSE (1996), Assaf & Al-Hejji (2006) and Mahamidi (2016). Nicholson et al. (1999) state that good management is even more important in projects adopting the observational method than in projects using traditional design methods. A successful implementation of the observational method requires more interaction between clients, designers, and contractors. This interaction should be managed and coordinated and requires commitment from the members of the project team. Therefore, an appropriate management system must be adopted when the observational method is implemented in complex and/or technically challenging projects. The additional management considerations in the implementation of the observational method to those generally required for traditional design methods, include culture, strategy, competence, and systems (Nicholson et al. 1999). Some management considerations of the observational method are presented in Figure 17.

For a successful implementation of the observational method, suitable policies have to be established on national, corporate, and project level accordingly. Policies are normally used to communicate the objectives of an organization or a project. National policies are, for example, design codes or design guides that define the observational method and the proper use of the method, as well as safety regulations that must be followed.

Figure 17: Management Considerations of the Observational Method (after Nicholson et al. 1999).

On a corporate and project level there should be appropriate contracts supported by specifications, and training and education programs, as well as systems for quality assurance. The project team must be organized to facilitate a successful implementation of the observational method. In this context, organization is the process of structuring a corporation or a project team and involves the establishment of responsibilities within the corporation or the project team. Some key components in corporate and project organization, with respect to the observational method, are presented in Nicholson et al. (1999).

4.8.1. Culture

The commitment of top management in the project is important for initiating a good culture. The top management should initiate the use of the observational method and lead the implementation of the process. In the context of the observational method, some of the cultural issues that must be considered are (Nicholson et al. 1999):

- The understanding within the project team or the corporation of the requirements and limitations of the observational method.
- The willingness to adopt an integrated design and construction approach to projects.
- The attitude of the project team members towards the aim of achieving quality, safety, and project cost optimization.
- A clear perception of hazards and risks, as well as the adoption of a risk-based approach to management.
- The willingness of the team members to recognize and manage the risks, and to face and solve problems together.
- The willingness to break down boundaries between different sections of a project team, and project team members to put their effort into supporting each other rather than having an attitude of “them versus us”.

- The willingness to adopt new business processes, such as partnering.
- The willingness to learn from past failures and successes.

Hartlén et al. (2012) point out that the success of the observational method largely depends on good cooperation between client and contractor. In a design-and-build contract, the coordinated efforts of the contractor's design and production department is also important. They also concluded that the adoption of a joint expert group was instrumental in managing the geotechnical risks, and that participants with professional competence and integrity, as well as mutual respect between the parties, are important for success.

A sustainable observational method culture within a corporation or a project team is dependent on its policies regarding quality, health and safety, education and training, and research and development in areas such as risk management, contractual conditions, and data collection and analysis. External and internal high-quality communication at all levels in the project team will promote the observational method culture.

4.8.2. Strategy

The strategic aspect of the observational method includes, for example, the contract, risk-based control strategy, team building, and resource planning. The contractual framework may have a strong influence on the implementation of the observational method and the success of the implementation, according to the previous discussion in Section 4.7. Thus, the design of the contractual framework is important. In many projects, the inclusion of a value engineering clause, or similar incentive, will be useful. This will allow the benefits obtained using the observational method to be shared among the actors involved in the project.

HSE (1996) suggests that the management strategy when using the observational method should be one of risk-based control. Thus, the observational method should be adopted within a risk management framework, e.g. the risk management framework described in Chapters 2 and 3. The following points should be noted (HSE 1996 & Nicholson et al. 1999):

- The staff from the designer's and contractor's organizations should be similar in authority and seniority to decrease the barriers to communication or approvals for action.
- The structure of the team will be affected by contractual arrangements.
- Design and construction (including monitoring) are closely integrated in projects adopting the observational method.
- Good buildability requires cooperation between designers and contractors.

Additionally, a successful implementation of the observational method also rests on highly motivated teamwork and complementary expertise between the client, designer, and the contractor. Clear and effective communication between the actors involved in the observational method process is a basic requirement. Procedures for documentation and communication of observations need to be established to make it possible to implement the appropriate contingency measures. Well-thought-out resource planning is needed since the observational method is a resource-intensive process. Resources needed for different construction schemes and critical assignments should be planned and available at the right time. The reliability of the delivery of material required for modifications in emergency should be considered.

Kadefors & Bröchner (2008) also mention the importance of long-term client strategies in the context of the observations besides contractual arrangements, risk allocation, competence, and communication. To create incentives to improve the knowledge, competence, and routines of the observational method among designers and contractors, it is important that the clients have consistent strategies which encourage this development and more innovative cooperation.

4.8.3. Competence

Competence may, in the context of the observational method, be defined as the skills, knowledge, and experience needed for a successful implementation of the observational method. A variety of skills are needed for a successful implementation and management of the observational method, e.g. commercial, conceptual, analytical, administrative, social, and interpersonal (Nicholson et al. 1999). In this context, experience will include, for example, an understanding of available technologies and their limitations, previously successful approaches to design, construction, and monitoring, and site-specific information (HSE 1996).

The competence needed can be considered at three stages: design and planning, construction, and review. The project should be managed by a balanced team that combines design soundness, innovative thinking, and construction ability to identify modifications to the construction process. During the construction phase, the management must make sure that the works are carried out as planned. Here, a project model including milestones and toll gates can be used as have been discussed in Chapter 3.8 and by Stille (2017). To avoid failures, it is important that the monitoring results are reviewed by engineers with relevant competence. The management should communicate the result of the review to the construction team. If one wants to predict and, subsequently, evaluate the overall performance of a design, a procedure that incorporates the evaluation of the results of the analyses must be established.

4.9. Project management

The importance of strict project planning has been considered as a major foundation of successful project since the 1950's, see e.g. Pinto & Slevin (1987). Pollack (2007) maintains that research and practice regarding project management has traditionally been based on a hard paradigm which assumes that the project has clear objectives and may be divided into several activities, which may be scheduled regarding time and costs on the basis of their dependence. Thus, project management research has been dominated by research regarding project planning, focusing on scheduling and budgeting. However, the importance of project planning has been questioned during recent decades, see e.g. Andersen (1996), Dvir & Lechler (2004) and Pollack (2007).

In complex geotechnical engineering projects, the possibility to modify the design and the construction process on the basis of new information and/or knowledge acquired during the execution phase is important. Complex projects, e.g. in terms of number of work activities and their dependency, as well as the degree of uncertainty, will require a high degree of flexibility in project management in order to meet deviations from the initial planning (Williams 1999, Olsson 2006, Kadefors & Bröchner 2015). Olsson (2006) describes some strategies for creating flexible processes in projects. These are late locking, step by step locking, and contingency planning. In this context, the observational method is a form of contingency planning where a master plan is established, together with contingency plans, which are activated if the actual conditions differ from those anticipated.

The observational method requires flexibility in the decision process and many researchers, e.g. Kadefors & Bröchner (2008), suggest that a more flexible project management should create better possibilities for a more innovative cooperation between the actors involved. More flexibility in the decision processes would lead to the possibility of modifying the design based on the observations made in the construction phase and, as a result, more cost-effective designs. They also point out that it is important that the organization is adapted to modify the design and construction, and that all actors involved are aware that modifications will probably happen.

Appropriate management of gathering of information, and processing and reviewing the information is essential in order to discover unacceptable levels of risk. The following issues should be considered (Nicholson et al. 1999):

- Reliable monitoring system operated by competent staff.
- Back-up instruments and staff.
- Visual display of monitoring results for all key personnel.

- Ability to recognize the onset of failure and to timely implement contingency measures.

The discovery of “new” hazards, i.e. hazards that have not been identified before, rests on an early detection of adverse changes from the information available. In this process it is important to have open minded and competent personnel on the construction site to detect geotechnical warning bells (Stille 2017). Ramasesh and Browning (2014) and Spross et al. (2021) present approaches to deal with these unknown hazards, so-called “knowable unknown unknowns”. This requires not only active monitoring, but also proactive monitoring in which timely, reliable, and easily interpretable data are gathered. Proactive monitoring provides opportunities for early discovery of adverse trends and events. The data should be critically examined by competent engineers and the conclusions passed on to an appropriate level of management for decision on whether to implement any planned modification or not. The predicted rate of adverse changes and the time needed to implement the appropriate measures, i.e. the lead time, should be considered when deciding the monitoring frequency and alarm thresholds.

Implementation of contingency measures includes both decision making and action. Therefore, the management structure must be adapted to these factors in order to control the level of risk. The technical and procedural audits can be performed as a part of the project’s quality assurance. The procedural audit should check if the prescribed procedures have been carried out. The technical audit should review construction quality and quality of workmanship and material, as well as the observation method process.

4.10. Conclusions

4.10.1. The concept of the observational method

The fundamental objective of the observational method is to ensure an acceptable safety level in projects including complex geotechnical conditions and geotechnical uncertainties. A central element of the observational method is to overcome the limitations of traditional design methods by evaluating observations of actual geotechnical conditions conducted during construction. The result of the observations reduces the epistemic uncertainty and is the basis for modifications during construction. Observations should be performed with the aim of reducing the epistemic uncertainties regarding the geotechnical conditions. The choice to adopt the observational method should be based on a thorough analysis of which design problems are critical to the performance of the project.

If the observational method is implemented successfully, the method promotes the following advantages:

- Increased safety during construction.
- Potential cost and time reductions.
- Stronger connection between design and construction.
- Improved knowledge of geotechnical behavior.
- Improved cooperation between the actors involved, i.e. the client, contractor, and designer.
- High-quality case history data.

The observational method can be applied “ab initio” or as a “best-way-out” application. In the “ab initio” application, the method is applied from the start of the project. In the “best-way-out” application, unexpected events have already occurred, and the method is used to solve the problems associated with these events. Nowadays, the observational method is mainly associated with the “ab initio” application and this is the application that has the greatest potential.

The implementation of the observational method requires an understanding of the geotechnical risks and uncertainties involved, the geotechnical and structural behavior, the design and construction process as well as close cooperation between the client, designer, and contractor and, preferably, also material suppliers. In the context of risk management, the observational method can be regarded as a risk treatment action. The observational method should be integrated into the overall risk management of the project.

When adopting the observational method, it must be acknowledged that the final design is not known until the completion of the work. In addition, it must be verified that the design complies with the design requirements. The observational method should not be regarded as a “design-as-you-go” process, considering the fundamental requirements and the demand for monitoring and planning of contingency measures before the start of the construction work.

The use of the observational method includes decision making under uncertainty and exploiting the information obtained during construction, with the aim of reducing the uncertainty regarding the geotechnical conditions. Thus, it must be possible to observe the geotechnical behavior and to define observable control parameters which should reflect the geotechnical behavior and the uncertainties involved. The selection of proper control parameters to observe and measure requires geotechnical knowledge and understanding of the physical phenomena governing the geotechnical behavior.

In addition, a reduction of the uncertainty of the geotechnical behavior by observations and analyses of the control parameters must be possible. Information obtained from site investigations and adequate case histories may be used to decrease the epistemic uncertainty before the construction starts. Observations of the geotechnical behavior may be used to decrease the epistemic uncertainty during construction.

4.10.2. The observational method in Eurocode 7

According to Eurocode 7 (CEN 2004), part 7 “Geotechnical design”, the observation method may be appropriate in situations where it is difficult to predict geotechnical behavior. In these situations, the use of traditional design methods may lead to unpredictable geotechnical behavior and uncertain safety margins. The term “geotechnical behavior” should be defined according to the type of uncertainty and the type of construction work involved. In geotechnical engineering, the uncertainties are mainly related to the level of accuracy in the assessment of the properties and geotechnical behavior of the existing soil/rock layers, the boundaries of existing soil/rock layers, and the behavior of structural elements, as well as the result and quality of planned contingency measures.

A fundamental condition in the description of the observational method in Eurocode 7, is that limits for acceptable behavior should be established and it should be shown that there is an acceptable probability that the actual behavior will be within these limits. How to satisfy this is, however, not explained explicitly in Eurocode 7. The “acceptable limits of behavior” may be seen as threshold values when the design needs to be modified. The “acceptable probability that the actual behavior will be within the acceptable limits” is related to the probability that any contingency measures must be implemented. In general, the initial design should be chosen so that no costly and/or time-consuming contingency measures have to be executed. Otherwise the confidence in the method may be lost.

4.10.3. Differences from traditional design methods

The design of geotechnical structures is traditionally based on cautious estimates of the properties of the ground. This procedure may lead to unnecessary costs if the actual conditions are better than those anticipated. In complex geotechnical engineering projects where there is a wide range of geotechnical uncertainty, using the observational method to manage uncertainty in geotechnical design and construction is probably worthwhile, even if the initial cost for design and the cost for monitoring is increased compared to traditional design methods. However, there is no need to implement the observational method if the present uncertainties are manageable in the normal risk management process or if the probable behavior lies well within the acceptable limits.

The observational method is more than a traditional design method complemented with monitoring. The fundamental difference between the observational and traditional design methods is that the initial design is considered to be preliminary, and actively uses the formal possibility to modify the design on the basis of the observations of actual conditions made during construction. In traditional design methods, a single robust design is established before the construction is started and monitoring is used to verify the design.

Whether or not to use the observational method is a decision problem regarding which design method provides the best opportunity to produce a design to the lowest total cost at an acceptable level of safety. The potential benefits of the observational method should be related to the additional costs for the initial design, extended monitoring during construction, reviewing of the design, and implementation of contingency measures during construction.

4.10.4. Contractual considerations

In most projects, the use of the observational method will probably be restricted to some specific work activities. Consequently, the implementation of the observational method will probably not decide which type of contract or payment method that is used for all the work. However, it may be possible to use a different contractual framework for the part of work that includes the observational method.

The contractual framework should be adapted to the fact that this part of work includes substantial uncertainties, and that the observational method assumes modifications of the design and construction work during the execution phase. The observational method should be carried out within a framework of a contract that is flexible if the planned contingency measures must be implemented due to unexpected geotechnical behavior. The contract should allow the design to change during construction. All decisions regarding the contingency measures should be made before the construction starts, e.g. regarding time for implementation, responsibilities, resources, and costs.

If the observational method is used in an environment where the actors are working together with the aim of delivering the optimal solution in terms of cost, time, safety, program, and environment and where gains and losses are shared, the observational method has the potential for delivering its maximum potential. As the observational method should be used when it is difficult to predict the geotechnical behavior, it will generally be difficult to estimate the costs and time schedules in these projects. This is an economical risk to the client or the contractor, depending on the contractual arrangement.

The client can reduce its risk exposure by adopting a design-and-build contract with a lump sum payment. Under these circumstances, the contractor is responsible for the design and has an opportunity to adopt the observational method in order to create a safe and cost-effective design, fulfilling the formal requirements, e.g. structural resistance, serviceability, and durability. However, the contractor will probably include a high-risk premium in the tender to compensate for the risk taking.

If a remeasurement contract is used, the client's exposure to risk is generally higher. In these situations, the bill of quantities should aim at covering the possible behavior in order to be able to handle changes in the design. Before the start of the construction process, the involved parties should negotiate and reach a mutual agreement on unambiguous and mutually exclusive indicators for the quantities, aiming to establish a fair compensation of costs (series and parallel works) and time (series works).

In design-bid-build contracts, there is typically a separation between the designer and the contractor, which may create obstacles to modifying the design during construction and, consequently, a barrier to the use of the observational method. The same kind of problems may arise in a design-and-build contract if the client keeps the right to approve all modifications of the design and has no incentives to do so. This separation can lead to disputes and confrontation between the actors involved. This must be avoided when implementing the observational method, where high-quality communication and cooperation are essential. This can generally be obtained through a collaborative agreement, alliance, or partnering, or by including a value engineering clause in a design-bid-build or design-and-build contract.

A strong compatibility has been found between the observational method and value engineering. Both aim to identify and eliminate unnecessary activities and, therefore, generate savings in cost and time. They also require an increased cooperation between design and construction. The inclusion of a value engineering clause in a construction contract can address the immediate contractual constraints on the implementation of the observational method and facilitate its introduction. The value engineering clause should include incentives to use the observational method, e.g. by sharing cost reductions among the actors involved in the project. Benefits obtained from the adoption of the observational method should be shared between the client, designer, and contractor. In addition, there should be incentives for the designer to optimize the design and undertake regular reviews during construction. Trust, commitment, and cooperation are the basis for a successful application of the observational method in all types of contracts.

4.10.5. Management considerations

The observational method leads to an active management of critical design issues. The design philosophy according to the observational method must be communicated, understood, and accepted among the actors involved. A briefing session on site before the start of each new construction activity may be used to increase understanding, commitment, and teamwork. At these sessions, the risks and the planned contingency measures may be discussed, and key personnel identified and given the responsibility and authority to make decisions. A design interface manager may be appointed to coordinate the design team and the construction team.

The use of the observational method will bring increased demands on the designers involved. The designer should have both the appropriate technical skills and construction management capability. Additionally, the designer needs to be fully acquainted with the specific construction methods and sequences, as well as the progression on site. When adopting the observational method, it is important that the designer has a high degree of availability at the site and sufficient integrity to withstand the demands from the production staff.

To obtain real benefits of the observational method, there needs to be sufficient flexibility in the design and construction plans. In addition, there must be enough time to implement the contingency measures, and time before the contingency measures are effective. The observational method should not be used when the geotechnical or structural behavior is brittle or where rapid deterioration in materials may occur. In these situations, there may be insufficient time to implement the planned contingency measures and progressive failure may occur.

Monitoring has an active and crucial role in the implementation of the observational method. The reliability of the monitoring system should be compatible with the risk control requirements. Monitoring includes observations, documentation, and analysis of the observations, as well as communication of important results in order to decide if any of the planned contingency measures should be implemented. It is important that the monitoring plan is understandable for all personnel involved in the project and that the personnel feel committed to the monitoring.

The contingency measures should be formulated before construction, with a clear set of instructions on the procedures to be followed if the alarm thresholds are exceeded. For site control of the observational method, it is important that clear responsibilities are established on site. Data interpretation should be rapid, and procedures must be established to ensure the timely triggering of contingency measures. Toll gates, or other control functions, may be used to facilitate the implementation of appropriate contingency measures and modifications of the design.

Adequate resources, e.g. personnel, equipment, and material, for the implementation must be prepared and activated at the right time, if necessary. The implementation of contingency measures should not be seen as a failure, but as an opportunity to improve performance or safety. Human obstacles, e.g. prestige, must not prevent the contingency measures from being implemented.

As the observational method may be appropriate in projects that include geotechnical uncertainties and difficulties in predicting geotechnical behavior, these projects should be organized and executed as innovation projects rather than implementation projects. In an innovation project, it is important that the organization, as well as the design and construction methods, are flexible enough to utilize the new information that evolves in the project to manage the uncertainties by implementing contingency measures. It is also important that the information paths, responsibilities, and authorities are unambiguous and well-known throughout the entire project organization.

4.10.6. Applicability of the observational method

As has been discussed, there are many aspects that influence the application of the observational method, e.g. technical, organizational, contractual and management aspects. A project using the observational method should strive to meet all relevant aspects. In conclusion, I propose that the observational method is an appropriate design method if the following principles are fulfilled:

P.1 The project includes complex geotechnical behavior that is difficult to predict.

P.2 There is a ductile geotechnical and structural behavior.

P.3 Geotechnical hazards and uncertainties are identified and analyzed.

P.4 Theoretical and practical framework for how observations can decrease the epistemic uncertainty are established.

P.5 The additional costs for the observational method outweigh the risks associated with other design methods.

P.6 There are flexible designs and construction schemes that can be altered during construction.

P.7 The monitoring system and the control parameters are based on the uncertainties involved and on a clear definition of critical design problems.

P.8 Commitment, knowledge, and competence in using the observational method exists among the actors involved.

P.9 Resources for the implementation of the contingency measures are available at the right time, e.g. personnel, equipment, and material.

P.10 There are flexible contracts including a value engineering approach that can handle changes in geotechnical behavior.

P.11 There is close cooperation between the actors involved in the project.

P.12 The observational method is an integrated part of the design process from the inception of the project.

P.13 The observational method has a prominent role in the construction phase and is an integrated part of the production process.

P.14 A strict and formal management framework with clear roles and responsibilities of the actors involved with respect to the observational method exists.

P.15 The project is managed as an innovation project.

5. Introduction to the case studies

5.1. Overview

This thesis presents three case studies including the risk management process, and the applicability of the observational method in geotechnical engineering projects executed in different countries. These are:

- Southern Link Road Construction, contract SL10, Sweden (Chapter 6).
- Delhi Metro, contract MC1A, India (Chapter 7).
- Tunnel under Hvalfjörður, Iceland (Chapter 8).

The case study of the tunnel under Hvalfjörður is presented in the appended paper in Appendix. Chapter 8 includes the abstract from the paper. Each case study concludes with a discussion regarding the fulfillment of the proposed principles for the applicability of the observation method presented in section 4.10.6.

The risk management processes in these projects did not follow the processes described in Chapters 2 and 3 in detail, partly because the projects were executed before the first version of ISO 31000. Instead, the risk management processes followed the client's and/or contractor's own risk management processes and procedures. Some of these were based on IEC 60300-3-9 (IEC 1995). An observational procedure was adopted in all three projects based on the methodology "active design" described by Stille (1986). This methodology has many similarities with the observational method discussed in Chapter 4.

However, it is my opinion that the findings are not restricted to the processes and methods that were used in the case studies, and that the findings can be utilized in projects using the risk management process and the observational method, as described in Chapters 2, 3 and 4.

6. Southern Link Road Construction, Contract SL10, Sweden

6.1. Project description

The Southern Link Road Construction (Södra Länken) is part of a system of roads around Stockholm consisting of an extensive system of urban tunnels in the southern part of the city (Figure 18). The road construction is approximately 6 km long, of which 4.5 km is tunnels. The total length of the tunnels, including access ramps and exit ramps, is about 17 km. The site of the SL10 contract was located in Årsta. It included a 460 m long underground structure, including approximately 40 m of rock tunnel with limited rock cover and a cut-and-cover concrete tunnel.

Figure 18: The South Link Road Construction project in Stockholm (Hintze et al. 2000).

Parts of the tunnel were supported by piles and other parts were founded on soil or bedrock. Extensive excavation work had to be carried out in some parts before the concrete tunnel was built. The excavation was approximately 40 m wide and up to 20 m deep. Distinguishing work activities in the project were temporary earth retaining structures, including steel sheet piling, deep excavations, and rock tunneling works.

The client was the Swedish Transport Administration, and the contract was a design-and-build contract with a lump sum. The contract was procured in competition with mostly domestic contractors. The work was executed by a contractor from Sweden who had its own design department. The construction work began in 1997 and concluded in 2004. The geotechnical works were finished in 2001.

An important part of the project was the temporary structures required for the excavation for the concrete tunnel. In the tender documents the excavation was proposed to be carried out inside supported diaphragm walls due to the restrictions regarding deformations of adjacent buildings and the ground water condition in the area. However, the contractor chose to use supported steel sheet pile walls instead of diaphragm walls. The requirements from the client to minimize any lowering of the groundwater level and the allowed settlement in the surroundings, required watertight structures with high stiffness. For the design, an observational procedure, based on the active design methodology (Stille 1986), was adopted including predictions of deformations using a finite element program together with a monitoring system.

The retaining structure, close to a 14-storey residential block called “Asplången”, was a special challenge. Here, the excavation was around 16 m deep and the distance between the sheet pile wall and the buildings was approximately 2.5 m at the minimum (Figure 19). The client had specified a total permissible settlement for the buildings of maximum 50 mm. Moreover, anchors were not allowed to penetrate the piled foundation of the existing buildings and the permissible vertical pressure from the sheet piles on the bedrock was limited due to the quality of the bedrock.

Figure 19: The sheet pile wall close to the residential block “Asplången” (Carlsson et al. 2004).

To reduce the groundwater flow under the sheet pile walls and in the bedrock, the soil and bedrock under the walls was injected with cement grout. Several design alternatives for the sheet pile walls were evaluated, and struts were judged to be the best way of supporting this part of the retaining wall. A jack was inserted at every strut to measure and/or adjust the force in the struts to influence the deformation scenario.

The concrete tunnel was built in two halves in order to use the tunnel walls as temporary support. Before the installation of the sheet pile walls started, the existing building was underpinned as a preventive measure to avoid damage. Experiences from the project have been reported by Hintze et al. (2000) and Hintze (2002).

6.2. Geotechnical conditions

The soil strata mainly consisted of 1-2 m of fill above an extensive layer of very soft clay on top of a thin layer of granular soil above the bedrock (Figure 20). The shear strength of the clay was between 15 and 30 kPa.

The soil strata reached its maximum depth in the central part of the working area with a total thickness of approximately 20 m. At greater depths, the soil shifted from clay to silt and sand close to the bedrock. The bedrock was partly fractured and consisted of gneiss with a surface layer mainly of hard unweathered granite. The bedrock included fault zones, with high water pressure in some places. The groundwater level was located approximately 1-2 m below the ground level.

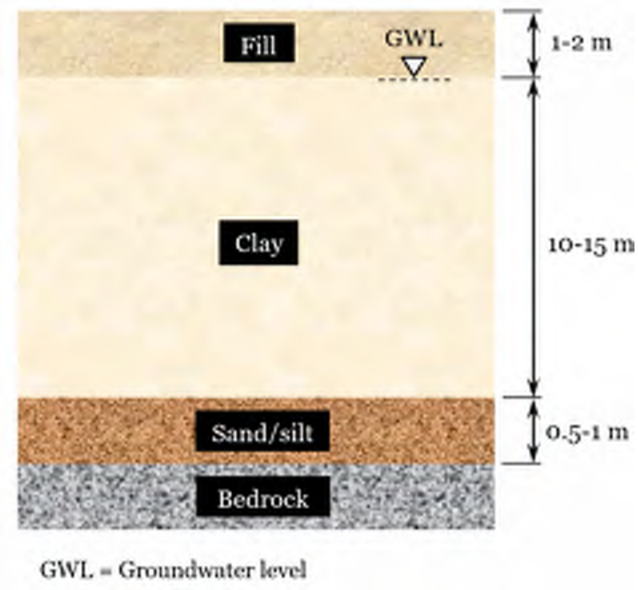


Figure 20: Typical geotechnical conditions at the site of SL10 (schematic presentation).

6.3. Management of geotechnical risks

6.3.1. The planning phase

Before the Southern Link Road Construction project started, the client was aware that the entire project had to be considered a high-risk project due to its complicated nature, e.g. the complex ground conditions, the groundwater condition in the area, the deep excavations in soft clay, the tunneling in partly fractured rock including fault zones, the location in an urban area, heavy traffic within and outside the working area, and the public and political focus. Therefore, risk management and safety issues had a central feature in the early phases of the project, and a risk management process was established by the client (Figure 21). General hazards and potential consequences identified in the planning phase by the client are presented in Table 11.

Table 11: Hazards and potential consequences identified in the planning phase (after Swedish Transport Administration 2002).

Hazards	**Consequences**
Design	Delay
Execution	Budget overruns
Organization	Quality deficiencies
Contract	Personal injury
Working environment	Property damage
Environment	Environmental damage
Residents	Economical (claims)
Media	Bad will
Traffic	
Government decisions	
Political decisions	

In a qualitative risk analysis, the risks were grouped into different categories. The categories regarding the probability were denoted 1-3 and the classes regarding the consequences 0-3. The probability categories were “extremely small likelihood”, “very small likelihood”, and “small likelihood” (Table 12).

The categories for the consequences were different groups of consequences, e.g. personal damage, property damage and claims, interruptions and time delays, and environmental damage (Tables 13-16).

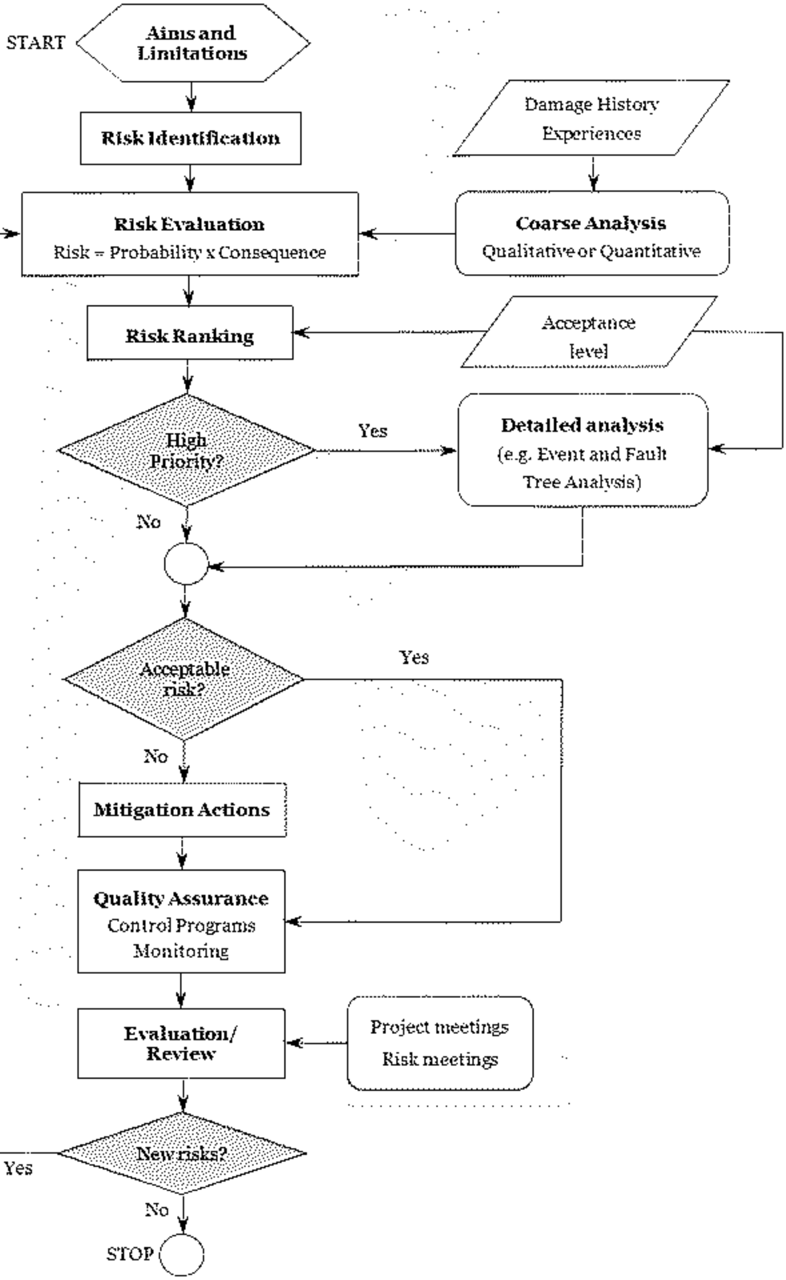


Figure 21: The risk management process in the Southern Link Road Construction (after Swedish Transport Administration 2002).

Table 12: Probability classes ant the associated “probability number” (after Swedish Transport Administration 2002).

Probability class (P)	Description
1 (7)	Extremely small likelihood
2 (14)	Very small likelihood
3 (21)	Small likelihood

Table 13: Consequence classes K_p “Human injuries” (after Swedish Transport Administration 2002).

Consequence class (K_p)	Description
0	No injuries
1	Minor injuries
2	Serious injuries
3	Loss of life (one or several)

Table 14: Consequence classes K_e “Property damage and claims” (after Swedish Transport Administration 2002).

Consequence class (K_e)	Description
0	No damage
1	Less than 50 million Swedish kronor
2	50-100 million Swedish kronor
3	More than 100 million Swedish kronor

Table 15: Consequence classes K_a “Interruption and delay” (after Swedish Transport Administration 2002).

Consequence class (K_a)	**Description**
0	No interruption or delay
1	Less than 1 month
2	1-3 months
3	More than 3 months

Table 16: Consequence classes K_m “Environmental damage” (after Swedish Transport Administration 2002).

Consequence class (K_m)	**Description**
0	No damage
1	Temporary damage
2	Long-lasting damage
3	Permanent damage

The total risk was calculated according to:

$$Total\, risk = P\ x\ (3\ x\ Kp + Ke + Ka + 2\ x\ Km), \qquad (1)$$

where P is the probability according to Table 12 and K_p, K_e, K_a and K_m are the consequence classes according to Tables 13-16. The consequence class for human injury (K_p) and for environmental damage ($K_{m)}$ had larger weights than other consequence classes as they were considered more important than the other consequence classes. This resulted in a total risk number for each risk. The acceptance level was set to 125 by the client, i.e. risks with a total risk number of 126 or greater were considered unacceptable risks that needed further treatment. These risks were given high priority in the risk management process.

In the contract SL10, the high priority risks were related to the design of the sheet pile walls, the soil and rock conditions, and the groundwater levels in the area. The risks that had been identified by the client were included in the tender documents.

6.3.2. The tender and design phase

In the tender phase, a project plan on the basis of SS-EN ISO 9000 was established by the contractor. The project plan included a description of responsibilities and authorities for the identified key roles in the project. Furthermore, the plan described chains of decisions and information in the project.

A technical risk assessment was performed in an early phase of the project by the contractor. Non-technical risks were not included in the risk assessment. The risks presented in the tender documents were included in the contractor's risk assessment. The risk assessment was performed with the aim of being an effective tool for managing the risks, as it should help the project staff not only to manage risks but also to consciously address the actual treatment of the risks. The underlying thought was that a better understanding of the hazards and the process from the hazards to the actual damage was going to lead to a safer and more cost-effective execution of the project.

The cyclic risk management process was repeated in all project phases. The contractor's risk management process started in the tender phase by studying the tender documents and specifications of the project. Thereafter, site visits and meetings with the client were held. Then, risks related to geotechnical and environmental issues were studied. Risks related to traffic in the site area, the temporary structures, and adjacent buildings were studied on site and in an extended study. The outcome of the risk management process included a description of the process from hazard to damage as described in Section 3.1.

In the design phase, the risk assessment focused on geotechnical and environmental risks, as well as the management of the project organization in relation to the design commitment. Well-planned internal and external communication and the transfer of adequate quality-assured information were identified to be important to manage the risks. The risk management process included the following activities:

- Identification and ranking of hazards and risk objects.
- Identification of damage events.
- Identification of initiating events for the most crucial hazards.
- Qualitative estimation of the risks.
- Identification of warning bells with the aim of detecting initiating events and damage events.
- Identification of risk treatment actions, e.g. preventive and/or mitigation actions.
- Planning and preparation of critical decisions, e.g. decisions regarding the support system of the retaining walls.
- Description of critical work activities.
- Preparations for the management of damage events.
- Planning for a separate inspection of the critical activities by an independent review team.

The most critical risk objects were:

(i) The fractured rock mass including fault zones with high water pressure.

(ii) The clay deposits that had very low shear strength.

(iii) The design of the sheet pile wall including the support system close to the residential block “Asplången”.

(iv) The design of the jet-grouting in the soil at the toe of the sheet piles.

(v) The design of the rock support.

(vi) The design of the excavations in both soil and rock.

Examples of identified risks related to design of the sheet pile wall close to the residential block “Asplången”, are presented in Table 17.

Table 17: Examples of risks related to the sheet pile wall close to the residential block “Asplången”.

Hazard	**Damage event**	**Damage**
The soil properties are worse than anticipated in the design	The sheet pile walls fail	Human injury, large deformation, settlement in adjacent buildings and other structures, time delay, redesign and reconstruction
The jet-grouted soil under the toe of the sheet piles is not water-tight due to boulders in the soil	Water leakage under the sheet pile wall, lowering of the groundwater level outside the sheet pile wall	Settlement in adjacent buildings and other structures
Machines working close to the struts	Collision between machine and strut, strut failure	Deformation in the sheet pile wall, settlement outside the sheet pile wall
Buildability (the design is easy to construct)	Redesign	Time delay, extra costs
Bad cooperation with the client	The client does not approve the design or the construction	Time delay, redesign, reconstruction, extra costs

These risks were gathered in risk registers including information of the damage event, observations (warning bells), initiating events, and treatment actions. The risk owner was also included in the risk registers. An example of the risk register for the sheet pile wall close to the residential block Asplången is shown in Table 18. A failure of the sheet pile wall was judged to be disastrous, even though the building had been underpinned as a preventive action before the work started.

Table 18: Part of the risk register for the sheet pile wall close to the residential block “Asplången” (after Hintze 2001).

Damage event	Observation	Initiating event	Treatment action
1. Failure of the sheet pile wall.	1.A.1 Visible deformation of the wall. 1.A.2 Measurements of the sheet piles show deformation. 1.A.3 Alarm via the settlement gauges. 1.A.4 Alarm via the inclinometers. 1.A.5 The anchor jacks show an increase in the anchor forces. 1.A.6 Settlement in adjacent buildings.	1.B.1 Excavation for the wale beams. 1.B.2 Installation of anchors or struts. 1.B.3 The surface load outside the wall is too large.	1.C.1 Stop the excavation and fill back the soil. 1.C.2 Install an extra anchor or strut. 1.C.3 Unload the sheet pile wall.
2. One or more anchors/struts fail.	2.A.1 The anchor jacks show an increase in the anchor/strut forces.	2.B.1 Excavation for the wale beams. 2.B.2 Installation of anchors or struts. 2.B.3 The surface load outside the wall is too large.	2.C.1 Stop the excavation and fill back the soil. 2.C.2 Install an extra anchor or strut. 2.C.3 Unload the sheet pile wall.

As mentioned earlier, a decision situation which was especially challenging was the decision regarding the type of support for the sheet pile wall close to the residential block “Asplången”. Here, the application of system analysis and reliability analysis were important tools in the decision situation regarding the choice of the type of supporting system; see Olsson (1998) and Carlsson et al. (2004). Struts or anchors could be used to support the wall, and the choice between these was judged to lead to different risks. In the decision analysis, two damage events were identified: wall failure and damage to the pile foundation of the adjacent building due to installation of the wall. The consequence of the first event was considered to be severe, as it would result in major damage to the adjacent building. The consequence of the second event was considered to be less severe, as it would only result in minor settlement of the building. A separate risk analysis was performed to evaluate the probability of damage for the different methods of supporting the wall. The aim of the risk analysis was to make a comparison between the two alternatives and not to calculate the exact probability of failure. The identified initiating events for the damage event “Sheet pile wall failure at Asplången” were:

- Collapse of the temporary sheet pile wall due to damage on struts or anchors.
- Incorrect construction.
- Incorrect blasting.
- Incorrect excavation.
- Fire.
- Collision, e.g. by an excavator.
- Damage caused by human error.

The probability of damage on struts and anchors was estimated by the use of a quantitative fault tree, with estimated probabilities of failure for each initiating event. The result for the alternative with a supporting system of struts is shown in Figure 22.

Thereafter, an event tree was established assuming that one strut or anchor has failed in order to establish a connection between the estimated probabilities in the fault tree and the probability of different degrees of damage on the adjacent building. The event tree for the alternative, assuming strut failure occurred, is shown in Figure 23.

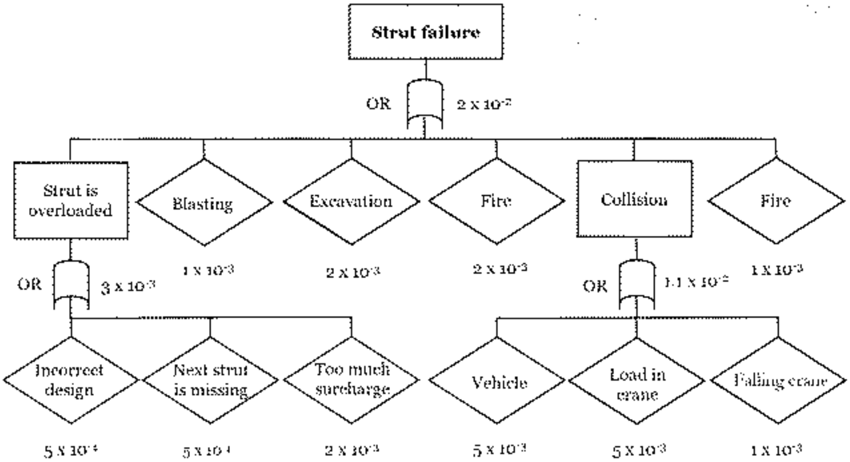


Figure 22: Fault tree for the damage event "*Strut failure*" (after Olsson 1998).

The concluding result of the analyses was that the probability of sheet pile wall failure was three times higher with struts than with anchors. The reason for this was that the struts were exposed to external impact to a greater degree than the anchors. Furthermore, the probability of limited damage on the adjacent building was almost equal for the two alternatives. The probability of major damage or total collapse of the building was around ten, and five times higher for the strut alternative. This was partly because the waling and the anchors are designed to be able to withstand a loading situation where one anchor has lost its capacity, according to Swedish practice. When using struts, the wale beam and the struts are usually not designed for this load situation. This means that the two systems are different, i.e. the system including anchors is a parallel system and the system with struts is a series system, and the system with anchors is more robust. Even though the system analysis showed that the system with anchors was preferable from a risk perspective, the client and contractor could not establish a mutual view of the risks. The decision situation regarding the supporting system of the sheet pile wall could have been evaluated using multi criteria decision analysis, e.g. Analytic Hierarchy Process, performed by an independent expert. However, a proposal to use an independent expert was rejected by the client.

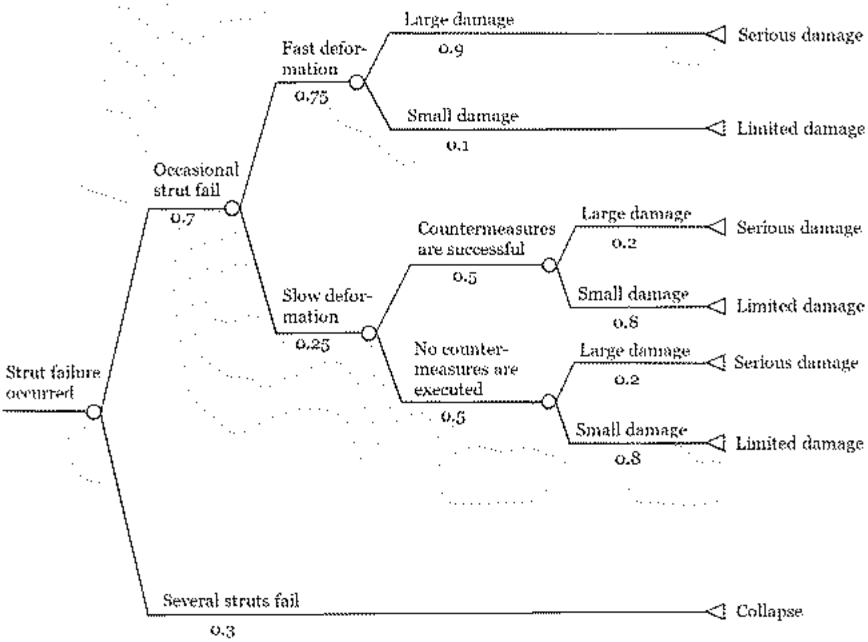


Figure 23: Event tree for damage on residential block “Asplången”, assuming strut failure occurred (after Olsson 1998).

To handle some of the identified risk, some mitigation actions were performed before the excavation work began. As mentioned previously, underpinning of the adjacent building “Asplången” was performed as a preventive action to reduce the consequence of the risk of damaging the building. Furthermore, a jack was inserted in every strut as a preventive action to make an adjustment of the deformation scenario possible.

6.3.3. The construction phase

The results from the previous phases in the risk management process were implemented into the working procedures and control programs before the start of the construction phase. This was considered to be especially important for all the activities that had been identified as critical to the success of the project. The project plan from tender phase was updated before the start of the construction work. However, the project plan did not become the governing document it was supposed to be, and the project plan was not updated during the construction phase. A comprehensive risk analysis, including technical and non-technical risks, was not established. This resulted in problems when modifications of the design were required and in the risk communication with the client.

Planning of the work activities was considered of great importance for managing the risks in the construction phase. A risk meeting was held with the geotechnical engineer in charge, the project manager, and the site personnel involved before the start of any critical activity. At these meetings, the geotechnical engineer and the project manager informed those present about the hazards, the initiating events, and the associated warning bells which were relevant for the activity at hand. Furthermore, a review team of independent experts in different areas was assigned to audit the project performance and the risk management process. Toll gates were presented on the drawings and in the working procedures, as well as in the project plan, together with the corresponding milestones.

However, some decisions had to be taken in a rush when they came into question because of inadequate preparation and planning of critical decisions. Therefore, the optimal decision alternative could not be chosen in some situations, e.g. regarding the rock support. Furthermore, due to the limited knowledge of the decision alternatives in some situations, there were occasionally disagreements regarding the most appropriate decision alternatives, e.g. regarding the type of supporting system for the sheet pile wall close the residential block “Asplången”. Here, the client was reluctant about the installation of anchors under the adjacent building, because of the risk of settlement and damage to the pile foundation. But the contractor had planned to install anchors instead of struts, since anchors were judged to involve less risk for damage on the building. These differences in opinion were probably due to prestige, different views of the risk assessment and communication problems and they resulted in extra costs and time delays.

Observations of warning bells and initiating events were performed continually during the construction phase. Observations of the behavior of the soil and the structures, e.g. the sheet pile walls, were performed with the aim of verifying the design and the material properties. The monitoring system was based on the risk assessment and the design specifications. The warning bells and the identification of initiating events were considered to be the most important factors for a safe and efficient execution of the project. A monitoring system was used during the construction phase in order to measure settlement, anchor forces, strut forces, deformations of the sheet pile walls and the pore pressures in the soil within the working area. The monitoring system was an automatic system, which continuously registered data from the gauges, piezometers, inclinometers etc.

To decide the time for implementation of the contingency measures, the expected deformations of the sheet pile wall in different excavation stages and cross-section calculations were undertaken with a finite element program. Deformation curves with upper and lower limits for the deformations in the sheet pile wall as well as for the forces in anchors and struts were generated.

The result of the measurements from the monitoring system was continually compared with predicted values, e.g. from the finite element analyses, to ascertain if any contingency measures were necessary. The contractor had a geotechnical engineer on the site to analyze the observations and to review the geotechnical work. The measurement data were discussed with the client at geotechnical meetings every second week. If the observations did not correspond to the prognosis, an analysis of the reasons was conducted, and in-advance prepared contingency measures were undertaken so that the deformations would not exceed the maximum levels stated in the contract. No strict alarm thresholds were defined, however. The decision to put any contingency measures into action was, more or less, taken by the geotechnical engineer in charge. This was different to the observational method described in Chapter 4. The observational method, as it is defined in Eurocode 7, rests on strictly defined alarm thresholds that automatically trigger the planned contingency measures.

In the evaluation of the measurements, the focus was principally on individual values and not on trends. Consequently, it was difficult to decide the right time for the contingency measures to be undertaken (Figure 24).

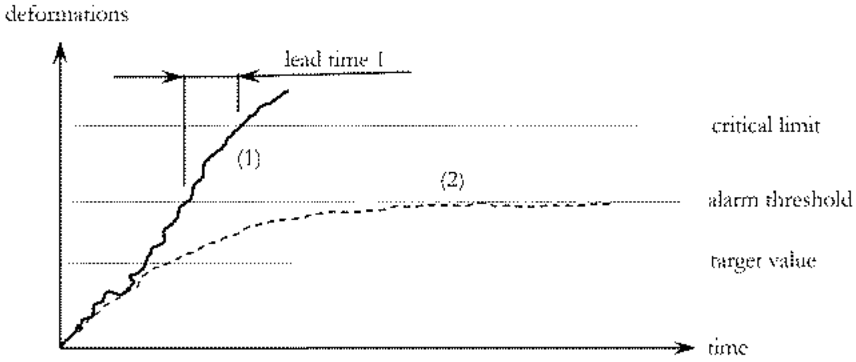


Figure 24: Different stress-strain relationships result in different lead times (after Paté-Cornell & Benito-Claudio 1987).

Depending on the stress-strain relationship, it could be too late to undertake a contingency measure; see curve (1) with a constant trend and a short lead time, and curve (2) which has a decreasing trend.

6.4. Fulfillment of the observational method principles

6.4.1. Geotechnical uncertainties

The design and construction of the sheet pile wall was critical in the project since the tunneling works could not be started before the sheet pile wall and the excavation were finished. In the contract, there were strict demands regarding permissible settlement outside the sheet pile wall because of several sensitive structures. The settlement behind the sheet pile wall due to the excavation depended on many factors, e.g. stratigraphy, soil properties, groundwater level, support system, construction activities, workmanship, and soil-structure interaction. Finite element analyses were used to estimate the deformation of the sheet pile walls and the settlement outside the sheet pile walls.

The design and construction of the sheet pile wall included epistemic and aleatory uncertainty and complex soil-structure interaction, which contributed to the difficulty in predicting the geotechnical behavior. This should motivate the adoption of the observational method for the design and construction of the sheet pile wall. The adoption of the observational method in this situation would result in increased costs for design and monitoring. However, these costs would probably outweigh the risk associated with traditional design methods, which could result in a design with an unpredictable safety level or a very costly design if cautious estimates of the soil parameters were used.

6.4.2. Management considerations

The adopted observational procedure could not be used to its full potential in the project due to several obstacles, e.g. a resistance to carry out the planned contingency measures. The reason for this was probably prestige, unclear risk ownership, lack of mutual commitment and understanding of the working procedure and potential benefits of an observational procedure. Consequently, the observations were, more or less, only used to verify the design. However, the observations fulfilled the aim of observing warning bells and initiating events. In addition, the project was managed as an implementation project, making it difficult to modify the design because of lack of time in some situations.

6.4.3. Contractual considerations

The contract was a design-and-build contract with a lump sum, and the client had a strong position as a large public client. In some situations, the client was reluctant to approve modifications of the design and the implementation of the planned contingency measures. For example, the client rejected proposals from the contractor regarding design or construction methods, e.g. the support system for the sheet pile wall, even when the analysis showed that one system was preferable from a risk and safety perspective. Consequently, the project was, more or less, executed under a somewhat fixed contractual framework, where the client had considerable influence on the design and execution. Under this contractual framework, the observation method would have been a tool for verifying the design, not for creating a safe and cost-effective design, as there were no incentives to modify the design and implement planned contingency measures.

6.4.4. Conclusions

The project fulfilled eight of the principles proposed in Section 4.10.6 (Table 19). The evaluation and comments in table are based on the case study and the interviews.

Table 19: Fulfillment of the observational method principles presented in Section 4.10.6.

Principle		**Y/N**	**Comment**
P.1	The project includes complex geotechnical behavior that is difficult to predict.	Y	Complex geotechnical conditions and soil-structure interaction made it difficult to predict the geotechnical behavior, e.g. the sheet pile walls.
P.2	There is a ductile geotechnical and structural behavior.	Y	The soil mainly consisting of clay and the sheet pile walls had a ductile geotechnical and structural behavior.
P.3	Geotechnical hazards and uncertainties are identified and analyzed.	Y	The contractor made a thorough risk assessment before the start of the works.
P.4	Theoretical and practical framework for how observations can decrease the epistemic uncertainty are established.	N	The observations were used to verify the design. No theoretical and practical framework for how the observations would decrease the uncertainty existed
P.5	The additional costs for the observational method outweigh the risks with other design methods.	Y	In contrast to traditional design, the observation method could lead to a design with unsatisfactory safety due to the uncertainties.
P.6	There are flexible designs and construction schemes that can be altered during construction.	Y	Several different designs and construction schemes and contingency measures were evaluated and planned.
P.7	The monitoring system and the control parameters are based on the uncertainties involved and on a clear definition of critical design problems.	Y	An identification and a definition of critical design problems were performed early in the design process, e.g. the design of the sheet pile walls, and the monitoring system was based on these design problems.

P.8	Commitment, knowledge, and competence in using the observational method exists among the actors involved.	N	Not all actors had adequate commitment, knowledge, and competence, e.g. the site personnel.
P.9	Resources for the implementation of the contingency measures are available at the right time, e.g. personnel, equipment, and material.	Y	Appropriate equipment and material were kept at the site, e.g. soil material to fill against the sheet pile wall in case of large deformations.
P.10	There are flexible contracts including a value engineering approach that can handle changes in geotechnical behavior.	N	Fixed design-and-build contract with a lump sum payment, unclear responsibilities and authorities in the contract.
P.11	There is close cooperation between the actors involved in the project.	N	The cooperation between the contractor and client was not good enough in some situations.
P.12	The observational method is an integrated part of the design process from the inception of the project.	Y	An observational procedure was adopted early in the design when it was realized that traditional design method could not manage the risks.
P.13	The observational method has a prominent role in the constructions phase and is an integrated part of the production process.	N	The adopted observational procedure had a distinguishing role in the construction phase but was not integrated into the production process.
P.14	A strict and formal management framework with clear roles and responsibilities of the actors involved with respect to the observational method exists.	N	There was no management framework with respect to the observational method and the roles and responsibilities were unclear.
P.15	The project is managed as an innovation project.	N	The project was managed as an implementation project based on traditional project management principles.

6.5. Concluding remarks on the case study

Before the work started, the client and the contractor were aware that it would be a high-risk project because of its characteristics, e.g. the complex geotechnical conditions, the deep excavations in soft soils, and the high public, political, and environmental focus.

A comprehensive risk assessment for including geotechnical risks was made in the early phases of the project. A detailed list of damage events and identified hazards, initiating events and warning bells, as well as planned contingency measures, was established. Environmental, organizational, and economic risks were not included explicitly. In addition, some decision alternatives were not completely explored. As a result, there were disagreements regarding decision alternatives in some situations, i.e. regarding the support system of the retaining walls. The reasons for these problems were probably prestige, different views, knowledge and/or experience of the identified risks, the risk management process, as well as the communication of risks. This could probably have been avoided if the client and contractor, in an early phase of the project, had discussed the identified hazards, both technical and non-technical, and the decision alternatives in order to establish a mutual view of the risks and the risk management process.

The contractor considered the planning of the work activities to be of great importance to managing the risks. Before the execution started, the contractor described how the identified hazards would be managed in the daily work. The contractor performed a risk assessment, including identification and prioritization of hazards, identification of initiating events and warning bells, and preparation of contingency measures. A review team of independent experts was used to audit the project performance and the risk management process. This way of working was successful in the project.

The working procedure, with identification of risk objects, hazards, initiating events, warning bells and damage events, together with the monitoring system and pre-defined contingency measures, worked well in the construction phase. The monitoring system fulfilled its aim of observing warning bells and initiating events. Therefore, contingency measures, e.g. pumping and infiltration of water, tensioning of the sheet pile anchors and additional reinforcement of the rock cuttings, could be implemented before any damage occurred.

Authorities and responsibilities were described in the project plan, which was established by the contractor in the tender phase. The work activities in the project plan were planned based on the identified risks. Revisions were conducted to ensure that the working procedures in the project plan were followed. The project plan was not updated during the construction phase and did not become a governing document as it was supposed to be.

The flow of information was successful in the project. The risk information was communicated regularly to all individuals involved, including the site personnel. The risks and the upcoming work activities were also communicated to the public at meetings every second week. This resulted in few complaints from the neighboring residents, and a positive opinion of the project.

An observational procedure was adopted for some critical design issues in the project, e.g. the design of a sheet pile walls, in order to manage the risks. However, the procedure could not be used to its full potential in the project due to several obstacles, e.g. technical, organizational and contractual obstacles. The project fulfilled eight of the fifteen proposed principles regarding the application of the observational method according to Table 19. The principles that were not fulfilled were related to both technical (P.4), organizational (P.8), contractual (P.10) and management (P.11, P.13, P.14, P.15) aspects. The conditions for a successful application of the observational method were thus not ideal and an application of the method would probably have faced many obstacles similar to those in the case study.

7. Delhi Metro, Contract MC1A, India

7.1. Project description

The Delhi Metro project included an underground railway system in New Delhi, India. The railway was planned to go in rock tunnels as well as cut-and-cover concrete tunnels. The MC1A contract included a 4.3 km railway and four new stations located 10-15 m below the ground level, and around 10 m below the groundwater level. The client was the Delhi Metro Rail Corporation Ltd. MC1A was a design-and-build contract with a lump sum payment.

The contract was procured in competition between both domestic and international competitors. The appointed contractor was a joint venture between four contracting firms: one from Sweden, one from India, and two from Japan. One of the Japanese contractors was the leading contractor in the joint venture. The design was carried out by a consulting company from Australia. The work started in 2001 and was completed in 2005. The contract was divided into four areas located around the stations A1–A4 (Figure 25). Each of these had a designated project manager, two from the Swedish contractor, and two from one of the Japanese contractors.

7.2. Geotechnical conditions

The geology in the area was characterized by the “Delhi ridge”, which is an anticline with steep layers of quartzite. The quartzite had layers of sandstone and shale which were less resistant to weathering. The upper part of the bedrock was, in places, weathered and fractured. The soil in the area consisted of 1-2 m of fill above silt and sand, which were weathered from the sandstone and shale. The thickness of the soil strata varied considerably between 3 and 50 m.

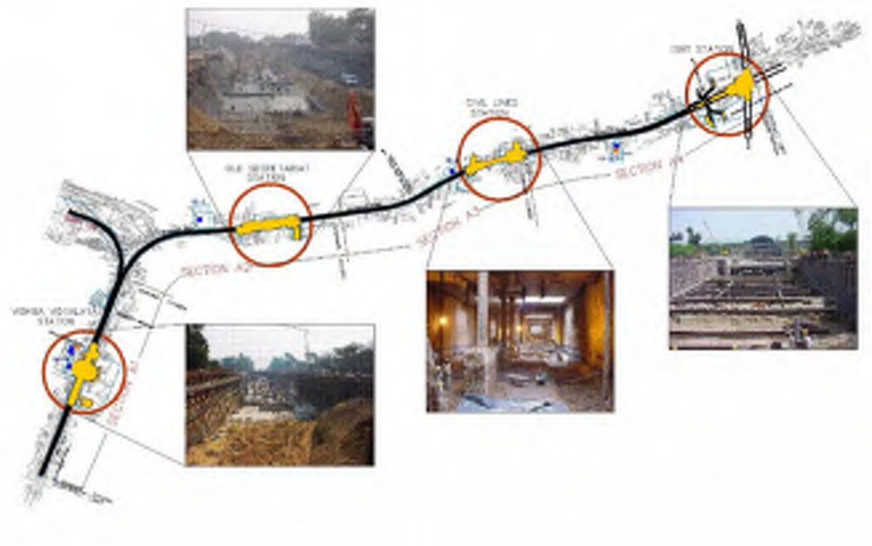


Figure 25: Delhi Metro, contract MC1A (Hintze et al. 2004).

The boundaries between the different soil layers and the soil and weathered rock were, however, indistinct (Figure 26). The bedrock was composed of quartzite that was partly weathered and fractured, especially close to the surface. There was a gradual transition from highly weathered rock in the surface to solid bedrock. The depth to solid rock varied between 50 and 100 m. The groundwater level was located approximately 2-4 m below the ground level.

The tunnel sections in the MC1A contract were to be constructed as concrete tunnels, built with a cut-and-cover technique. The excavation depth was about 13 m from the ground level and about 9-11 m below the groundwater level. Two of the stations were built using a bottom-up technique (Figure 27), and the other two with a top-down technique, i.e. the stations are built from the roof and down, with successive excavation inside supported by retaining walls.

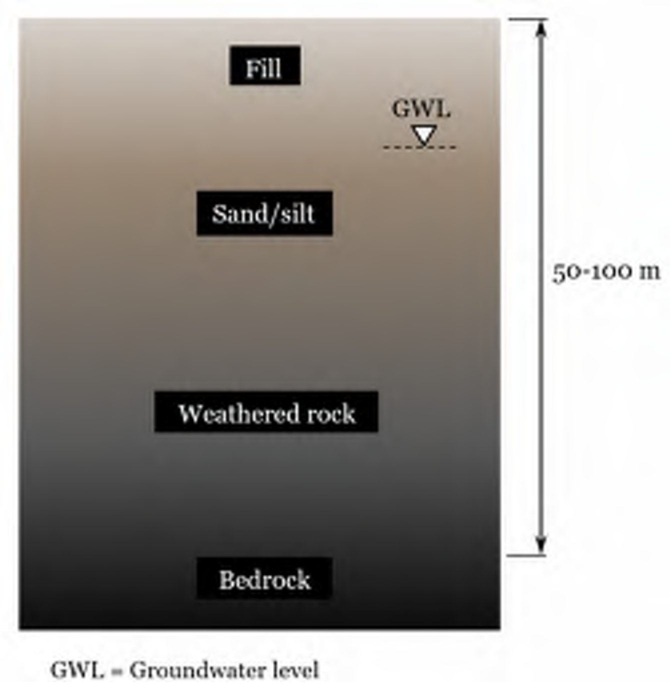


Figure 26: Typical geotechnical conditions at the site of MC1A (schematic presentation).

7.3. Management of geotechnical risks

7.3.1. The planning phase

Before the start of the project, the client performed a schematic risk identification, primarily related to environmental issues and risks related to adjacent buildings and traffic. The identified risks were included in the tender documents. Risks related to the geotechnical conditions were, however, not identified.

Figure 27: Cut-and-cover concrete tunnel in the Delhi Metro project (Hintze et al. 2004).

7.3.2. The tender and design phase

The risk management process started in the tender phase with a risk assessment conducted by the joint venture. The risk assessment included both non-technical risks, such as contractual and organizational risks, and technical risks, such as geotechnical risks. The following risk sources were identified in the tender phase of the project:

- The location of the project.
- The client.
- The soil and rock conditions.
- The precipitation and groundwater.
- The type of contract and payment method.
- The temporary structures and their impact on the environment.
- The installation of the diaphragm walls.

The location was identified as a risk since the project was located in a densely populated area in the middle of the city of Delhi. A major challenge during the construction work was the rearrangement of the traffic, as well as the transportation of building material and excavated soil and rock material. The client was considered a risk since it was unknown to the contractors in the joint venture.

The site investigation of the soil and rock condition was limited. Around 20 standard penetration tests and a few core samples of the bedrock were presented in the tender documents. Therefore, the uncertainties regarding the soil and rock conditions were judged to be considerable. During the rain period it may rain up to 200 mm in 24 hours in the area. The groundwater level varied considerably over the year, which could affect the execution of the excavations and the retaining walls. The heavy rain could also influence the stability of slopes and the work in general, with changes of work procedures and time delay as potential consequences.

The limited knowledge of the soil and rock conditions and the limited possibility to conduct more site investigations before the start of the design made it clear that a thorough follow-up of the conditions used in the design had to be conducted in the construction phase. Therefore, an observational procedure similar to the concept of “active design” was adopted. This was considered essential to ensure a cost-effective design and to secure the reliability of the structures and the safety of the workers.

The contract was a design-and-build contract which meant that the joint venture was responsible for both the design and execution of the project. In the contract there was a clause stating that the client had the option to review and approve all documents, e.g. method statements and work procedures, before the related activity could start. Therefore, all work procedures and methods had to be described thoroughly. The need for a suitable contract with the external designer, that clearly specified the scope of the design commitment and the client’s requirements, was identified to be important for the success of the project, together with an appropriate management of the designer. A cost-effective design with an appropriate level of safety, delivered at the right time was also considered crucial to the project’s success.

The possible impact on adjacent buildings was considered a hazard due to the geotechnical uncertainty. Several buildings close to the excavations were in a bad condition when the works began. The contract stated that no additional damage was allowed. Consequently, the design was performed with a finite element program in order to estimate the deformations of the temporary retaining walls. The finite element program was also used to determine alarm thresholds. Identified warning bells were related to deformations of the retaining walls and monitored forces in anchors and struts.

In the tender documents, the tunnel inside the diaphragm walls was proposed to be executed according to a top-down method, i.e. using the permanent internal structure as the temporary support to the retaining wall, cast in a top-down sequence. Furthermore, blasting works had to be performed close to the retaining walls. A blasting test was carried out outside the city as there was little experience of blasting works in the area. The bedrock on the test site was found to be hard and partly weathered and fractured. Consequently, the proposed working procedure according to the top-down method was identified as a hazard because the available equipment was not designed to install the diaphragm walls into hard weathered bedrock.

During the design phase, additional hazards related to the design were identified, mainly due to the insufficient site investigation and the limited knowledge of the local conditions. In the tender phase, some of the excavations for the tunnels were assumed to be performed without any retaining structures. However, an excavation test executed in the design phase revealed that the maximum excavation depth was around 5 m without any earth supporting structure. Signs of liquefaction around 2 m below the groundwater level were also apparent in the test. Therefore, the original plan of building the stations had to be changed. An extensive groundwater pumping system was planned to be installed to lower the groundwater level inside the excavations. To maintain the groundwater level outside the excavation, a water infiltration system was prepared.

The identified hazards were gathered in a risk register, together with observations (warning bells) and initiating events; see example in Table 20. A qualitative estimation of the likelihood and consequence of the risks was also performed.

Table 20: Example of a risk register for the excavation inside the retaining structures.

Damage event	**Warning bell**	**Initiating event**	**Treatment action**
Stability problems (slope failure)	Visible deformation on the ground surface within the excavation (tension cracks)	Excavation Vibrations	Stop the excavation and backfill the soil Stop the vibrating works Excavate with less slope
Soil liquefaction	Flowing soil “Water boils” or “sand boils” at the surface within the excavation	Excavation Vibrations	Stop the excavation Stop the vibrating works Lower the groundwater level within the excavation Compaction of the soil

A problem that became apparent in the design phase was the differences in risk perception and design philosophy between the different actors involved in the project, e.g. when interpreting the site investigations and designing the temporary retaining structures. From the Swedish contractor’s point of view, the Australian design consultant was conservative and risk-averse. Here, a value engineering clause in the contract with the design company that shared potential cost savings between the joint venture and the design company could have created incentives for the design company to be less conservative and risk-averse. This could probably have helped to enable a less conservative and a more cost-effective design. Risk meetings between the client, joint venture, and design consultant before the start of the design could have lead to a mutual view of the possible risks and a more effective implementation of the observational procedure.

7.3.3. The construction phase

Important work processes to manage the risks and hazards that had been identified, and analyses in the design phase were technical support, design management, design optimization, and monitoring. An important issue for the engineers involved in the project was to ensure that the identified hazards were managed in an optimal way using monitoring systems and by the use of an external review team of experts. Technical reviews were carried out at the site three times during the project. The aim of the use of a review team was to obtain objective feedback on the design and the construction methods, as well as a review of the risk management process and the project performance. Information of the progress of the project was continually sent to the review team.

An observational procedure was used in the construction phase to manage the identified risks and ensure a safe and cost-effective execution of the project. By using a monitoring system, the knowledge of the soil and rock conditions increased during the progress of the project. The monitoring system was designed to observe the warning bells that had been identified in the tender and design phase, for example:

- Groundwater levels outside the retaining structures were measured with submersible pressure transmitters in open wells to avoid too large water pressures against the retaining structures that could result in wall failure.
- Groundwater levels within the excavation were measured with submersible pressure transmitters in open wells to avoid soil liquefaction that would reduce the strength of the soil and make the excavation and the foundation works more complicated and time-consuming.
- Settlement on adjacent buildings was measured with level gauges to avoid damage to the buildings.
- Vibrations from traffic, piling and other vibrating works were measured on adjacent buildings with vibration meters to avoid damage to the buildings.

- Deformations of the retaining walls were measured with inclinometers and measurements horizontally and vertically on the top of the walls and on some of the wale beams to avoid too large ground movements on the outside of the walls. The alarm thresholds were related to the permissible settlement on adjacent structures.

A minor complementary site investigation was carried out during this phase of the project. The results from the monitoring and the site investigation could be used for a reevaluation of the design of the structures and to update the risk register. Consequently, some risks could be discarded, and new risks were added in the register. The increased knowledge could also be used to redesign the temporary retaining structures to make them more cost-effective without compromising safety. This led to cost and time savings.

However, there were obstacles to using the observational procedure in the project. The client was reluctant to approve some modifications of the design and construction scheme based on the observations. Furthermore, part of the joint venture's internal project organization did not understand some of the benefits of adopting an observational procedure, including the necessity of making observations and preparing modifications of the design. In addition, some of the changes were considered too difficult to carry out and an obstacle to daily work. The Swedish contractor considered the client and the design consultant to be too conservative, as they both considered the design to be fixed and tried to obtain a project execution without any major changes. There were also different views on the risk management inside the joint venture, mainly because of different risk perceptions due to social and cultural differences. A value engineering clause in the contract with the client that shared potential cost savings between the client, contractor, and design consultant could probably have helped to ensure a more effective implementation of the observational procedure. Despite these obstacles, the result from the measurements could be used to optimize the design regarding time and cost to some extent. For example, the number of anchors, struts, and prop levels was reduced, some of the temporary struts for the diaphragm walls could be excluded, and the amount of reinforcement in the diaphragm walls could be reduced.

Thus, the observational procedure was implemented “backwards” compared to the definition of the observational method in Eurocode 7. Eurocode 7 assumes that a possibly unsafe design, because of the uncertainties involved, is made safer if the alarm thresholds are exceeded and contingency measures are put into action. In the case of the Delhi Metro, the observational procedure started with a safe design that was made less safe based on the observations. Notably, Nicholson et al. (1999) in fact recommend this way of implementing the observational method. This could have influenced the possibility to implement the observational procedure effectively. In a design-and-build contract with a lump sum payment, the client has no incentives to approve modifications that result in a less safe design, since the contractor gets all the savings. Therefore, a value engineering clause should have been included in the contract. On the other hand, in a design-build contract with a bill of quantities, the contractor has no incentives to modify design to save money, as the quantities include profit for the contractor and the client gets all the savings.

7.4. Fulfillment of the observational method principles

7.4.1. Geotechnical uncertainties

The project included extensive retaining structures for the excavation of the tunnels and the stations. The site investigation performed before the tendering phase was extremely limited, and the uncertainty of the geotechnical conditions was considerable. Consequently, it was difficult to predict the geotechnical behavior of the excavations and the retaining structures. In this situation, the use of traditional design methods probably would have resulted in a design with an unpredictable safety margin. Therefore, the use of the observational method would have been motivated.

7.4.2. Management considerations

The joint venture's project organization at the site did not understand the benefits of modifying the design, and the modifications were sometimes considered to be too difficult and/or time-consuming to carry out. The project management on the site wanted an execution without any major changes. Additionally, the client considered the design to be fixed, and tried to maintain a safe project execution without any major changes. This resulted in resistance to implement some of the planned contingency measures. There were different views of the risk management in the joint venture, mainly due to social and cultural differences, which complicated the risk management process.

7.4.3. Contractual considerations

There were several obstacles to the adoption of an observational procedure and the observational method in the project. The contractual framework was not suitable for the implementation of the observational method. The contractual framework included a design-and-build contract with a lump sum payment, which generally promotes the observational method and gives the contractor the possibility to implement the observational method. However, the alarm thresholds and the contingency measures were not approved by the client before the start of the construction as the client had no incentives to approve the modifications suggested by the contractor. Additionally, the client maintained the original requirements in the contract even if they were inadequate. The design consultant was procured with a fixed price and had no incentives to modify the design as new information became available during the construction through additional site investigations and observations.

7.4.4. Conclusions

The project fulfilled some of the principles of the observational method proposed in Section 4.10.6 (Table 21). The evaluation and comments in Table 21 are based on the case study and the interviews.

Table 21: Fulfillment of the observational method principles presented in Section 4.10.6.

Principle		**Y/N**	**Comment**
P.1	The project includes complex geotechnical behavior that is difficult to predict.	Y	Limited site investigations, complex geotechnical conditions and soil-structure interaction made it difficult to predict the geotechnical behavior.
P.2	There is a ductile geotechnical and structural behavior.	Y	The soil and the retaining walls had mostly a ductile behavior.
P.3	Geotechnical hazards and uncertainties are identified and analyzed.	Y	The joint venture performed an extensive risk assessment, including technical and non-technical risks before the start of the works.
P.4	Theoretical and practical framework for how observations can decrease the epistemic uncertainty are established.	N	No theoretical framework existed. The observations were used to verify the design and to trigger modifications if the observations differed from those anticipated.
P.5	The additional costs for the observational method outweigh the risks with other design methods.	Y	Traditional design method could lead to a design with unsatisfactory safety or unnecessary large safety due to the geotechnical uncertainties.
P.6	There are flexible designs and construction schemes that can be altered during construction.	Y	Several different designs and construction schemes and contingency measures were evaluated and planned. However, they were not approved by the client before the start of the execution.
P.7	The monitoring system and the control parameters are based on the uncertainties involved and on a clear definition of critical design problems.	Y	An identification and a definition of critical design problems were performed early in the design process, e.g. the design of the retaining structures, and the monitoring system was designed on the basis of these design problems.

P.8	Commitment, knowledge, and competence in using the observational method exists among the actors involved.	N	The client and the design consultant were not committed to the use of the observational method as they had no incentives to be a part of it.
P.9	Resources for the implementation of the contingency measures are available at the right time, e.g. personnel, equipment, and material.	Y	Appropriate equipment and material were kept at the site, e.g. soil material to fill against the sheet pile wall in case of large deformations.
P.10	There are flexible contracts including a value engineering approach that can handle changes in geotechnical behavior.	N	Design-and-build contract with a lump sum payment, the client and the design consultants had no incentives to modify the design or the construction scheme.
P.11	There is close cooperation between the actors involved in the project.	N	The cooperation between the client, contractor, and design consultant was problematic in some situations.
P.12	The observational method is an integrated part of the design process from the inception of the project.	Y	An observational procedure was adopted by the contractor early in the design when it was realized that traditional design methods could not manage the risks due to the geotechnical uncertainties.
P.13	The observational method has a prominent role in the constructions phase and is an integrated part of the production process.	N	The adopted observational procedure had a distinguishing role in the construction phase but was not integrated into the production process.
P.14	A strict and formal management framework with clear roles and responsibilities of the actors involved with respect to the observational method exists.	N	The management framework included only the contractors in the joint venture; the client and the design consultant were not included.
P.15	The project is managed as an innovation project.	N	The client considered the design to be fixed and the project management on site wanted an execution without any modifications.

7.5. Concluding remarks on the case study

The complex nature of the project led to an extensive risk management process throughout the entire project. The limited knowledge of the local conditions, e.g. the client and the geotechnical and hydrological conditions, as well as the contractual arrangement, created hazards and uncertainties that needed to be addressed in the risk management process. The large amount of uncertainties required a systematic approach to risk management. A review team was used to obtain an objective review of the management of the project, as well as the construction methods and the work procedures. Monitoring of key parameters and the utilization of information obtained during the execution phase had a distinguishing role in the construction phase.

The social and cultural differences between the actors in the project created some problems in the risk management process and the execution of the project. The client, contractor, and the designer had, to some extent, different views of risks, the risk management process, and the design. In addition, risk perceptions differed among the actors involved. There were also different opinions within the joint venture regarding the management of the risks, which resulted in problems when deciding and implementing appropriate contingency measures.

The work with the risk assessment worked well in the project due to a systematic approach and the use of an independent expert group which visited the site. The later phases of the risk management process, i.e. the monitoring and treatment of the risks, did not work so well due to difficulties in the implementation of these in the corporate culture, and in getting them accepted among the workers in the project.

There were some problems in using an observational procedure in the execution phase of the project. The client and the design consultant considered the design to be fixed to some extent, and the client was reluctant to approve changes in the design. Moreover, the workers on site were sometimes unwilling to carry out changes, probably because they did not understand the benefits and regarded them as something that disturbed their normal work. Another problem was the differences in the interpretation of the site investigations and the design of the temporary retaining structures among the actors involved.

The project fulfilled eight of the fifteen proposed principles regarding the application of the observational method according to Table 19. The principles that were not fulfilled were related to both technical (P.4), organizational (P.8), contractual (P.10) and management (P.11, P.13, P.14, P.15) aspects. Thus, the conditions for a successful application of the observational method were not optimal. An application of the method would probably have faced obstacles like those in the case study.

8. Tunnel under Hvalfjörður, Iceland

8.1. Overview

The case study is presented in the appended paper. It should preferably be read before continuing. The abstract from the paper is presented in Section 8.2.

8.2. Abstract

Rock tunnel construction is associated with considerable geotechnical uncertainty, often due to limited knowledge about the ground conditions. This warrants the use of stringent risk management procedures to reduce the likelihood of cost increases, delays, and structural failure events. The observational method is often promoted as a tool to achieve cost-effective designs in cases of large geotechnical uncertainty, but its practical use is still limited. One reason may be the lack of guidelines and experiences from previous projects where the observational method has been used. In this paper we therefore present a case study of the design and construction of the tunnel under the Hvalfjörður fjord in Iceland, where the observational method played a key role in the risk management that was performed to deal with the challenging geological conditions at the site. The project was a success and completed four months earlier than originally planned. In light of the case study, we discuss the definition of the observational method in Eurocode 7 and the related contractual aspects to consider in such projects.

8.3. Fulfillment of the observational method principles

8.3.1. Geotechnical uncertainties

Due to the project team's limited knowledge and experience of subsea tunneling on Iceland, as well as the severe consequences of many of the identified hazards and the failures in other similar tunnel projects, an observational procedure, or the observational method, was probably the only appropriate design method. In addition, the geotechnical uncertainty involved, and the complex geotechnical conditions, made it difficult to predict the geotechnical behavior of the tunnel. Consequently, traditional design methods would probably lead to a costly, conservative design based on most unfavorable design parameters but still with an unpredictable safety margin due to the uncertainties involved. In this situation, the extra costs for the implementation of the observational method outweighed the risks with other design methods.

8.3.2. Contractual considerations

The contractual arrangement was a turnkey contract for the design and construction, with a lump sum payment after the tunnel had been operated for some time. This gave the contractor the possibility to adopt the observational method and to implement the planned contingency measures when necessary, without permission from the client, as long as the formal requirements were fulfilled.

8.3.3. Management considerations

Observations of the geotechnical conditions and the geotechnical behavior were made during the execution phase as planned. The cooperation between the actors involved worked well and the actors had adequate knowledge regarding the observations. However, no practical and technical framework for the reduction of the uncertainties existed.

8.3.4. Conclusions

The project fulfilled most of the principles of the observational method proposed in Section 4.10.6 (Table 22). The evaluation and comments in Table 22 are based on the case study and the interviews.

Table 22: Fulfillment of the observational method principles presented in Section 4.10.6.

Principles		**Y/N**	**Comment**
P.1	The project includes complex geotechnical behavior that is difficult to predict.	Y	Limited site investigations and complex geotechnical conditions made it difficult to predict the geotechnical behavior of the tunnel.
P.2	There is a ductile geotechnical and structural behavior	Y	The rock mass and the supporting system had a ductile behavior.
P.3	Geotechnical hazards and uncertainties are identified and analyzed.	Y	The joint venture performed an extensive risk assessment, including technical and non-technical risks, before the start of the works.
P.4	Theoretical and practical framework for how observations can decrease the epistemic uncertainty are established.	N	No theoretical framework existed. The observations were used to verify trigger contingency measures if the observations differed from those anticipated.
P.5	The additional costs for the observational method outweigh the risks with other design methods.	Y	Traditional design method could lead to a costly design or a design with unsatisfactory safety due to the substantial geotechnical uncertainties.
P.6	There are flexible designs and construction schemes that can be altered during construction.	Y	Several different designs and construction schemes were prepared based on the rock classification.
P.7	The monitoring system and the control parameters are based on the uncertainties involved and on a clear definition of critical design problems.	Y	An identification and a definition of critical design problems were performed early in the design process, e.g. the rock support, and the monitoring system was

			designed on the basis of these design problems.
P.8	Commitment, knowledge, and competence in using the observational method exists among the actors involved.	Y	All actors were committed to the adoption of the observational method and had adequate knowledge of and competence in the method.
P.9	Resources for the implementation of the contingency measures are available at the right time, e.g. personnel, equipment, and material.	Y	Appropriate equipment and material were kept at the site, e.g. grouting equipment in case of inflow of water in the tunnel.
P.10	There are flexible contracts that can handle changes in geotechnical behavior.	Y	The joint venture had the possibility to adopt the observational method as long as the formal requirements were fulfilled.
P.11	There is close cooperation between the actors involved in the project.	Y	The cooperation between the client, contractor, and design consultant was good.
P.12	The observational method is an integrated part of the design process from the inception of the project.	Y	An observational procedure was adopted early in the design when it was realized that traditional design methods could not manage the risks due to the geotechnical uncertainties.
P.13	The observational method has a prominent role in the constructions phase and is an integrated part of the production process.	Y	The adopted observational procedure had an important role in the construction phase and was integrated into the production process.
P.14	A strict and formal management framework with clear roles and responsibilities of the actors involved with respect to the observational method exists.	N	The roles and responsibilities were not clearly described and, in some situations, there were ambiguities in the decision-making process.
P.15	The project is managed as an innovation project.	Y	The project management understood that modifications of the design were very likely and that the final design could not be decided before the tunnel was constructed.

8.4. Concluding remarks on the case study

Due to the characteristics of the project, e.g. the contract, the organization, the limited knowledge and experience of subsea tunneling, and the recorded failures in similar tunnel projects, both the client and the joint venture that were assigned to build the tunnel were aware of the potential risks in the project. Consequently, a lot of effort was put into the risk management process in the early phases of the project. In the early phases, the focus was on the identification of hazards, initiating events and warning bells, and on the monitoring of warning bells in the execution of the project.

The extensive dialog between the risk analysis group, the joint venture, the client, and the Icelandic geological experts increased the awareness of both geological and organizational hazards in the project. This resulted in a mutual view of the risks and hazards, as well as of the risk management process in the project. Fault and event trees were used for identifying hazards and the chain of events leading to actual damage. The use of an independent analysis group and the combination of traditional risk assessment methods and engineering judgement were successful.

The risk management in the construction phase was performed by the design department of one of the contractors, as the independent expert group was separated from the project. The risk management methodology and the monitoring outlined in the early phases of the risk management process were mainly adopted as the contractors implemented parts of the risk analysis in the work procedures and excluded other parts.

The monitoring of the identified warning bells and the use of predefined contingency measures to manage the risks had a distinguishing role in the construction phase. Several preventive methods were used, e.g. pre-probing, georadar, and geophysics, and several contingency measures were implemented during the execution. These played a crucial role in ensuring a safe and cost-effective execution of the project.

The project fulfilled thirteen of the fifteen proposed principles regarding the application of the observational method according to Table 19. The principles that were not fulfilled were related to technical (P.4) and management (P.14) aspects. However, the observational method could probably have been applied successfully in the project if decision-making procedures regarding the implementation of contingency measures were established.

9. Discussion and recommendations

9.1. Overview

In the previous chapters, the concepts of risk and risk management, risk management in geotechnical engineering, and the observational method in geotechnical engineering have been considered. Furthermore, the management of geotechnical risks and the applicability of the observational method in three executed geotechnical engineering projects have been analyzed.

Despite the general development in the construction industry, e.g. new construction methods and sophisticated design methods, the number of cost overruns, time delays, disputes, claims, and construction failures do not appear to have decreased during the last decades, according to several studies, e.g. Flyvbjerg (2017) and Aljohani et al. (2017). There are many reasons for these problems. Many researchers, e.g. Tonks et al. (2017), consider the unsuccessful management of geotechnical risks to be one of them. In geotechnical engineering projects, the geotechnical conditions can never be characterized completely due to the aleatory and epistemic uncertainty involved. Therefore, geotechnical risks will always exist, and these risks must be managed to ensure a successful outcome of the project.

The case studies exposed some important problems in the management of geotechnical risks. These are related to:

- Implementation of the risk management process.
- Allocation of risks.
- Perception of risks among the actors involved.
- The application of an observational procedure, or the observational method, to manage the geotechnical risks.

All these issues influence the result of the management of geotechnical risks. The implementation of the risk management process influences the quality of the process and the possibility to assess and treat the risks. The allocation of risks determines which actor is responsible for a risk, i.e. the risk owner, and influences the cooperation between the actors involved. An inappropriate and/or unclear risk allocation may lead to claims and disputes. The integration of the risk management process into other project activities influences, for example, how the risks will be managed in the different phases, from feasibility to design, construction, operation, maintenance and dismantling. The perception of risk influences how different individuals will perceive a risk and act when facing a risk. Studies have shown that different individuals perceive risk differently due to, for example, psychological, social, and cultural factors.

The following sections include the findings from the case studies regarding these issues (Section 9.2), and my recommendations to the client, designer, and contractor regarding how to behave as a competent and risk-conscious actor in a geotechnical engineering project (Section 9.3, 9.4 and 9.5). These recommendations are based on the literature review and the case studies.

9.2. Findings from the case studies

9.2.1. The risk management process

All three case studies included a structured risk management process. However, the risk management process was performed by different actors in different phases of the project. In the planning phase, the clients performed their own risk management process. Only one of the clients considered both technical and non-technical risks in the risk assessment. Geotechnical risks were considered in only two of the case studies. The identified risks were included in the tender documents, but the descriptions of the risks were rather brief. The contractors performed their own risk management process in the design and construction phase. One of the contractors considered only technical risks, e.g. geotechnical risks.

This resulted in a dispersed risk management process where risk information was possibly lost on the way from the client to the designer and contractor. Additionally, there were different views of the risks, and a consensus of the risks was difficult to establish. This could probably have been avoided if the client and contractor met in an early phase to discuss the risks. A joint development of a geotechnical risk profile in the projects could probably have helped.

The risk management process was treated as a separate activity and was not fully integrated into the planning, design, and execution process. The risk management process should not be regarded as a separate activity but should permeate all other work activities and the daily work of the client, designer, and contractor. The risk management should be on the agenda of all meetings and not only on separate risk meetings.

9.2.2. Risk allocation

The allocation of risks will determine which actor is responsible for the risks. Studies have shown that the allocation of risks has a significant impact on the total construction cost and the quality, e.g. Levitt & Ashley (1980). The problem of risk allocation concerns both qualitative issues, i.e. what type of risks should be allocated and to whom, as well as quantitative issues, i.e. how much of the risk should be allocated.

It is generally agreed that the party with the best opportunity to manage a risk should be responsible for it, see e.g. Cooper et al. (2006). It may be tempting for clients to transfer the risks to the contractors to “get rid of them” by using a design-and-build contract. However, this is seldom the most optimal way to allocate risks since there is a possibility that the contractor cannot manage them. Transferring the risk to a contractor will also cause a cost, a risk premium in the bid, for the client since no contractor is willing to take on a risk for free unless they have not understood the risk taken, which, however, causes other issues. If the contractor cannot manage the risk nor has the possibility to manage the risk, this cost is a waste of money since the risk, if it is unmanaged, will lead to some unwanted consequence. To avoid this, the client will have to manage the risk anyway. Additionally, if one actor is forced to take a large part of the risks without being compensated for it, disputes, a bad working climate, and poor overall performance tend to occur. Transferring the responsibility of geotechnical risks to the contractor could also lead to reduced competition if contractors are not willing to submit tenders for projects including substantial geotechnical risks.

All three case studies included a design-and-build contract that transferred most of the risks to the contractor. The allocation of the geotechnical risks was, however, unclear. The allocation of risks would have been clearer if a risk allocation matrix had been used, see e.g. Yamaguchi et al. (2017). None of the contracts included a geotechnical baseline report or a differing site condition clause. This made the allocation of the geotechnical risks ambiguous. Some of the performance requirements stated in the contracts were partly irrelevant and, in some situations, it was difficult to change these when new information became available. Similar experiences have been presented by Bröchner et al. (2006).

The absence of an appropriate risk allocation based on the identified risks in the case studies resulted in discussions regarding the responsibility of the geotechnical risks and the appropriate risk treatment actions. Additionally, in some situations it was difficult to implement risk treatments that required a design modification, as the client had no incentives to approve the modifications. The inclusion of a risk allocation matrix, a geotechnical baseline report, and a value engineering clause in the contract could probably have avoided these problems.

9.2.3. Perception of risk

The differences in risk perception between the actors created obstacles in the risk management process and the execution of the project. Consequently, the client, contractor, and designer had different views of the risks and the risk management process. It is important to understand the risk perception among the actors involved. Loosemore & McCarthy (2008) conclude that contractual risk allocation and technical risk assessment have little meaning if they are separated from the social and behavioral context in which risk is experienced by those involved in a project. The different actors' risk perception must be analyzed before the start of the risk management process.

The aforementioned study by the Transportation Research Board (2017) showed that without a differing site condition clause, the geotechnical risks were perceived to be higher among contractors than among the client's own staff. This will result in high contingencies in the contractors' price proposals. The recommended solution to this problem was to align the perceptions of geotechnical risks of the client and contractor early in the process. This can be accomplished be a joint development of the geotechnical risk profile of the project.

9.2.4. The applicability of the observational method

A successful application of the observational method requires that relevant technical, organizational, contractual and management aspects are fulfilled. In the case studies, the most critical obstacle seems to be related to the contractual arrangement with design-and-build contracts and lump sum payments. This type of contract does not promote the cooperation between the client, contractor and designer as the method requires. In addition, without a value engineering clause in the contract, the client and designer do not have incentives to modify and optimize the design and construction.

9.3. Recommended role of the client

The fundamental aim for most clients is to gain maximum value for their invested capital. However, in many projects it is almost equally important for clients to have a predetermined outcome for their projects in terms of time, cost, and quality. As geotechnical risks may cause time delays, cost increases, and quality problems, it is in the client's interest that the geotechnical risks are managed appropriately.

The client's risk acceptance and the attitude towards risks will reflect the way in which risks are managed in a project since the client generally sets the standard or level for the risk management process. If the client does not emphasize the importance of the risk management, it is unlikely that the other actors will lead this task. Therefore, the client's attitude towards risk management has a major influence on the risk management process of the entire project. A sound attitude should be to adopt a comprehensive view of the risks and to focus on the most important issues and risks that were found in the risk identification phase. Successful management of geotechnical risks is also dependent on the client's full and true engagement and commitment to the risk management process.

The risk management process is not only influenced by the client's attitude but also by the client's ability to establish the formal requirements in an early phase of a project. Changes in the client's requirements are generally undesirable and should be avoided if possible, since successful risk management requires that the design objectives can be defined before the design phase is started. On the other hand, the requirements should be changed if they are found to be irrelevant. Successful design comes from a careful definition of the requirements, which gives the designer maximum flexibility in seeking the most cost-effective design with respect to the geotechnical uncertainties.

For a successful management of geotechnical risks, the client should ensure that a structured risk management system is established during the planning of the project. The methodology presented in ISO 31000 (CEN 2018) and SGF (2017) could be adopted. Documentation and communication are especially important during the early phases of the project to ensure that all the risks identified during project conception are managed in later phases. The identified risks and hazards should, together with the planned risk treatment actions, be communicated to all actors involved. Clients need to ensure that, as far as possible, their requirements are recognized by the designer and contractor and are considered in the risk management process.

The result of the risk management process should include a risk register and a description of the potential consequences of the risks. A risk treatment plan should also be included where the risk objects, hazards, initiating events, damage events, risk owners, treatment actions, and the time for the treatment actions are presented. Additionally, the documentation should include recommendations of any further work necessary to determine the geotechnical conditions before the project proceeds. These documents should be passed on to key individuals in the project organization to ensure that these individuals have the relevant information, and no information is lost.

Furthermore, the client needs to decide the appropriate risk allocation and the type of contractual arrangement. It is important that clients select a type of contractual arrangement that reflects their intentions regarding the allocation of geotechnical risks. If the risk allocation is not described clearly in the contract, an unproductive working climate, misinterpretations, and disputes are more likely, but also lead to expensive arbitration and litigation after the project is completed. The fundamental aim should be that the risks are distributed so that the actor that has the best opportunity to control the risk is the risk owner. In addition, the risk owner should be given the opportunity to manage the risk and be provided reasonable compensation for it.

In many projects, clients and production teams want a detailed design at a very early phase of the project to facilitate planning and procurement. However, this will create a conflict of interest between design optimization and construction. Therefore, the client should focus on achieving the quality and performance of the work according to the contract, instead of a detailed control of the design and construction. The client should accept that the final design is produced at the same rate as the uncertainties are revealed and should provide sufficient time for the design phase.

The best contractual framework in many construction projects is where the technical resources of the client, the designer, and the contractor are combined to manage geotechnical risks and uncertainties as they become apparent. In complex projects, it should be worth investigating partnering and other collaborative arrangements. Formal dispute avoidance procedures should preferably be introduced from the beginning of the project as discussed by Turner & Turner (1999). Melvin (1998) suggests that the working climate and co-operation in the project can be improved by the use of a dedicated risk engineer, whose main task is to look after all the major contracts involved in a project and thereby anticipate any disagreement and dispute. This may lead to better construction site relationships, a deeper involvement and commitment among the actors involved, and fewer claims.

In conclusion, the main tasks of the client in the management of geotechnical risks are:

- Clients should take an active role to ensure that the risk management process is started during planning with an identification and estimation of geotechnical risks, as well as deciding procedures for risk management and establishing a geotechnical risk register.
- Clients should take a leading role in coordinating the work with the management of geotechnical risks in the project and ensure that a mutual view of the risks and risk management process is established in the project.
- Clients should declare their fundamental objectives and requirements, as well as the acceptable risk level, i.e. the risk criteria, in an early phase of the project.
- Clients should invest in adequate geotechnical advice to allow an identification of projects which could be significantly affected by geotechnical conditions.
- Clients should analyze the impact of the contractual framework between the client and the contractor on the allocation of risks.
- Clients should include a risk allocation matrix and a geotechnical base line report in the contract.
- Clients should communicate the result of the client's risk management to the designers, contractors, and all other actors involved in the construction process.
- Clients should give the contractor authorization to implement the contingency measures which are a part of the contract.
- Clients should consider the use of an independent dispute review board from the start of the project.

In complex geotechnical engineering projects where it is difficult to predict the geotechnical behavior, the client should consider the adoption of the observational method. A client who wants to obtain advantages using the observational method should arrange for that in the contracts with the other actors involved, e.g. designer, contractor, advisors, and reviewers. In the tendering phase, the client should find out which designers and contractors are willing and competent enough to implement the observational method successfully. In addition, the client should appoint a competent reviewer of the works. The reviewer should be comfortable in, and have confidence, using the observational method, otherwise it will be difficult to implement the method successfully. The client should set up an organizational and management framework suitable for the observational method. The client should also consider the following issues:

- Clients need to understand that the final design cannot be established until the construction is completed.
- Clients should initiate the observational method before tendering.
- Clients should use a flexible contractual framework that can handle changes in design and execution, e.g. a collaborative arrangement.
- Clients should include a value engineering clause in the contractual framework with the designer, contractor, and other actors significantly involved in the construction process, regardless the type of contract.

9.4. Recommended role of the designer

In geotechnical engineering projects, design is a continuous process requiring regular review to ensure that the client's needs are being met. The main goal of the designer is, in general, to design a planned facility based on the conditions at a given site, a description of the desired function and quality of the facility, as well as societal laws and regulations. The designer generally wants to create a good relationship with the client in a long-term business view to have a good reputation as a competent advisor.

An appropriate design requires not only adequate theoretical knowledge but also relevant experience, engineering intuition, and engineering judgement. In many situations, this will include the establishment of design concepts which need to be modified during construction. In complex design situations, monitoring is essential, and the adoption of the observational method has advantages over traditional design methods.

Designers need to understand that the geotechnical conditions are never known in detail because of epistemic and aleatory uncertainty. An effective design results in effective risk treatment strategies, and residual risks can be focused on and suitable ownership defined. To be effective, geotechnical design should be systematic and recognize the geotechnical uncertainties. The design process should be integrated within a risk management framework to ensure that uncertainties are managed effectively. Geotechnical design should be carried out systematically, using a stepwise approach to design in order to ensure that the client's needs are correctly identified, and optimal solutions are found.

I recommend using Clayton's (2001a) suggestions to improve the risk management process:

- For effective hazard identification, the first geotechnical investigation must be carried in an early phase of the project and a geotechnical engineer should therefore be involved from the project start.
- Several geotechnical investigations must be performed as the geotechnical design will generally be carried out in several phases of the project.
- The geotechnical conditions should be observed and recorded during construction. The actual conditions should be compared to those assumed in the risk identification phase and the design.

- For low-risk projects a limited site investigation in combination with construction review will be enough. In high-risk and complex geotechnical engineering projects, e.g. construction of dams, tunnels, and deep excavations in urban areas, extensive investigations will be necessary to manage the risks.
- Geotechnical data, including the motives for geotechnical investigations and their interpretation, should be made available to all actors in the project.

However, most designs will be based on limited investigations and the shortcomings of this must be recognized by the designer. Six approaches can be helpful in projects with limited geotechnical investigations. These are (Clayton 2001b):

- An independent team of experts can be used to review the design to ensure that key mechanisms of failure are not overlooked, that realistic parameters are selected, and that the design calculations are performed correctly.
- The use of sensitivity analyses and/or probabilistic calculations allows the designer to understand the effects of uncertain parameters on the result of analyses.
- Critical failure mechanisms especially can be prevented from occurring by adopting more than one risk treatment action.
- Observation and monitoring of the geotechnical conditions should be used during construction to ensure that the assumptions made in the design are representative for the geotechnical design to perform satisfactorily.
- Where design can be flexible, monitoring of key components can be formalized in the observational method.
- An active design approach or the observational method may be adopted to reduce the uncertainties.

If the observational method is planned to be used, the designer should make the client aware of the circumstances under which the observational method is to be adopted and the likely costs of the most probable and most unfavorable scenarios. In addition, the designer should have an open mind when using the observational method to avoid forcing the results of the observations to fit preconceived ideas. The designer should discuss the following issues with client (Nicholson et al. 1999):

- The options of design by the observational method and by the traditional design method, and how each method can manage the risks.
- The increased cost for design that might occur.
- The scope for use of the observational method on different parts of the project, and the procedure to be adopted for planned modifications.
- The potential cost and time savings when using the observational method.
- The expenditure on site investigation, design, planning monitoring etc. associated with the use of the observational method.

In conclusion, the main tasks of the designer in the risk management process are:

- Designers should be systematic and identify the client's needs and risk acceptance.
- Designers should recognize that the geotechnical conditions always are uncertain and should adopt design strategies that are effective in managing uncertainties.
- Designers should acknowledge that risk management is a part of everyday work.

- Designers should always consider the contradicting objectives of safety and adequate usage of resources to create cost-effective structures which are easy to construct.
- Designers should emphasize conceptual design and sensitivity analysis to understand unfavorable design interactions and the effect of uncertain parameter values.
- Designers should decide the extent of geotechnical site investigations in relation to the degree of geotechnical uncertainties involved as well as the planned works.
- Designers should recognize the limited accuracy of many geotechnical design calculations, e.g. due to the epistemic uncertainty about the site conditions.
- Designers should observe the geotechnical conditions during construction in an adequate manner and compare these to those presumed in the risk identification phase and the design.
- Designers should identify, analyze, and monitor warning bells based on the geotechnical behavior and implement predefined contingency measures if necessary.

9.5. Recommended role of the contractor

In general terms, the fundamental aim for contractors is to maximize the profit, both in the short and long term, without compromising safety and quality. Most contractors are also anxious to create a good long-term relationship with clients. There is a trend that clients are increasingly adopting methods of contracting by which the risks are transferred to the contractor. Thus, it is important that the contractor's geotechnical risk management strategy recognizes the impact of the contractual framework within which the work is to take place.

In all projects, the contractor should introduce a structured risk management framework as early as possible. Geotechnical uncertainties and hazards should preferably be identified and analyzed in the tendering phase. The risk assessment should be based on the client's risk register in the tender documents. The risk register should be reviewed and complemented before the start of construction. It should also be reviewed regularly during construction to ensure that risks have been managed as planned and that the risks are relevant to the conditions encountered. If a risk register is not received from the client, the contractor should start to establish one as soon as possible.

The risk register should be updated regularly during the design and construction. If the contractor takes on design responsibilities, a geotechnical design review should preferably be carried out to ensure that the geotechnical risks have been effectively managed. The risks associated with geotechnical construction techniques should be assessed as soon as possible. The result of the contractor's geotechnical risk management should be communicated to the relevant individuals involved in the project, including site personnel, sub-contractors, and geotechnical designers.

During the project execution, the contractor should observe, monitor, and record the actual geotechnical conditions and the structural behavior. The result from the monitoring will allow an evaluation of the adequacy of the design. A comparison of observed and expected geotechnical conditions may give early warning of possible problems, allowing changes to be made before additional costs and time delays become significant. The result of the observation and monitoring during construction should be fed back to designers as it becomes available, to ensure any unexpected condition and behavior is detected.

To avoid "filing and forgetting" of the result from the risk management process, the agreed risk treatment actions should be on the same level as normal work, as Lewin (1998) and Stille (2017) suggests. Note that if the risk treatment actions are considered only as extra work, they may likely be given second rate status behind the ordinary work activities. Only if the risk treatment actions are considered to be an important task that make a significant contribution to achieving the objectives of the project, will the risk management process be taken seriously and the risks actually managed. The following steps might help in this matter:

(i) Accept that the risk treatment actions might require changes to the project cost or time schedule.

(ii) Ensure that every risk treatment action is fully defined with a duration, cost, resource requirement, owner, and completion criteria.

(iii) Add an extra task to the project plan for every agreed risk treatment action.

(iv) Monitor the progress on the risk treatment actions in the same way as for all other tasks.

In conclusion, my key recommendations regarding the contractor's tasks in the process of managing geotechnical risks can be summarized as:

- The contractor should allocate an adequate amount of staff and financial resources to work with the management of geotechnical risks.
- The contractor should make the risk management work equally important as other work activities.
- The contractor should start the risk management process as early as possible, i.e. during the tender phase.
- The contractor should review and supplement the client’s risk register before the start of the execution regarding the planned construction methods, and review the risk register regularly during construction.
- The contractor should establish method statements and working procedures to manage identified risks.
- The contractor should establish procedures which may identify and manage unexpected risks, e.g. by adopting the observational method.

- The contractor should observe, monitor, and record the actual geotechnical conditions and geotechnical behavior during the project execution.
- The contractor should review the geotechnical aspects of the design and identify opportunities where redesign could make construction safer and more cost-effective.
- The contractor should, together with all other actors involved in the project, exploit the information collected during risk management in order to allow continuous improvement of the risk management process.

10. Concluding remarks and proposals for future work

> "… a scientific discipline without a large number of thoroughly executed case studies is a discipline without systematic production of exemplars, and a discipline without exemplars is an ineffective one."
>
> – Bent Flyvbjerg (2006, pp. 219)

10.1. Concluding remarks

This doctoral project was initiated with the aim of giving the construction industry tools to manage geotechnical risks. The background to the project was the many cost overruns and time delays reported around the world, and the problems with poor management of geotechnical risks that has long been noticed in the construction industry.

The risk management process in geotechnical engineering projects is complex, but no less important. From a societal perspective, it is important to manage the geotechnical risks effectively to increase the use of society's resources, to ensure a sustainable development and to avoid accidents. From the construction industry's perspective, it is important to manage the geotechnical risks effectively to decrease the number of cost overruns and time delays that negatively affect the industry.

The aim of the thesis was to facilitate a better management of geotechnical risks in construction projects, to improve the quality of geotechnical works and to decrease costs related to geotechnical risks. To fulfill this aim, experiences and best practice were obtained from literature, and from case studies of three geotechnical engineering projects.

The thesis addresses many of the concerns regarding the observational method discussed during the Géotechnique symposium in 1994, as well as the objectives for future work based on the symposium discussion presented in Powderham & Nicholson (1996), see Section 4.6.1. It can be concluded that many of these concerns still persist today.

The literature review and the analysis of the case studies resulted in recommendations regarding the implementation of the risk management process, the application of the observational method, the contractual framework, and the roles of the client, designer, and contractor in the risk management process and the application of the observational method. Hopefully, these recommendations can strengthen the construction industry and inspire to an improved management of geotechnical risks using the observational method.

The client has a leading role in the risk management process considering that the client is initiating and funding the project. The client should set the standard and initiate the geotechnical risk management process in an early phase of the project. The interaction and cooperation between the parties strongly influence the possibility to manage the risks. Clients should consider these issues in the procurement phase and in the contractual arrangement with other parties. Nevertheless, all parties involved have an important role to play in the process of managing geotechnical risks. Most important, however, is to grow a risk-conscious culture in the project, where the actors understand that risk management is a part of their everyday work.

10.2. Proposals for future work

Based on the findings in the thesis, I suggest the following objectives for future work:

- *Identification of risks.* Both the understanding of the context and the identification of critical risks are important parts of the risk management process since the costs of unidentified and unmanaged geotechnical risks are large in many construction projects. However, it is not always obvious which risks have the greatest impact on the project cost and the time schedule. Future work should focus on finding methods to identify the most critical risks in geotechnical engineering projects.

- *The perception of risk.* Risk is a function of perception of the actors involved in the risk management process and the perception of risk is different between different individuals and organizations. Consequently, geotechnical risks are managed in different ways in different projects. In the case studies, it was obvious that, for example, individual, social, and cultural factors influence the risk management process and the implementation of the observational method. Furthermore, there are many psychological factors in the risk evaluation that need to be understood. Future work should focus on identifying the key factors influencing the perception of geotechnical risks and methods to “balance” the risk perception of the actors involved in the risk management process.
- *Methods of risk allocation.* The allocation of geotechnical risks is a source of disputes and poor working climate in many projects. The fundamental idea of risk allocation seems to be that the risk allocation should be fair, and that the party that has the best opportunity to manage the risk should be the risk owner and should be reasonably compensated for it. It is rather easy to discuss these issues in qualitative terms as “fair” and “reasonable” but much more difficult to determine the appropriate risk allocation in quantitative terms. Methods for quantitative risk allocation in construction projects have been developed, see e.g. Lam et al. (2007) Khazaeni et al. (2012), Hanna et al. (2013), and Nasirzadeh et al. (2014, 2016). However, researchers have not reached consistent conclusions on how specific kinds of risks should be allocated. Future work should

focus on finding or developing methods for an appropriate allocation of geotechnical risks in construction projects.

- *Implementation of the observational method*. The use of the method has been limited by the lack of general recommendations and guidelines. The thesis presents some guidelines and recommendations based on the literature review and the case studies. Future work should focus on increasing the knowledge regarding the key aspects influencing the implementation of the method, e.g. by studying successful implementations of the method in geotechnical engineering projects.

References

Abrahamson M W, 1973, Contractual Risks in Tunnelling: How They Should be Shared, *Tunnels and Tunnelling*, pp. 587-598.

Abrahamson M W, 1984, Risk Management, *Journal of International Construction Law Review, vol. 1, no. 3,* pp. 241-264.

Akintoye A S & MacLoed, 1997, Risk Analysis and Management in Construction, International *Journal of Project Management, vol. 15, issue 1,* pp. 31-38.

Aljohani A, Ahiaga-Dagbui D & Moore D, 2017, Construction Projects Cost Overrun: What Does the Literature Tell Us?, *International Journal of Innovation, Management and Technology, vol. 8, no. 2*, pp. 137-143.

Andersen E S, 1996, Warning: Activity Planning is Hazardous to Your Project's Health!, *International Journal of Project Management, vol. 14, issue 2*, pp. 89-94.

Andersen P H & Kragh H, 2010, Sense and Sensibility: Two Approaches for Using Existing Theory in Theory-Building Qualitative Research, *Industrial Marketing Management, vol. 39, issue 1,* pp. 49-55.

Andersson J, 1999, Data and Data Uncertainty – Compilation of Data and Data Uncertainties for Radionuclide Transport Calculations, *Swedish Nuclear Fuel and Waste Management Co, Technical report TR-99-09*, Stockholm, Sweden.

Anderson J M, 1997, World Wide Research Points to the Need for New Approaches to Control Tunneling Risks, Tunneling under Difficult Conditions and Rock Mass Classification, In: *Proceedings of One Day Seminar and International Conference, Basel, Switzerland*, pp. 87-95.

Andersson L, 1988, The Theory of Possibility and Fuzzy Sets – New Ideas for Risk Analysis and Decision Making, *Swedish Council for Building Research, Document D8:1988*, Stockholm, Sweden.

Ang A H-S, 1970, Extended Reliability Basis of Structural Design under Uncertainties, *SAE Technical Paper no. 700656.*

Ang A H-S & Tang W H, 1975, *Probability Concepts in Engineering Planning and Design, volume I – Basic Principles*, John Wiley & Sons, New York, USA.

Ang A A-S & Tang W H, 2007, *Probability Concepts in Engineering – Emphasis on Applications to Civil and Environmental Engineering*, 2nd edition, John Wiley & Sons, New York, USA.

Assaf S A & Al-Hejji S, 2006, Causes of Delay in Large Construction Projects, *International Journal of Project Management, vol. 24, issue 4,* pp. 349-357.

Aven T, 2012, The Risk Concept – Historical and Recent Development Trends, *Reliability Engineering & System Safety, vol. 99,* pp. 33-44.

Aven T, 2016, Risk assessment and Risk Management: Review of Recent Advances on their Foundation, *European Journal of Operational Research, vol. 253, issue 1,* pp. 1-13.

Baecher G, 1981, Risk Screening for Civil Facilities, *MIT CR R-81-7*, Massachusetts, USA.

Baker S, Ponniah D & Smith S, 1999, Risk Response Techniques Employed Currently for Major Projects, *Journal of Construction Management and Economics, vol. 17, issue 2*, pp. 205-213.

Bedford T & Cook R, 2003, *Probalistic Risk Analysis: Foundations and Methods*, Cambridge University Press, Cambridge, United Kingdom.

Bjureland W, Spross J & Johansson F, Reliability 2017, Aspects of Rock Tunnel Design with the Observational Method, *International Journal of Rock Mechanics and Mining Sciences, vol. 98*, pp. 102-110.

Blockley D, 1995, Uncertain Ground: On Risk and Reliability in Geotechnical Engineering, *Ground Engineering 27,* pp. 28-28.

Brandl H, 2004, *The Civil and Geotechnical Engineer in Society: Ethical and Philosophical Thoughts*, The Deep Foundation Institute, Hawthorne.

British Tunnelling Society, 2003, *Joint Code of Practice for Risk Management for Tunnel Works in the UK.*

Bröchner J, Håkansson U & Hässler L, 2006, Contractors and Design Risk in Major Civil Works Design/Build Projects, In: *Proceedings of Canadian Society for Civil Engineering 1st International Construction Specialty Conference, Calgary, Alberta, Canada*, pp. 23-26.

BSI, 2020, *BS EN 12973:2000, Value Management*, British Standards Institution (BSI).

Card G B & Carder D R, Movements Trigger Limits When Using the Observational Method to Embedded Retaining Wall Construction on Highway Scheme, *TRL report 228, Transport Research Laboratory,* Berkshire, England.

Carlsson M, 2005, *Management of Geotechnical Risks in Infrastructure Projects: An Introductory Study*, Lic. Thesis, Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden.

Carlsson M, Hintze S & Olsson L, 2004, Application of System Analysis in Geotechnical Engineering - An Example from the South Link Road Construction, In: *Proceedings of the Nordic Geotechnical Meeting 2004, Ystad, Sweden*, pp. J39-J49.

CEN, 2004, *EN1997-1:2004 Eurocode 7: Geotechnical design—Part 1: general rules*, European Committee for Standardization, Brussel, Belgium.

CEN, 2018, *ISO 31000 Risk Management – Guidelines*, European Committee for Standardization. Brussels, Belgium.

Chan A P C, Ho D C K & Tam C M, 2001, Design and Build Project Success Factors: Multivariate Analysis, *Journal of Construction Engineering and Management, vol. 127, no. 2*, pp. 93-100.

Chan D W M & Kumaraswamy M M, 1997, A Comparative Study of Causes of Time Overruns in Hong Kong Construction Projects, *International Journal of Project Management, vol. 15, issue 1,* pp. 55-63.

Chapman C & Ward S, 2004, Why Risk Efficiency Is a Key Aspect of Best Practice Projects, *International Journal of Project Management, vol. 22, issue 8,* pp. 619-632.

Chen W T, Chang P Y & Huang Y H, 2010, Assessing the Overall Performance of Value Engineering Workshops for Construction Projects, *International Journal of Project Management, vol. 28, issue 5,* pp. 514-527.

Chen Y, Nicholson D, Ingram P, Hardy S, Liew H L, Farooq I & Biscontin G, 2015, Application of the Observational Method on Crossrail Projects, In: *Crossrail: A Specialist Foundation Construction Lessons Learnt Conference,* pp. 63-72.

Chowdhury R, 1995, Geotechnical System Reliability and Decisions, In: *Proceedings of Bengt Broms Symposium on Geotechnical Engineering, Singapore*, pp. 79-94.

Christian J T, 2004, Geotechnical Engineering Reliability: How Well Do We Know What We Are Doing?, The Thirty-Ninth Karl Terzaghi Lecture, *Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, vol. 130, no. 10*, pp. 985-1 003.

CIRIA, 1984, Design of retaining walls embedded in stiff clay, Construction Industry Research and Information Association, *CIRIA Report 104*, London, United Kingdom.

CIRIA, 2002, A Simple Guide to Controlling Risk, Construction Industry Research and Information Association, *CIRIA Report 154*, London, United Kingdom.

Clayton C R, 2001a, Managing Geotechnical Risk: Time for Change?, *Journal of Geotechnical Engineering, vol. 149, , issue 1*, pp. 3-11.

Clayton C R, 2001b, *Managing Geotechnical Risk - Improving Productivity in the UK Building and Construction*, Thomas Telford Publishing, London, United Kingdom.

Connaughton J N & Green S D, 1996, Value Management in Construction – a Client's Guide, *CIRIA Special Publication no. 129*, CIRIA, London, United Kingdom.

Cooper D, Grey S, Raymond G & Walker P, 2006, *Project Risk Management Guideline,* John Wiley and Sons, England.

Corotis R B, 2003, *Risk and Uncertainty*, Applications of Statistics and Probabilities in Civil Engineering, Millpress, Rotterdam, The Netherlands.

Cox Antony Jr L, 2008, What's Wrong with Risk Matrices?, *Risk Analysis: An International Journal, vol. 28, issue 2,* pp. 497-512.

Dell'Isola A J, 1982, *Value Engineering in the Construction Industry,* 3rd edition, Van Nostrand Reinhold Company, New York.

Denyer D & Tranfield D, 2009, Producing a Systematic Review, In: *Buchanan D A & Bryman A (eds.), The Sage Handbook of Organizational Research Methods, Sage Publications Ltd*, pp. 671–689.

Der Kiureghian A & Ditlevsen O, 2009, Aleatory or Epistemic? Does It Matter?, *Structural Safety, vol. 31, issue 2*, pp. 105-112.

Douglas M & Wildavsky A, 1982, *Risk and Culture*, Berkeley, University California Press, Los Angeles, USA.

Duncan J M & Brandon T L, 2019, Use of the Observational Method as the Sole Basis for Design, In: *Geo-Congress 2019: Data, Software, Education, and a Tribute to Ralph Peck,* Reston, VA: American Society of Civil Engineers, pp. 107-116.

Dvir D & Lechler T, 2004, Plans are Nothing, Changing Plans is Everything: The Impact of Changes on Project Success, *Research Policy, vol. 33, issue 1*, pp. 1-15.

Engwall M, 2002, *Ledarskapets olika skepnader – exemplet Hallandsås*, Danielsson A & Holmberg I (eds.), Studentlitteratur, Lund, Sweden. (In Swedish).

Eriksson P E, Larsson J & Pesämaa O, 2017, Managing Complex Projects in the Infrastructure Sector — A Structural Equation Model for Flexibility-Focused Project Management, *International Journal of Project Management, vol. 35, issue 8,* pp. 1 512-1 523.

Flyvbjerg B, 2006, Five Misunderstandings About Case Study Research, *Qualitative Inquiry, vol. 12, no. 2*, pp. 219-245.

Flyvbjerg B, 2008, Curbing Optimism Bias and Strategic Misrepresentation in Planning: Reference Class Forecasting in Practice, *European Planning Studies*, vol. *16, issue* 1, pp. 3-21.

Flyvbjerg B, 2012, Five Misunderstandings about Case Study Research, Corrected, *Qualitative Research: The Essential Guide to Theory and Practice, London and New York: Routledge*, pp. 165-166.

Flyvbjerg B, 2014, What you Should Know about Megaprojects and Why: An Overview, *Project Management Journal, vol. 45, no. 2*, pp. 6–19.

Flyvbjerg B, 2017, Introduction: The Iron Law of Megaproject Management, In: Flyvbjerg (eds.), *The Oxford Handbook of Megaproject Management*, Oxford: Oxford University Press, pp. 1-18.

Frank R, 2004, *Designers' Guide to EN 1997-1 Eurocode 7: Geotechnical Design - General Rules*, vol. 17, Thomas Telford.

GeoTechNet, 2005, Innovative Design Tools in Geotechnics - part 1: In: Patel D (ed.), *The Observational Method in Geotechnics, European Geotechnical Thematic Network*, Belgium.

Geraldi J, 2009, Reconciling Order and Chaos in Multi-Project Firms, *International Journal of Managing Project in Business, vol. 2, issue 1*, pp. 149-158.

Glass P R & Powderham A J, 1994, Application of the Observational Method at the Limehouse Link, *Géotechnique, vol. 44, issue 4*, pp. 665-679.

Godfrey P S & Halcrow W, 1996, *Control of Risk: A Guide to the Systematic Management of Risk from Construction*, Construction Industry Research and Information Association, CIRIA, London, United Kingdom.

Gordon M, 1994, Choosing Appropriate Construction Contracting Method, *Journal of Geotechnical Engineering, vol. 120, issue 1*, London, United Kingdom, pp. 196-210.

Gough D, Oliver S & Thomas J, 2017, Introducing Systematic Reviews, In: *Gough D, Oliver S & Thomas J (eds.), An Introduction to Systematic Reviews*, Los Angeles: Sage Publications Ltd.

Guba E G, 1981, Criteria for Assessing the Trustworthiness of Naturalistic Inquiries, *Educational Communication and Technology Journal, vol. 29, issue. 2*, pp. 75–91.

Gustafsson M, 2002, *Att Leverera ett kraftverk – förtroende, kontrakt och engagemang i internationell projektindustri*, Ph. D. Thesis, Åbo Akademis Förlag, Turku.

Guthrie P & Mallet H, 1995, Waste Minimisation and Recycling in Construction – A Review, *CIRIA Special Publication no. 122*, CIRIA, London, United Kingdom.

Hammersley H, 2002, *Value Management in Construction*, Association of Local Authority Business Consultants, Hammersley Value Management Ltd, Coventry, UK.

Hanna A S, Thomas G & Swanson J R, 2013, Construction Risk Identification and Allocation: Cooperative approach, *Journal of Construction Engineering and Management, vol. 139, issue 9*, pp. 1 098-1 107.

Hansson S O, 1991, An Overview of Decision Theory, National Board for Spent Nuclear Fuel, *SKB Report 41*, Stockholm, Sweden.

Hansson S O, 1993, The False Promises of Risk Analysis, *Ratio 6.1*, Blackwell Publishers, Oxford, United Kingdom, pp. 16-26.

Hansson S O, 2002, Philosophical Perspectives on Risk, *Techné: Research in Philosophy and Technology, vol. 8, issue. 1*, pp. 10-35.

Hansson S O, 2004, *The Epistemology of Technological Risk*, Internal Report, The Philosophy Unit, Royal Institute of Technology, Stockholm, Sweden.

Hardy S, Nicholson D, Ingram P, Gaba A, Chen Y & Biscontin G, 2017, New Observational Method Framework and Application, In: *Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul*, pp. 1 995-1 998.

Hardy S, Nicholson D, Ingram P, Gaba A, Chen Y & Biscontin G, 2018, New Observational Method Framework for Embedded Walls, *Geotechnical Research, vol. 5, issue 3*, pp. 122-129.

Harr M E, 1987, *Reliability-Based Design in Civil Engineering*, McGraw–Hill, New York, USA.

Hartlén J, Jansson S & Christensen H, 2012, Citytunneln, Malmö: Geotechnical Hazards and Opportunities. In: *Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, vol. 165, issue 1*, pp. 35-44.

Harrison H, Birks M, Franklin R & Mills J, 2017, Case Study Research: Foundations and Methodological Orientations, In: *Forum Qualitative Sozialforschung/Forum: Qualitative Social Research, vol. 18, no. 1.*

Harvey-Jordan S & Long S, 2001, The Process and the Pitfalls of Semi-Structured Interviews, *Community Practitioner, vol. 74, issue 6,* pp. 219-221.

Hintze S, 2001, *Kvalitets- och miljöstyrning vid byggande i jord och berg*, Report no. 3085, KTH Royal Institute of Technology, Stockholm, Sweden. (In Swedish).

Hintze S, 2002, Prediction and Impact on Nearby Structures During Deep Excavation for the Southern Link Road Construction, In: *Proceedings of Planning and Engineering for the Cities of Tomorrow, 2nd International Conference on Soil Structure Interaction in Urban Civil Engineering, Zurich,* Switzerland.

Hintze S, Ekenberg M & Holmberg G, 2000, Southern Link Road Construction, Foundation and Temporary Constructions, In: *Proceedings of the 16th International Association of Bridge and Structural Engineering Conference*, *Zurich*, Switzerland.

Hintze S, Håkansson U & Täljsten B, 2004, Delhi Metro – risker och riskhantering i miljonformat, *Bygg & Teknik, no. 1*, Stockholm, Sweden. (In Swedish).

HMSE, 1996, *The Construction (Health, Safety and Welfare) Regulations 1996,* Her Majesty's Stationary Office, Statutory Instruments no. 1592, London, UK.

Holmberg M & Stille H, 2007, Observationsmetodens grunder och dess tillämpning på design av konstruktioner i berg, *SveBeFo Report 80*, Stockholm, Sweden. (In Swedish).

HSE, 1996. *Safety of New Austrian Tunnelling Method (NATM) Tunnels, A Review of Sprayed Concrete Tunnels with Particular Reference to London Clay*, Health and Safety Executive, HSE Books, Sudbury.

HSE, 1997, *Successful Health and Safety Management*, Health and Safety Executive HSE Books, London, United Kingdom.

Ibbs C W, Kwak Y H, Ng T & Odabasi A M, 2003, Project Delivery Systems and Project Change: Quantitative Analysis*, Journal of Construction Engineering and Management, vol. 129, issue 4*, pp. 382-387.

ICE, 1996, *Creating Value in Engineering*, ICE Design and Practice Guide, Institution of Civil Engineers, Thomas Telford, London.

IEC 60300-3-9, 1995, *Dependability Management - Part 3: Application Guide - Section 9: Risk Analysis of Technological Systems*, International Electrotechnical Commission, Geneva, Switzerland.

Ikuta Y, Maruoka M, Aoki M & Sato E, 1994, Application of the Observational Method to a Deep Basement Excavation Using the Top-Down Method, *Géotechnique, vol. 44, issue 4*, pp. 655-679.

International Tunnelling Insurance Group, 2006, *A Code of Practice for Risk Management of Tunnel Works*.

Isaksson T & Stille H, 2005, Model for Estimation of Time and Cost for Tunnel Projects Based on Risk Evaluation, *Rock Mechanics and Rock Engineering, vol. 38, issue 5*, pp. 373-398.

Jaafari A, 2001, Management of Risks, Uncertainties and Opportunities in Projects: Time for a Fundamental Shift, *International Journal of Project Management, vol. 19, issue 2,* London, United Kingdom, pp. 89-101.

Jepson J, Kirytopoulos K & London K, 2020, Insights into the Application of Risk Tools and Techniques by Construction Project Managers, *International Journal of Construction Management, vol. 20, issue 8*, pp. 848-866.

Johnson R M & Babu R I I, 2020, Time and Cost Overruns in the UAE Construction Industry: A Critical Analysis, *International Journal of Construction Management, vol. 20, issue 5*, pp. 402-411.

Kadefors A, 2004, Trust in Project Relationships – Inside the Black Box, *International Journal of Project Management, vol. 22, issue 3,* pp. 175-182.

Kadefors A & Bröchner J, 2008, Observationsmetoden i bergbyggande: kontrakt och samverkan (The observational method in rock engineering: contracts and collaboration), *SveBeFo Report 28*, Stockholm, Sweden. (In Swedish, Summary in English).

Kadefors A & Bröchner J, 2015, Organisering och kontrakt i bergtunnelprojekt – Kunskap i samverkan (Contracting for rock tunnel projects – knowledge in collaboration), *SveBeFo Report 138*, Stockholm, Sweden. (In Swedish, Summary in English).

Kaplan S & Garrick B J, 1981, On the Quantitative Definition of Risk, *Risk Analysis, vol. 1, issue 1*, pp. 11-27.

Kastbjerg S M, 1994, *Large Transports Projects – Forecast versus Actual Traffic and Costs*, M. Sc. Thesis, International Technology Planning, Aalborg University, Denmark.

Khazaeni G, Khanzadi M & Afshar A, 2012, Fuzzy Adaptive Decision Making Model for Selection Balanced Risk Allocation, *International Journal of Project Management, vol. 30, issue 4*, pp. 511-522.

Kleivan E, 1989, NoTCoS: The Norwegian Tunnelling Contract System, *Tunnelling and Underground Space Technology, vol. 4, issue 1*, pp. 43-45.

Knight F H, 1921, *Risk, Uncertainty and Profit,* Hart, Schaffner & Marx, Houghton Mifflin Company, Boston, USA.

Kolveit B J & Grønhaug K, 2004, The Importance of the Early Phase; The Case of Construction and Building Projects, *International Journal of Project Management, vol. 22, issue 7*, London, United Kingdom, pp. 545-551.

Korff M, 2017, Learning From Case Studies and Monitoring of Dutch Tunnel Projects, In: *Proceedings of the Institution of Civil Engineers - Forensic Engineering, vol. 170, issue 3*, pp. 134-143.

Korff M, de Jong E & Bles T J, 2013, SWOT Analysis Observational Method Applications, In: *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris: Presses des Ponts, pp. 1 883- 1 888.

Kutsch E, Browning T R & Hall M, 2014, Bridging the Risk Gap: The Failure of Risk Management in Information Systems Projects, *Research Technological Management, vol. 57, issue 2,* pp. 26-32.

Lacasse S & DiBiagio E, 2019, Two Observational Method Applications: An Ideal Solution for Geotechnical Projects with Uncertainty, In: *Geo-Congress 2019: Data, Software, Education, and a Tribute to Ralph Peck*, Reston, VA: American Society of Civil Engineers, pp. 117-128.

Ladd C C, 1991, Stability Evaluation During Staged Construction, *Journal of Geotechnical Engineering, vol. 117, issue 4,* London, United Kingdom, pp. 540-615.

Lam K C, Wang D, Lee P T & Tsang Y T, 2007, Modelling Risk Allocation Decision in Construction Contracts, *International Journal of Project Management, vol. 25, issue 5,* pp. 485-493.

Laryea S & Hughes W, 2008, How Contractors Price Risk in Bid; Theory and Practice, *Construction Management and Economics, vol. 26, issue 9,* pp. 911-924.

Latham M, 1994, *Constructing the Team, Final Report of the Government/Industry Review of Procurement and Contractual Arrangements in the UK Construction Industry*, HMSO, London, United Kingdom.

Lehtiranta L, 2014, Risk Perceptions and Approaches in Multi-Organizations: A Research Review 2000–2012, *International Journal of Project Management, vol. 32, issue 4,* pp. 640-653.

Levitt R E & Ashley D B, 1980, Allocating Risk and Incentive in Construction, *Journal of the Construction Division, vol. 106, issue 3,* pp. 297-305.

Lewin C (ed.), 1998, *RAMP (Risk Analysis and Management of Projects),* The Institution of Civil Engineers and the Faculty and Institute of Actuaries, Thomas Telford Publishing, London, United Kingdom.

Loosemore M & McCarthy C S, 2008, Perceptions of Contractual Risk Allocation in Construction Supply Chains, *Journal of Professional Issues in Engineering Education and Practice, vol. 134, issue 1,* pp. 95-105.

Lundman P, 2011, *Cost Management for Underground Infrastructure Projects: A Case Study on Cost Increase and Its Causes*, Ph. D. Thesis, Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Division of Mining and Geotechnical Engineering.

Luu D T, Ng S T & Chen S E, 2003, *Parameters Governing the Selection of Procurement System – an Empirical Survey*, Engineering, Construction and Architectural Management, vol. 10, issue 3, pp. 209-218.

Mahamid I, 2016, Factors Contributing To Poor Performance in Construction Projects: Studies of Saudi Arabia, *Australian Journal of Multi-Disciplinary Engineering, vol. 12, issue 1,* pp. 27-38.

Malmtorp J, 2007, *Framgångsfaktorer i bergbyggande,* Etapp 2: Förbättrad kostnadsstyrning - en riskanalytisk processtillämpning, opublicerad rapport, JLM tunnelkonsult. (In Swedish).

March J G, 1991, Exploration and Exploitation in Organizational Learning, *Organization Science, vol. 2, no. 1*, pp. 71-87.

Malhotra D & Murnighan J K, 2002, The Effects of Contracts on Interpersonal Trust, *Administrative Science Quarterly, vol. 47, issue 3,* pp. 534-559.

Melvin B, 1998, Risk Management in Insurance, *Tunnel Management International, vol. 3, issue 1,* pp. 31-38.

Miles L D, 1947, *The cost problem and the value engineering approach.*

Merriam S B, 2009, *Qualitative Research: A Guide to Design and Implementation*, 2nd edition, San Francisco, CA: Jossey-Bass.

Miranda T, Dias D, Pinheiro M & Eclaircy-Caudron S, 2015, Methodology for Real-Time Adaption of Tunnel Support Using the Observational Method, *Geomech Engineering, vol 8, issue 2,* pp. 153-171.

Moritz B & Schubert W, 2009, Application of the Observational Method in Geotechnical Safety Management, *Geomechanics and Tunnelling, vol. 2, issue 3,* pp. 269-281.

Mostafa S, Chileshe N & Abdelhamid T, 2016, Lean and Agile Integration Within Offsite Construction Using Discrete Event Simulation: A Systematic Literature Review, *Construction Innovation, vol. 16, issue 4*, pp. 483-525.

Muir Wood A M, 1990, The Observational Method Revisited, In: *Proceedings of 10th Southeast Asian Geotechnical Conference, Taipei*, pp. 37-42.

Muir Wood A M, 1994, *Control of Uncertainty in Geotechnical Engineering*, *ISSMFE Special Publication on Geotechnical Engineering*, London, United Kingdom.

Munfah N, 2006, Contracting Methods for Underground Construction, *North American Tunnelling*, Balkema, Rotterdam, pp. 99-105.

Nasirzadeh F, Khanzadi M & Rezaie M, 2014, Dynamic Modeling of the Quantitative Risk Allocation in Construction Projects, *International Journal of Project Management, vol. 32, issue 3*, pp. 442-451.

Nasirzadeh F, Mazandaranizadeh H & Rouhparvar M, 2016, Quantitative Risk Allocation in Construction Projects Using Cooperative-Bargaining Game Theory, *International Journal of Civil Engineering, vol. 14, issue 3*, pp. 161-170.

Nicholson D P, 1994, Preface to the Ninth Géotechnique Symposium in Print: The Observational Method in Geotechnical Engineering, *Géotechnique, vol. 44, issue 4*, pp. 613-618.

Nicholson D P & Low A, 1994, Performance of Foyle Bridge East Abutment, *Géotechnique, vol. 44, issue 4*, pp. 757-769.

Nicholson D P (ed.), 1996, *The Observational Method in Geotechnical Engineering*. Thomas Telford Publishing, London.

Nicholson D P, Tse Che-Ming & Penny C, 1999, The Observational Method in Ground Engineering: Principles and Applications, Construction Industry Research and Information Association, *CIRIA Report 185*, London, United Kingdom.

Nylén K-O, 1996, *Cost of Failure in Quality in Major Civil Engineering Projects*, Lic. Thesis, Division of Construction Management and Economics, Department of Real Estate and Construction Management, KTH Royal Institute of Technology, Stockholm, Sweden.

Nylén K-O, 1999, *Civil Works – Unique Projects or Repeatable Processes?,* Ph. D. Thesis, Division of Construction Management and Economics, Department of Real Estate and Construction Management, KTH Royal Institute of Technology, Stockholm, Sweden.

Obeng E, 1995, *The Role of Project Management in Implementing Strategy*, I S Craner (ed.), London, United Kingdom.

Oehmen J, Olechowski A, Robert Kenley C & Ben-Daya M, 2014, Analysis of the Effect of Risk Management Practices on the Performance of New Product Development Programs, *Technovation, vol. 34, issue 8*, pp. 441-453.

Ollila P, 2004, *New Institutional Analysis on Economic Coordination – with Special Emphasis on Agricultural Cooperatives*, Institutionen för ekonomi, SLU, Uppsala, Sweden. (In Swedish).

Olsson L, 1998, *Södra Länken 10, spont vid kv Asplången – översiktlig riskanalys*, Stockholm, Sweden. (In Swedish).

Olsson L & Stille H, 2002, Observation Systems with Alarm Thresholds and Their Use in Designing Underground Facilities, *Report R-02-45, Swedish Nuclear Fuel and Waste Management Company*, Stockholm, Sweden.

Olsson N O E, 2006, Management of Flexibility in Projects, *International Journal of Project Management, vol. 24, issue. 1*, pp. 66-74.

Osterberg J, 1999, *Value Engineering – A Great Concept*, Ohio River Soils Seminar, USA.

Otway H, 1987, Experts, Risk Communication and Democracy, *Risk Analysis, vol. 7, no. 2*, Blackwell Publishing, Oxford, United Kingdom, pp. 125-129.

Ouchi W G, 1980, Markets, Bureaucracies, and Clans, *Administrative Science Quarterly, vol. 25, no. 1*, pp. 129-141.

Palmström A & Stille H, 2007, Ground Behaviour and Rock Engineering Tools for Underground Excavations, *Tunnelling and Underground Space Technology, vol. 22, issue 4*, pp. 363-376.

Palmström A & Stille H, 2015, *Rock Engineering*, 2nd edition, ICE Publishing, London, UK.

Paté-Cornell M E & Benito-Claudio C P, 1987, Warning Systems: Response Models and Optimisation, In: *Uncertainty in Risk Assessment, Risk Management and Decision Making*, Springer, Boston, MA, pp. 457-468.

Park J, Young & Kwak Y H, 2017, Design-Bid-Build (DBB) vs. Design-Build (DB) In the U.S. Public Transportation Projects: The Choice and Consequences, *International Journal of Project Management, vol. 35, issue 3*, pp. 280-295.

Peck R B, 1969a, Advantages and Limitations of the Observational Method in Applied Soil Mechanics, *Géotechnique, vol. 19, issue 2*, pp. 171-187.

Peck R B, 1969b, Deep Excavations and Tunnelling in Soft Ground, In: *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico*, pp. 225-290.

Peck R B, 1985, The Last Sixty Years, In: *Proceedings of the XI International Conference on Soil Mechanics and Foundation Engineering, San Francisco,* Balkema, Rotterdam, The Netherlands, pp. 123-133.

Perera S, Hayles C S & Kerlin S, 2011, An Analysis of Value Management In Practice: The Case of Northern Ireland's Construction Industry, *Journal of Financial Management of Property and Construction, vol. 16, issue 2*, pp. 94-110.

Perez D, Gray J & Skitmore M, 2017, Perceptions of Risk Allocation Methods and Equitable Risk Distribution: A Study of Medium to Large Southeast Queensland Commercial Construction Projects, *International Journal of Construction Management, vol. 17, issue. 2*, pp. 132-141.

Pinto J K & Slevin D P, 1987, Critical Factors in Successful Project Implementation, *IEEE Transactions Engineering Management, vol. 34, issue 1*, pp. 22-27.

Pollack J, 2007, The Changing Paradigms of Project Management, *International Journal of Project Management, vol. 25, issue 3,* pp. 266-274.

Powderham A J, 1994, An Overview of the Observational Method: Development in Cut and Cover Bored Tunnelling Projects, *Géotechnique, vol. 44, issue. 4*, pp. 619-636.

Powderham A J, 1998, The Observational Method - Application Through Progressive Modification, Civil Engineering Practice, *The Boston Society of Civil Engineers Section/ASCE, vol. 13, issue 2*, pp. 87-109.

Powderham A J, 2002a, The Observational Method – Learning from Projects, *Journal of Geotechnical Engineering, vol. 155, issue 1,* London, United Kingdom, pp. 59-69.

Powderham A J, 2002b, The Observational Method - Managing Risk, Winning Value, In: *Proceeding of the 2nd International Conference on Soil Structure Interaction in Urban Civil Engineering, Zurich, Switzerland*, pp. 83-96.

Powderham A J & Nicholson D P, 1996, The Way Forward, In: *The Observational Method in Geotechnical Engineering, Institution of Civil Engineers*, Thomas Telford, London, pp. 195-204.

Powderham A J & O’Brien A, 2020, *The Observational Method in Civil Engineering - Minimising Risk, Maximising Economy*, CRC Press.

Powderham A J & Rutty P C, 1994, The Observational Method in Value Engineering, In: *Proceeding of the 5th International Conference on Piling and Deep Foundations*, Bruges, Belgium.

Raiffa H, 1970, *Decision Analysis – Introductory Lectures on Choices under Uncertainty*, Addison–Wesley Publishing Company, Reading, United Kingdom.

Ramasesh R V & Browning T R, 2014, A Conceptual Framework for Tackling Knowable Unknown Unknowns in Project Management, *Journal of Operations Management, vol. 32, issue. 4*, pp. 190-204.

Reilly J J, 1996, Introduction: Management, Policy and Contractual Considerations for Major Underground Design and Construction Progress Programs, *North American Tunneling, vol. 2*, pp. 533-540.

Ridder H G, 2017, The Theory Contribution of Case Study Research Designs, *Business Research, vol. 10, issue. 2,* pp. 281-305.

Rosenberg T (ed.), 1989, *Att skydda och rädda liv, egendom och miljö. Handbok i kommunal riskanalys inom räddningstjänsten*, Räddningsverket, Karlstad, Sweden. (In Swedish).

Rostami A & Oduoza C F, 2017, Key Risks in Construction Projects in Italy: Contractors' Perspective, Engineering, *Construction and Architectural Management, vol. 24, issue 3*, pp. 451-462.

Rowe W D, 1977, *An Anatomy of Risk*, Robert E Krieger Publishing Company, Florida, USA.

SAVE International, Society of Value Engineering, *https://www.value-eng.org/.*

Szavits-Nossan A, 2006, Observations on the Observational Method, In: *Proceeding of Active Geotechnical Design in Infrastructure Development, Ljubljana,* Slovenian, pp. 171-178.

Sekaran U, 2003, *Research Methods for Business: A Skill-Building Approach*, John Wiley & Sons, New York, NY.

Schmidt C, 2004, The Analysis of Semi-Structured Interviews, *A Companion to Qualitative Research*, pp. 253-258.

Shenton A K, 2004, Strategies for Ensuring Trustworthiness in Qualitative Research Projects, *Education for Information, vol. 22, no. 2*, pp. 63-75.

SGF, 2017, Risk Management in Geotechnical Engineering Projects-Requirements, *Report 1:2014*, 2nd edition, Swedish Geotechnical Society, Linköping, Sweden.

SGI, 2013, *Effektivare markbyggande, förslag till handlingsplan 2013-2016*, Statens geotekniska institut (SGI), Linköping, Sweden. (In Swedish).

Sjöberg L, 1978, *Beslutsfattande – Psykologiska studier av valsituationer*, Engvall & Krantz Grafiska AB, Stockholm, Sweden. (In Swedish).

Slovic P, 2000, *The Perception of Risk*, Earthscan Publications, Sterling, Virginia, USA.

Smith R E, 2008, An Evolving View of Geotechnical Engineering — A Focus on Geo-Risk Management, In: *GeoCongress 2008: Geosustainability and Geohazard Mitigation, New Orleans, Louisiana,* United States, pp. 231-238.

Spross J, 2016, *Toward a Reliability Framework for the Observational Method*, Ph. D. Thesis, Department of Civil and Architectural Engineering, Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden.

Spross J & Johansson F, 2017, When is the Observational Method in Geotechnical Engineering Favourable? *Structural Safety, vol. 66*, pp. 17-26.

Spross J, Johansson F & Stille H, 2014, Towards an Improved Observational Method, In: *ISRM Regional Symposium - EUROCK 2014*, International Society for Rock Mechanics and Rock Engineering, pp. 214-238.

Spross J & Gasch T, 2019, Reliability-Based Alarm Thresholds for Structures Analysed With the Finite Element Method, *Structural Safety, vol. 76*, pp. 174-183.

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, vol. 73, no. 2*, pp. 401-408.

Spross J, Olsson L, Hintze S & Stille H, 2015, Would Risk Management Have Helped? – A Case Study, In: *Proceedings of the International Symposium on Geotechnical Safety and Risk 2015*, Rotterdam, IOS Press.

Spross J, Olsson L & Stille H, 2018, The Swedish Geotechnical Society's Methodology for Risk Management: A Tool for Engineers in Their Everyday work, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 12, issue 3*, pp. 183-189.

Spross J, Olsson L, Stille H, Hintze S & Båtelsson O, 2021, Risk Management Procedure to Understand and Interpret the Geotechnical Context, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, pp. 1-16.

Spross J, Stille H, Johansson F & Palmström A, 2020, Principles of Risk-Based Rock Engineering Design, *Rock Mechanics and Rock Engineering, vol. 53, issue 3*, pp. 1 129-1 143.

SRA, 2018, *Society for Risk Analysis Glossary*, Society for Risk Analysis, *www.sra.org/risk-analysis-overview/risk-analysis-glossary/*.

Stake R E, 1995, *The Art of Case Study Research*, Thousand Oaks, CA: Sage.

Stake R E, 2005, Qualitative Case Studies, In: *Denzin N K & Lincoln Y S (eds.), The Sage Handbook of Qualitative Research*, Sage Publications, Thousand Oaks, CA, pp. 443-466.

Stake R E, 2006, *Multiple Case Study Analysis*, New York, NY: Guilford.

Starr C & Whipple C, 1980, Risk of Risk Decision, *Science, vol. 208, issue 4448*, Stanford, USA, pp. 1 114-1 119.

van Staveren M T, 2006. *Uncertainty and Ground Conditions: A Risk Management Approach*. Oxford: Butterworth Heinemann.

van Staveren M T, 2009, Extending to Geotechnical Risk Management, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 3, issue 3*, pp. 174-183.

van Staveren M T, 2013, Geotechnics on the Move: Guidance for a Risk-Driven Way of Working, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, vol. 7, issue 3*, pp. 225-236.

van Staveren M T, 2018, *Uncertainty and Ground Conditions: A Risk Management Approach*, CRC Press.

van Staveren M T & Knoeff J G, 2004, The Geotechnical Baseline Report as Risk Allocation Tool, In: *Proceedings of Engineering Geology for Infrastructure Planning in Europe*, Springer, Berlin, Heidelberg, pp. 777-785.

Stille H, 1986. Experiences of Design of Large Caverns in Sweden, In: *K H O Saari (ed.), Proceedings of the International Symposium on Large Rock Caverns, Helsinki*, Oxford, UK: Pergamon Press, pp. 231-241.

Stille H, 2017, Geological Uncertainties in Tunnelling – Risk Assessment and Quality Assurance, In: *ITA-AITES World Tunnel Congress 9.-15. June 2017*, The International Tunnelling and Underground Space Association, Paris, France.

Stille H, Andersson J & Olsson L, 2003, Information-Based Design in Rock Engineering, *Swedish Rock Engineering Research Report no. 61*, Stockholm, Sweden.

Suprapto M, Bakker H L M, Mooi H G & Hertogh M J C M, 2017, How Do Contract Types and Incentives Matter to Project Performance?, *International Journal of Project Management, vol. 34, issue 6*, pp. 1 071-1 087.

Sturk R, 1998, *Engineering Geological Information - Its Value and Impact on Tunnelling*, Ph. D. Thesis, Division of Soil and Rock Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden.

Swedish Transport Administration, 2002, *Riskhantering i Södra Länken projektet*, Stockholm, Sweden. (In Swedish).

Szentes H & Eriksson P E, 2016, Paradoxical Organizational Tensions Between Control and Flexibility When Managing Large Infrastructure Projects, *Journal of Construction Engineering and Management, vol. 142, issue 4*, pp. 1-10.

Tengborg P, 1998, Risker vid stora undermarksprojekt – planering, produktion och förvaltning, *Swedish Rock Engineering Research Report no. 38*, Stockholm, Sweden. (In Swedish).

Tadelis S, 2012, Public Procurement Design: Lessons from the Private Sector, *International Journal of Industrial Organization, vol. 30, issue 3,* pp. 297-302.

Terzaghi K. 1945, In Advantages and Limitations of the Observational Method in Applied Soil Mechanics, *Géotechnique, vol. 19, issue 2,* pp. 171-187.

Terzaghi K, 1961, Past and Future of Applied Soil Mechanics, *Journal of Boston Society of Civil Engineers, vol. 68,* pp. 110—139.

Terzaghi K & Peck R B, 1948, *Soil Mechanics in Engineering Practice*, John Wiley and Sons, New York, USA.

Terzaghi K & Peck R B, 1967, *Soil Mechanics in Engineering Practice*, 2nd edition, John Wiley & Sons, New York, USA.

Thompson K M, Deisler P H Jr & Schwing R C, 2005, Interdisciplinary Vision: The first 25 years of the Society for Risk Analysis (SRA), 1980-2005, *Risk Analysis: An International Journal, vol. 25, issue 6*, pp. 1 333-1 386.

Tjäder J, 2000, *Systemimplementering i praktiken: en studie av logiker i fyra projekt*, University of Linköping, Linköping, Sweden. (In Swedish).

Tonks D, Gallagher E, and Nettleton I, 2017, Grounds for Concern: Geotechnical Issues from Some Recent Construction Cases, In: *Proceedings of the Institution of Civil Engineers – Forensic Engineering, vol. 170, issue 4*, pp. 157–164.

Trafikverket, 2020, Trafikverkets arbete med produktivitet och innovation i anläggningsbranschen. Regeringsuppdrag, *TRV 2018/36109*. (In Swedish).

Transportation Research Board, 2017, Guidelines for Managing Geotechnical Risks in Design-Build Projects, *NCHRP Project 24-44,* Institute for Transportation Research.

Turner J R & Sinister S J, 2001, Project Contract Management and a Theory of Organization, *International Journal of Project Management, vol. 19, issue 8*, pp. 457-464.

Turner D F & Turner A, 1999, *Building Contract Claims and Disputes*, Longman, London, United Kingdom.

Ward S C & Chapman C B, 2003, Transforming Project Risk Management into Project Uncertainty Management, *International Journal of Project Management, vol. 21, issue 2*, pp. 97-105.

Ward S C, Chapman C B & Curtis B, 1991, On the Allocation of Risk in Construction Projects, *International Journal of Project Management, vol. 9, issue 3*, London, United Kingdom, pp. 140-147.

Welch C, Piekkari R, Plakoyiannaki E & Paavilainen-Mäntymäki E, 2011, Theorising from Case Studies: Towards a Pluralist Future for International Business Research, *Journal of International Business Studies, vol. 42, issue 5*, pp. 740-762.

Verzuh E (ed.), 2003, *The Portable MBA in Project Management*, John Wiley & Sons.

Whitman R V, 1984, Evaluating Calculated Risk in Geotechnical Engineering, *Journal of Geotechnical Engineering, American Society of Civil Engineers, vol. 110. issue 2*, USA, pp. 145-188.

Whyte I L, 1995a, Analysis and Management of Financial Risks Arising from Ground Conditions, *International Journal of Rock Mechanics and Mining Sciences and Geomechanics, vol. 32, no. 5*, pp. A34-A40.

Whyte I L, 1995b, The Financial Benefit from a Site Investigation Strategy, *Journal of Ground Engineering, vol. 28, issue 8*, pp. 33-36.

Whyte I L & Tonks D M, 1994, *Project Risks and Site Investigation Strategy*, Risk and Reliability in Ground Engineering, Skipp (ed), Thomas Telford Publishing, London, United Kingdom.

Wied M, Koch-Ørvad N, Welo & Oehmen J, 2020, Managing Exploratory Projects: A Repertoire of Approaches and Their Shared Underpinnings, *International Journal of Project Management, vol. 38, issue 2*, pp. 75-84.

Williams T M, 1999, The Need for New Paradigms for Complex Projects, *International Journal of Project Management, vol. 17, issue 5*, pp. 269-273.

Willumsen P, Oehmen J, Stingl V & Geraldi J, 2019, Value Creation Through Project Risk Management, *International Journal of Project Management, vol. 37, issue 5*, pp. 731-749.

Yamaguchi H, Uher T E & Runeson G, 2001, *Risk Allocation in PFI Projects*, Akintoye A (Ed.), In: *Proceedings of the 17th Annual ARCOM Conference, University of Salford, UK*, Association of Researchers in Construction Management, vol. 1, pp. 885-894.

Yin R K, 2018, *Case Study Research and Applications: Design and Methods*, Sage Publications, 6th edition, Thousand Oaks, CA:Sage, United States of America.

You J, Chen Y, Wang W & Shi C, 2018, Uncertainty, Opportunistic Behavior, and Governance in Construction Projects: The Efficacy of Contracts, *International Journal of Project Management, vol. 36, issue 5,* pp. 795-807.

Xia N, Zou P X W, Griffin M A, Wang X & Zhong R, 2018, Towards Integrating Construction Risk Management and Stakeholder Management: A Systematic Literature Review and Future Research Agendas, *International Journal of Project Management, vol. 36, issue 5*, pp. 701-715.

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Appendix: Interview instrument

Introduction:

Present yourself, describe the purpose of the study and that the interviewee will by anonymous.

General questions:

- Which were the key characteristics of the project?
- Which were the main challenges?
- From your point of view, what is risk management?
- Did you participate in the risk management process in the tender phase?
- Did you participate in the risk management process after the contract was awarded?
- How important is risk management compared to your other daily tasks?

The risk management process in the tender and design phase:

- Which geotechnical risks were included in the tender documents?
- How were the geotechnical risks presented in the tender documents?
- How were the risks allocated between the contractor and the client?

- In your opinion, which techniques are useful to perform risk identification, risk analysis and risk evaluation?
- How were the risks identified?
- How were the risks analyzed?
- How were the risks evaluated?
- Which geotechnical risks were considered to be most crucial?
- Which risk treatment actions were identified?
- How was the risk information documented and communicated to the construction phase?
- Were there any obstacles that hindered the management of geotechnical risks?
- How do you think the geotechnical risk management process in the tender and design phase can be improved?

The risk management process in the construction phase:

- Describe the method of risk management that was adopted.
- Which geotechnical risks were considered as the most critical?
- Who was responsible for the decisions regarding the implementation of the risk treatment actions?
- Who was responsible for the implementation of the risk treatment actions?
- Which geotechnical risks were realized?
- Were there any “new” (unidentified) geotechnical risks?
- How was it decided when risk management measures were to be implemented?
- Which geotechnical risk treatment actions were implemented?
- What was the result of the risk treatment actions?

- Were there any obstacles that hindered the management of geotechnical risks?
- How do you think the geotechnical risk management process in the construction phase can be improved?

Project management: (project manager only)

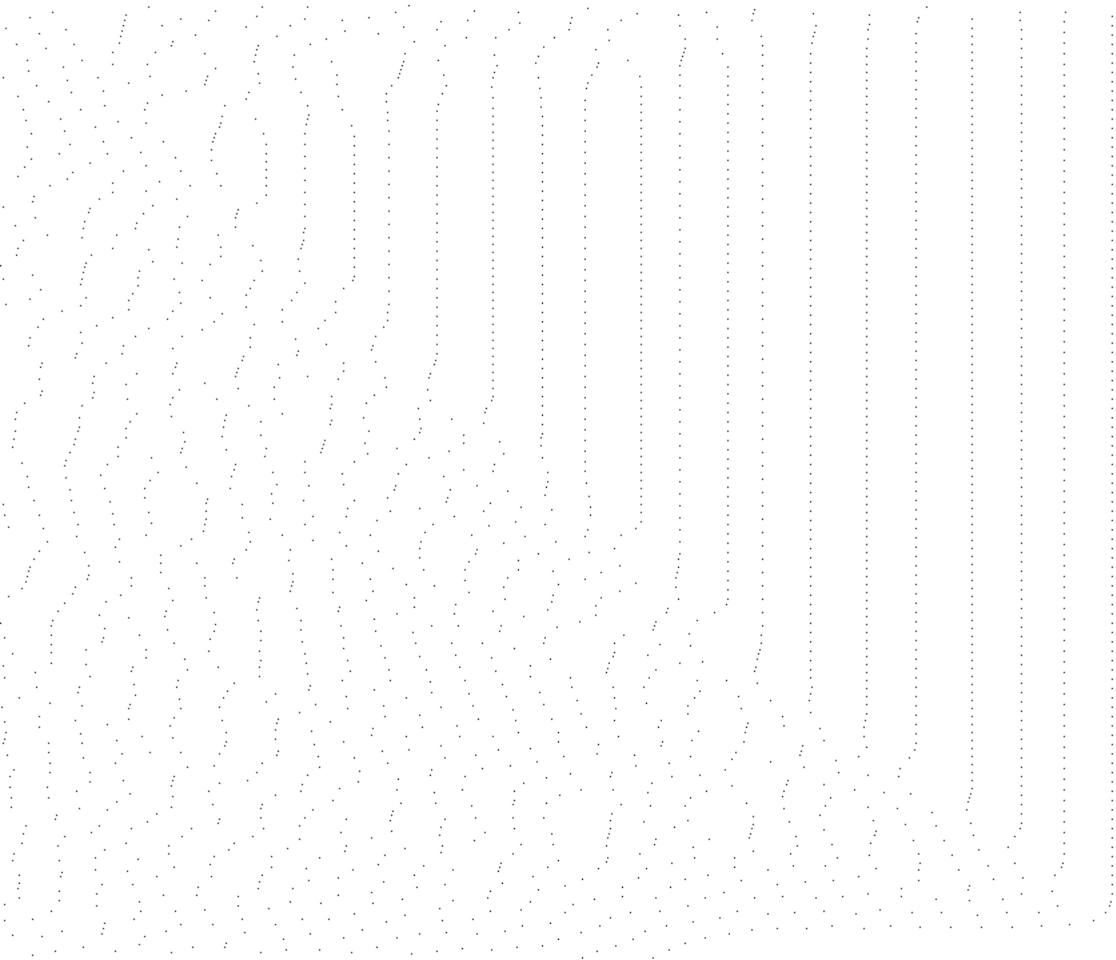
- Describe the project management method/model in the project.
- Which factors were critical to the outcome of the project?
- How was the work with geotechnical risk management incorporated into the other project activities?

Ending:

- Are there any other observations?
- Anything we have not covered?
- Any relevant observations with regards to your specific perspective in the project?

Finish with a brief summary, thank the interviewee, and ask if it is ok to come back with questions afterwards.

Paper A



Observational Method as Risk Management Tool: The Hvalfjörður Tunnel Project, Iceland

Submitted to *Engineering Geology*

Authors

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Abstract

Rock tunnel construction is associated with considerable geotechnical uncertainty, often due to limited knowledge about the ground conditions. This warrants the use of stringent risk management procedures to reduce the likelihood of cost increases, delays, and structural failure events. The observational method is often promoted as a tool to achieve cost-effective designs in cases of large geotechnical uncertainty, but its practical use is still limited. One reason may be the lack of guidelines and experiences from previous projects where the observational method has been used. In this paper we therefore present a case study of the design and construction of the tunnel under the Hvalfjörður fjord in Iceland, where the observational method played a key role in the risk management that was performed to deal with the challenging geological conditions at the site. The project was a success and completed four months earlier than originally planned. In light of the case study, we discuss the definition of the observational method in Eurocode 7 and the related contractual aspects to consider in such projects.

Keywords

Risk management; observational method; Turn-key contract; Eurocode 7; Tunnel; Case study.

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1. Introduction

Design and execution of underground structures involve risks related to the geotechnical conditions. The geotechnical risks may lead to cost overruns, time delays as well as safety issues if they are not managed properly. To avoid such consequences, many authors have recommended employing a risk-based project management approach in geotechnical engineering projects, such as Clayton (2001), van Staveren (2006, 2013), Stille (2017), and Spross et al. (2018). General principles of risk-based rock engineering design have been discussed by Spross et al. (2020).

In ISO 31000 (CEN 2018), risk is defined as the "effect of uncertainty on objectives". Today this is probably the most widely used definition of risk in technical contexts. Risk is often characterized by reference to potential events and expressed in terms of the combination of the likelihood of occurrence of an event and the associated consequences. For geotechnical engineering projects, the uncertainty about the geotechnical conditions at the site normally contributes the most to the total project risk. The geotechnical uncertainty arises from epistemic or aleatory uncertainty regarding the geotechnical conditions (Ang & Tang 2007). The epistemic uncertainty is caused by incomplete knowledge about the geotechnical conditions, often owing to very limited investigations of the geotechnical conditions before construction. The aleatory uncertainty is caused by the spatial variability or randomness in the parameters that govern the geotechnical behavior.

Since the early days of civil engineering, observations have been used by engineers to deal with geotechnical uncertainties and to reduce risks by observing the performance of structures. Historically, modifications of the design based on observations were often made using a trial-and-error process or ad-hoc process. With the development of modern geotechnical engineering, an integrated process of predicting, monitoring, reviewing and modifying the design gradually evolved. This process was eventually named the observational method by Peck (1969). Application examples have recently been provided by, for example, Nicholson et al. (1999), Prästings et al. (2014), Spross et al. (2016, 2021a), Bjureland et al. (2017), Fuentes et al. (2018), Lacasse & DiBiagio (2019), Duncan & Brandon (2019), Powderham & O'Brian (2020), and Spross & Larsson (2021b).

2. Purpose and structure of the paper

Geotechnical risk management with the observational method has the potential to provide a safe and cost-effective design in projects including geotechnical uncertainties. However, there is a lack of recommendations regarding the implementation of the observational method, in particular regarding its connection to risk management and contractual aspects. This may have restricted the use of the method. In addition, cases of successful implementation of the observational method are rarely published; the aforementioned examples are among the rare exceptions. Therefore, this paper presents a case study of the design and construction of the tunnel under the Hvalfjörður fjord in Iceland. The study presents the experiences from the risk management process and highlights key aspects thereof in relation to the implemented observational method and the contractual framework used. A comparison is made with the definition of the observational method in Eurocode 7 (CEN 2004) since this is the current geotechnical design code in many European countries, including Iceland.

3. Methodology

The management of risks in a geotechnical engineering project is influenced by many factors, such as the perception, communication and allocation of risk, as well as the cooperation between the parties involved. It is therefore normally difficult to isolate and study the effect of each factor separately. For complex situations, or in contexts where it is difficult to study a specific phenomenon, Yin (2018) suggests that a case study is generally an appropriate research methodology. Therefore, due to the complexity of the risk management process in geotechnical engineering projects, a qualitative case study was chosen as the research method.

This case study was conducted in two steps. The first step consisted of an analysis of the tender documents, the contractual documents, the geotechnical site investigation reports, and the geotechnical risk management process in the design and execution phase. The second step consisted of semi-structured interviews performed in 2004 with key personnel involved in the geotechnical risk management process, i.e., the Swedish contractor's project manager, the principal geotechnical engineer, and the engineers responsible for the geotechnical risk management in the design and execution phase. Appendix A provides the interview instrument.

As in all qualitative research, it is important to ensure trustworthiness in case study research. Examples of difficulties to ensure trustworthiness are those related to credibility and generalizability (Guba 1981). The difficulty with credibility was addressed by using different information sources, i.e., written material from the project and interviews with several individuals involved in the risk management process and the design and execution of the project. Concerning the generalizability, it may be questioned whether general conclusions may be drawn from one case study. Stake (2005) argues however that a single case, even if it is unique, can be used to generalize since it could be an example of a broader group of cases. We believe that the conclusions in this paper are not specific for the case study and that the conclusions may be used in a broader context.

4. The observational method in geotechnical engineering

The conceptual idea behind the observational method is to actively use information obtained from observations during construction to reduce the epistemic uncertainty and, based on this information, modify a preliminary design to the actual geotechnical conditions on site (Peck 1969). The observational method consists of the following steps:

establishment of a preliminary design, preparation of contingency measures to put into operation in case of deviations from the preliminary design conditions, monitoring or other observations during the execution of the project, and finally, modification of the preliminary design to the actual conditions based on the observations into a final design. Thus, the final design is not known before project completion. Notably, implementation of contingency measures (i.e. modification of the design) has contractual implications, as this affects the cost and time schedule of the project.

In principle, the most appropriate design method is the one that results in the lowest cost while fulfilling the formal requirements, e.g., structural safety, serviceability, durability, and allowable environmental impact. On the one hand, the observational method is associated with extra costs compared to traditional design methods because of extra design work and extended monitoring while executing the work. Although the final design using the observational method is likely to be better suited to the actual ground conditions, these extra costs can, however, be outweighed by savings from avoiding overdesigning; this can be analyzed with statistical decision theory (Spross & Johansson 2017).

According to European design code EN 1997 ("Eurocode 7") (CEN 2004), limit states can be verified by one or a combination of the following methods: calculations, adoption of prescriptive measures, experimental models and load tests, or an observational method. Eurocode 7 specifies the principles that must be fulfilled when applying the observational method. These principles are further discussed in chapter 8 in light of the case study. The recognition of the observational method as an allowed design method in Eurocode 7 formally allows the designer to exploit observations during the execution of work to decrease the geotechnical uncertainty.

5. The Hvalfjörður tunnel project

5.1. Project description

The road tunnel under the Icelandic Hvalfjörður fjord is located approximately 20 km north of Reykjavík. At the location of the tunnel, the fjord is approximately 3.5 km wide. The tunnel under the fjord connects the northern and southern parts of Iceland (Figure 1). The tunnel's length is around 5.8 km and it is located approximately 165 m beneath the water's surface at its deepest point.

The planning of the project started in 1987 when the Icelandic Public Road Administration published a study that presented the benefits of building a tunnel under the Hvalfjörður fjord. After several years of feasibility studies regarding the location of the tunnel, site investigations, and design, the excavation of the tunnel started in June 1996. The tunnel was entirely excavated in October 1997 and opened for traffic in July 1998, which was approximately four months before the originally estimated completion date.

The client was the Icelandic Public Road Administration, and an Icelandic private enterprise obtained the concession to design, build, own, and operate the tunnel for twenty years. After the operating period, the tunnel was transferred to the client. A joint-venture consisting of contractors from Iceland, Denmark and Sweden was contracted with a turn-key contract through a public procurement process, where the joint-venture guaranteed the financing of the project during the construction period. The tunnel works were paid with a lump sum payment, with a minor remeasurement payment made when the tunnel was completed, tested and had been operating for two months. The tunnel project was unique for Iceland for two reasons: it was the first subsea road tunnel built in young geothermally active basaltic lavas, and it was the first design-build-own-transfer project.

Figure 1 Location of the tunnel under the Hvalfjörður fjord (published with permission from kartdata, 2021).

The tunnel was excavated by drilling and blasting, and it was supported by rock bolts and shotcrete. The rock mass was grouted ahead of the tunnel face to reduce the water inflow. This construction method was chosen by the joint-venture to ensure a flexible design approach that considered the actual geotechnical conditions using an observational method that was known in Sweden at the time as “active design” (Stille 1986), which is conceptually equivalent to Peck’s (1969) observational method.

5.2. Performed site investigations

The geotechnical survey presented in the tender documents consisted of surface mapping along the shores of the fjord, core drilling of the rock mass, and a geophysical investigation. The core drilling at the southern shore consisted of two vertical holes and one inclined hole about 200 m along the planned tunnel route. The geophysical investigation consisted of reflection and refraction seismic surveys along the tunnel route to estimate the level of the rock surface and the potential presence of weak zones.

5.3. Geological conditions

The geology in the area is characterized by the Mid Atlantic Ridge with previous volcanic activities. The bedrock consists of layers of solidified magma with sedimentary rock layers in between (Figure 2).

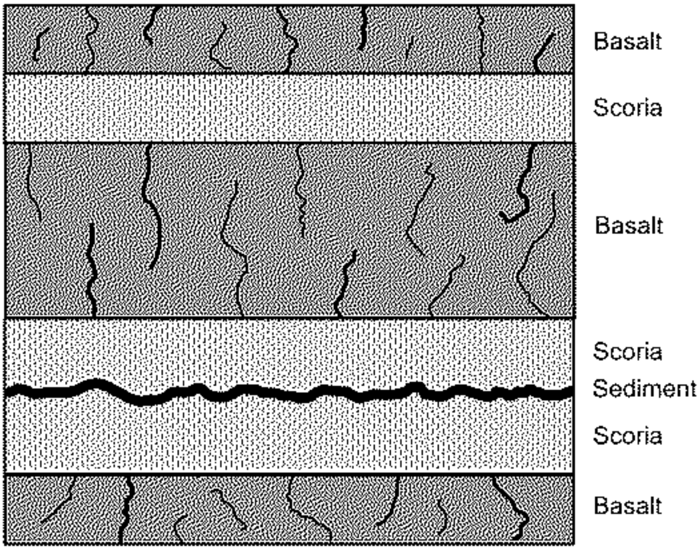

Figure 2 Typical geological conditions (schematic presentation).

The solidified magma layers often had an impermeable central layer of good-quality basalt (high Q-value), but with vertical fractures due to the solidification process. The outer layers of the solidified magma, called scoria, usually had less strength and higher permeability than the central layers. Due to earlier magma flows, there were basalt dikes that cut through the sequence of horizontal layers. The rock cover was approximately 40 m at the deepest point of the tunnel. The thickness of the layers of sediments on the bottom of the fjord varied between 10 to almost 80 m (Figure 3).

To ensure that there would be appropriate support measures for all possible rock conditions, an engineering geological forecast was prepared and presented in the tender documents. The forecast specified five rock support classes with suitable support measures for the possible Q-values along the tunnel route. The use of the support classes is discussed in Section 6.3.

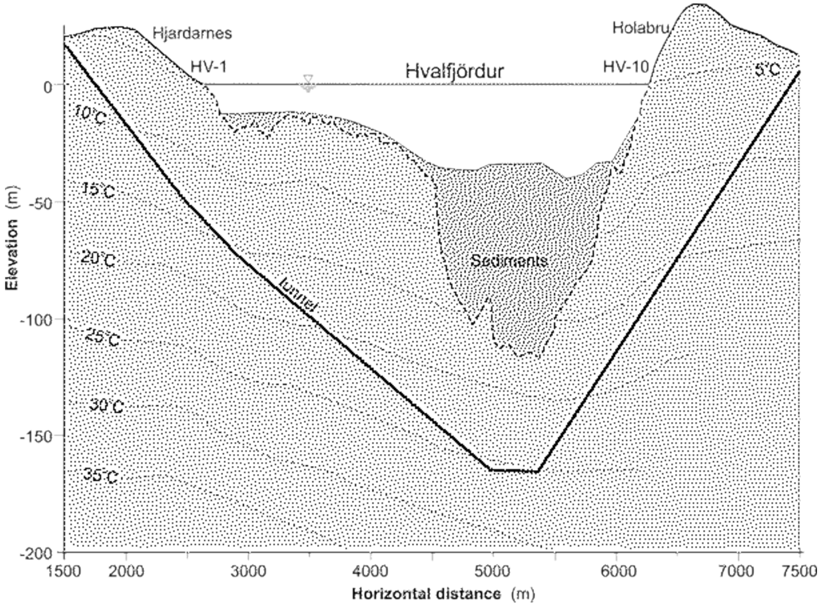

Figure 3 Longitudinal cross section of the tunnel with expected temperature conditions (Republished with permission of ICE Publishing from Palmström & Stille (2015); permission conveyed through Copyright Clearance Center, Inc.).

5.4. Hydrogeological conditions

The water depth in the fjord is generally around 10–30 m at the location of the tunnel. The bedrock in the area is partly crossed by faults and dikes due to earlier tectonic movements. The contact zone between the dikes and the original basalt layer was found to have high hydraulic conductivity in some places. The preinvestigations indicated that high water inflow of fresh or salt water could be expected from faults, vertical pipes, and in areas of contact with dikes. The water temperature in the tunnel was estimated to rise from 5°C at the ends of the tunnel to 25°C at the deepest part (Figure 3).

6. Geotechnical risk management using the observational method

6.1. General concepts

Based on the definition of risk management in ISO 31000 (CEN 2018), a geotechnical risk management process can be described as a "systematic application of management policies, procedures and practices to the activities of communication, consulting, establishing the context, and identifying, analyzing, evaluating, treating, monitoring, and reviewing geotechnical risks". The main activities of the risk management process are shown in Figure 4. A key activity is the first step, which is to create an understanding of, and to interpret, the geotechnical context in which the project is to be carried out (Spross et al. 2021c). Using the observational method in the Hvalfjörður project can be viewed as a risk treatment to deal with the identified risk of having considerable geotechnical uncertainties at the site; thus, the observational method becomes an integrated tool in the risk management process, and not a substitute for it. In the following subsections, the risk management process used in the Hvalfjörður project is discussed in relation to the activities in Figure 4.

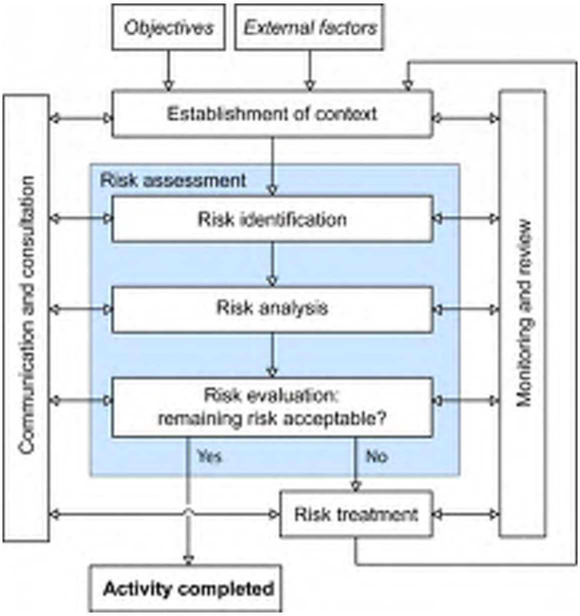

Figure 4. The risk management process in ISO 31000 (Republished from Spross et al. (2020), http://creativecommons.org/licenses/by/4.0/).

6.2. Risk management in the design phase

6.2.1. Organization

In previous tunnel projects in Iceland, there had been problems related to the geological formations significant for the area. Therefore, the client was aware of the technical challenges of the project. In the design phase, risk management was conducted by a system analysis group consisting of engineers that were independent from the client, contractor, and concession owner organizations. The group's main task was to identify and describe the potential hazards and their associated initiating events and warning bells and, based on these, propose additional site investigations, an appropriate design, and suitable construction methods. The risk management process addressed the evolution from hazard to damage (Figure 5).

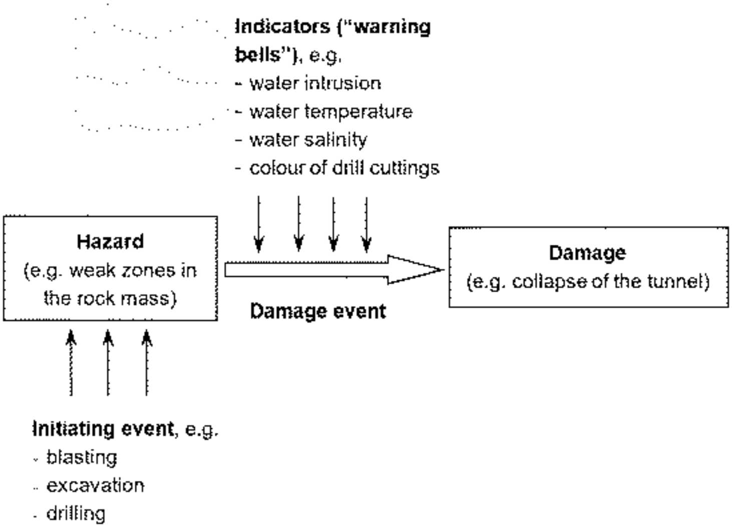

Figure 5 Risk evolution from hazard to damage.

6.2.2. Establishing the geotechnical context

The first step of the risk management process consisted of gathering information regarding the geological conditions at the site in order to create an understanding of the geotechnical context. As no one in the system analysis group had any experience tunneling in Iceland, an extensive literature review was performed, and several Icelandic and Norwegian experts in this type of project were contacted. Experiences from tunnels in similar geological conditions in Iceland and subsea tunnels in other countries were also studied. This first phase resulted in a preliminary model of the geology, hydrology, and the geothermal conditions at the site.

6.2.3. Risk and hazard identification

This second step included a qualitative fault tree analysis to identify the hazards and chains of events that could lead to technical failure of the project, such as a collapse or inundation of the tunnel. The aim of the initial fault tree analysis was not to quantify the risk, but to identify as many potential hazards as possible. Two groups of hazards were identified: geotechnical hazards and organizational hazards.

This fault tree analysis resulted in a register of the identified geotechnical hazards. Only those damage events that were obviously not present were disregarded in the analysis. Six damage events that were crucial to the technical success of the project were identified:

- *Water inflow that cannot be controlled.* Inflow of salt water or fresh water could stop the tunneling and make the project too expensive to continue.
- *Stability problems.* Large deformations and/or rock fall in the tunnel, primarily due to weak rock formations.
- *Heat problems.* Inflow of hot water or high temperatures in rock formations that stops the tunneling work or makes the tunneling work more complicated and time-consuming.
- *Harmful gases in the tunnel.* Suffocating or poisonous gases that stops the tunneling work or makes the tunneling work more complicated and time-consuming.
- *Damage due to seismic activity.* Damage to the tunnel from seismic activity (e.g., an earthquake) that stops the tunneling.
- *Insufficient tunnel durability.* The tunnel starts to deteriorate because of environmental impact, resulting in high maintenance costs.

The second step also included a reassessment of the preliminary geological model and the identified hazards and damage events with assistance from the involved experts. The contractor had considerable influence over the choice of excavation techniques. The experts served as a review group during the risk management process. The second step resulted in a list of the hazards that could endanger the execution of the project. Organizational hazards were also identified. The process of gathering, documenting, interpreting, and communicating the information from the observations was identified as important since this should be the basis for the decisions made regarding the execution of mitigation actions. Figure 6 shows the chain of events from observation of the indicator “existence of poor rock in front of the tunnel” to the execution of the mitigation action, i.e., increased grouting. Each of the four events—designated A, B, C, and D—were further analyzed with separate fault trees in order to find the sub-events that could result in these undesired events. Examples of sub-events were human errors and lack of personal resources, lack of knowledge, and poor cooperation.

6.2.4. Risk analysis

Due to the limited rock cover under the fjord, the unlimited access of water, and the uncertainties regarding the geological formation, the damage event dealing with “water inflow that cannot be controlled” was considered to be the most critical damage event and a major threat to the completion of the project.

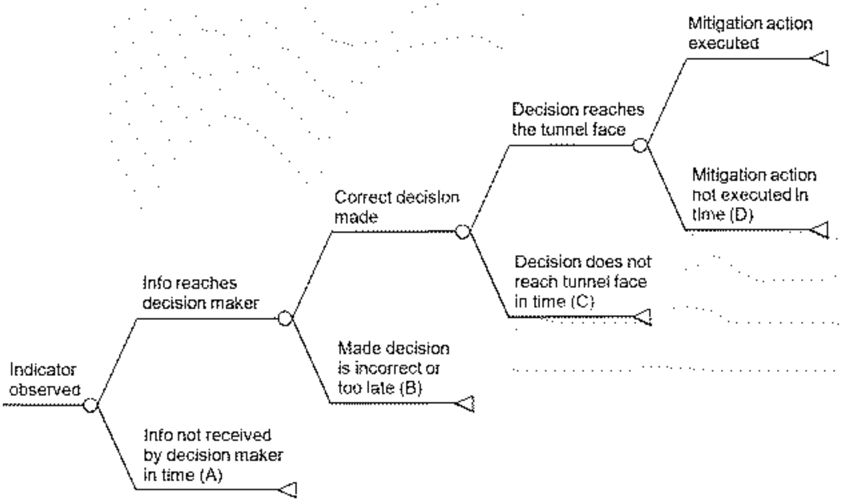

Figure 6 Event tree for the chain of events from indication of a hazard to the execution of a mitigation action.

This damage event was further analyzed in detail while the other damage events were analyzed more schematically. The fault tree for the top event "water inflow that cannot be controlled" is presented in Figure 7. Each of the four events at the bottom of the tree was further analyzed in separate fault trees.

The risk analysis step also included the identification of observable damage indicators ("warning bells") as well as methods for observing and measuring these during the execution of work. For example, the identified warning bells for the damage event "water inflow that cannot be controlled" were:

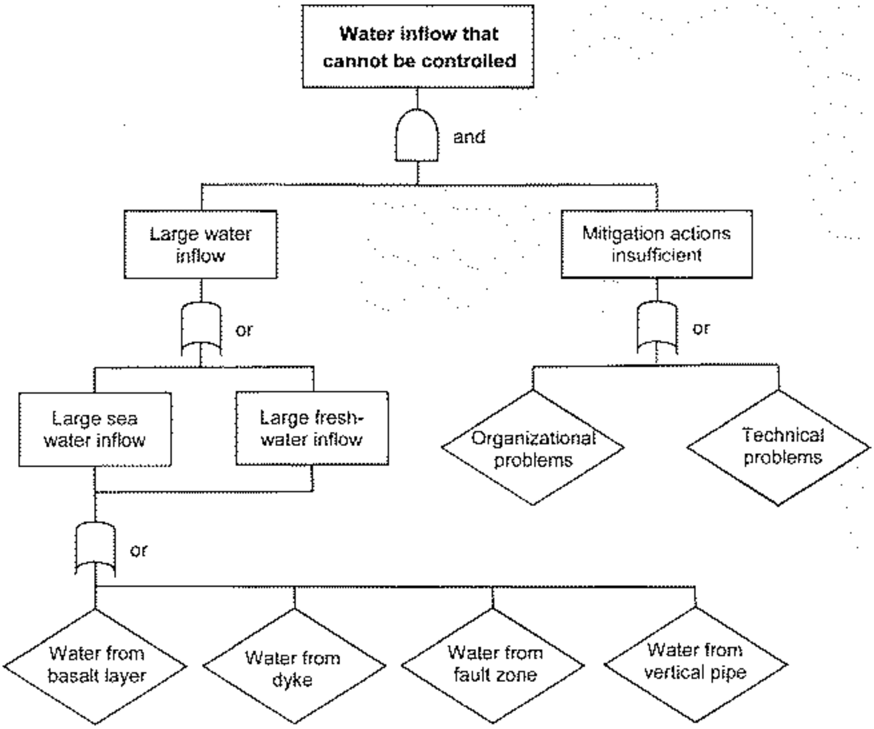

Figure 7 Fault tree for the damage event "Water inflow that cannot be controlled".

- The occurrence of vertical geological formations: may indicate contact with the fjord.
- Water temperature: deviations from expected values based on the thermal properties of the rock mass and temperature measurements in the bore holes during the site investigations may indicate connections with deeper layers (high temperature) or shallower layers (low temperature) of the rock mass.
- Water salinity: high values may indicate connection with salt water from the fjord. The chloride content in the groundwater was expected to be quite low due to the flow of fresh groundwater from high terrain on both sides of the tunnel.
- Water pH value: deviations from expected values depending on the type of rock indicate connections with deeper (high pH) or shallower layers (low pH) of the rock mass.
- Colored drill water / drill cuttings: may indicate presence of sediments or weak rock mass which can affect the stability of the tunnel. Five possible colors were identified together with their geological interpretation.
- Drill penetration rate: indicates changes in the properties of the rock mass, e.g., the type and quality of the rock.

6.2.5. Complementary site investigations as risk treatment

After the risk analysis, complementary site investigations were planned based on the identified hazards. The aim of the complementary site investigations was to increase the amount of data available in the decision-making process, i.e., reducing the uncertainty. The investigation methods were chosen by the contractor after considering recommendations from the expert group. The methods were chosen to give obvious and exclusive indications of the hazards. Thus, the contractor made additional site investigations before the excavation started by drilling a long vertical core hole at the north shore to investigate the quality of the rock mass, and six shorter vertical holes to investigate the rock cover.

6.3. Risk management in the construction phase

6.3.1. Organization

By analyzing the contractual framework, the contractors understood that a considerable part of the risks was owned by the joint-venture, meaning that this entity was responsible for these risks and any decision-making regarding their treatment (Spross et al. 2018). Therefore, risk management had a prominent role in the execution of the tunnel. The risk management process in the construction phase was conducted by the contractor, and the independent expert group was removed from the project since their support was no longer needed.

6.3.2. Planning of risk treatment and monitoring

Risk management served as a basis for the organization and quality assurance of the project, and improvement of the working procedures. Several risk treatment actions were performed before the start of the execution of the tunnel, such as training the site personnel to perceive hazards, initiating events and warning bells, and gathering materials and equipment for stand-by at the site in the event of, for example, weak rock conditions or the inflow of water.

The predetermined rock support classes played an important role in allowing the adjustment of tunnel support in accordance with the observational method. To determine the support class, continuous probe drilling ahead of the tunnel face was executed, and the Q-value of the rock mass was mapped after every blasted round. The information was used to determine the rock support and to monitor the other hazard indicators, as shown in Table 1 along with the corresponding expected behavior, threshold values and contingency actions.

The deformation of the tunnel was also observed by convergence measurements, which were conducted in four sections in the tunnel by using angular measurements and extensometer measurements. The selected locations were sections with potential stability problems, high pore pressures, or a larger tunnel span than the rest of the tunnel.

However, no strict threshold values for allowable deformation were established in advance.

6.3.3. Examples of monitoring and risk treatment during construction

The identified damage indicators in Table 1 were monitored during the execution of the tunnel. The measurements of the water temperature and the salinity in the tunnel are presented in Figure 8. The highest water temperature at the face of the tunnel was approximately 58°C which was more than 30°C higher than the temperature forecast. This indicated connections with deeper layers of magma. Therefore, the application of shotcrete was changed, and each newly blasted round was left without shotcrete and the rock surface was watered as a contingency measure, as planned (Table 1). To decrease the air temperature, the ventilation of the tunnel was increased. These measures gave a rather rapid cooling effect, so the plan was successful. The high salinity in some places indicated direct contact with sea water through dikes, fault zones, or vertical pipes. In these areas, the grouting and thickness of the shotcrete were increased as a contingency measure (Table 1).

The excavation also passed through a number of smaller fault zones and dikes. They were treated as planned with the appropriate support classes (class 3 or 4A) and grouted if the water leakage warranted this action. At an area with sandstone cut by several small faults and dikes, the water flow in the probe drill holes measured 28–72 l/m, so the area was pre-grouted. During excavation, stability problems occurred at this location, causing rockfalls, so class 3 and 4A support was used. Extra bolts, strapping, and thicker shotcrete were used in one part of this area where rock was splitting up in slabs. Afterwards, there was no indication of further displacement.

The deformation measurements at the four monitored sections all showed small deformations (less than 1 mm). The stability of the rock mass was generally better than expected in terms of the Q-value, so the final amount of rock support was around 20% less than the predicted amount for both rock bolts and shotcrete.

Table 1 Examples of indicators of geotechnical hazards, expected behavior, threshold values, and contingency measures.

Hazards and indicators	**Expected behavior**	**Threshold value**	**Contingency measure**
Insufficient rock support:			
▪ Rock support class, 1–5	Class 1–3: normal conditions, i.e., mixed face with mainly basalt but some smaller layers of scoria. Class 4a and 4b: crushed and poor rock at dikes. Class 5: very poor conditions not caused by dikes.	Class 1: Q > 4 Class 2: 1 < Q < 4 Class 3: 0.1 < Q < 1 Class 4a: Q < 0.1 and zone < 4 m Class 4b: Q < 0.1 and zone > 4 m or high water pressure Class 5: Q < 0.1 or high water pressure	For each class, specified support in terms of bolt length and spacing, shotcrete thickness and type (plain or fiber-reinforced), use of spiling, use of concrete lining, and installation of concreted floor.
Dike, fault zone, vertical pipe, permeable basalt layer:			
▪ Temperature	≤1°C per 100 m tunnel (8-25°C)	>10°C per 100 m tunnel	Ventilation, watering of rock surface, watering of shotcrete
▪ Salinity	50-150 ppm	Higher content in general, an increase with depth	Extended grouting
▪ pH-value	pH=7 (close to the surface) pH=9.5 (at great depth)	pH<6.5 pH>10	Extended grouting
Weak rock, sediments:			
▪ Color of drill water and drill cuttings	Greyish	Reddish, yellowish	Extended grouting and more rock bolts
▪ Drill penetration rate	“Normal” rate of drill penetration	High and low rate of drill penetration	Extended grouting and more rock bolts
Water-bearing zones:			
▪ Inflow of water	<5 l/min for one hole <10 l/min for four holes	>5 l/min for one hole >10 l/min for four holes	Extended grouting

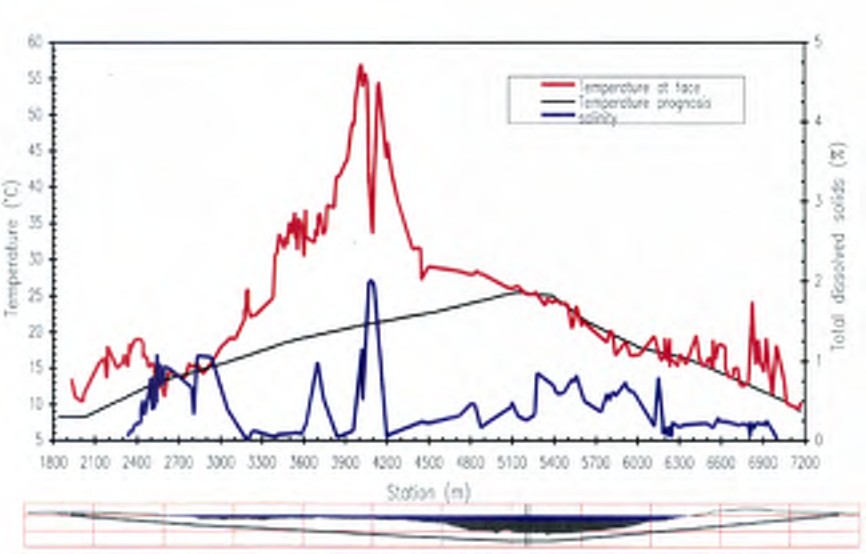

Figure 8 Result of the measurement of water temperature and water salinity in the tunnel. The corresponding longitudinal profile is shown at the bottom (© Brantmark et al. 1998. Reproduced by permission of Taylor and Francis Group, LLC, a division of Informa plc).

7. Discussion

7.1. Applicability of the observational method

7.1.1. Introduction

The design and execution of the tunnel under the Hvalfjörður fjord as described above has many similarities with the principles of the observational method as defined in Eurocode 7, with five paragraphs (CEN 2004). Because of this, and also considering the lack of well-documented case studies on the practical use of the observational method, we find it highly relevant to discuss the tunnel project in light of the Eurocode definition of the observational method. The first paragraph refers to the suitability of the method:

> *(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."*

Prediction of geotechnical behavior is often challenging in cases of substantial epistemic uncertainty (lack of knowledge) regarding the geotechnical conditions. This was also the case with the Hvalfjörður project, as is clear from the project description. In addition, the project team had limited knowledge and experience with subsea tunneling in Iceland, and there had been failures in other similar tunnel projects. Under these circumstances, the observational method can be expected to be the most cost-effective solution.

7.1.2. Preparations during the design phase

The second paragraph in Eurocode 7 includes five requirements to be fulfilled in the design phase (P stands for principle and implies a mandatory clause). Each of these requirements are considered below:

> *"(2)P The following requirements shall be met before construction is started:*
>
> *— acceptable limits of behaviour shall be established;"*

This requirement on acceptable limits of behavior corresponds to the Table 1 threshold values for when the design needs to be modified and/or contingency measures implemented. Additional threshold values were established regarding the deformation of the rock surface in the tunnel. Some of these thresholds were expressed in qualitative terms, e.g., "high and low rate of drill penetration", which made the decision-making process regarding the implementation of contingency measures more difficult, as the interpretation of these limits were rather ambiguous.

> *— "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;"*

The range of possible behavior was not established for the behavior of the rock mass in terms of all observed indicators. Thus, it was not demonstrated that the actual behavior likely would fall within the range of acceptable behavior (i.e., not violate the threshold values). An exception was the rock support classes. They were connected to the Q-value mapped at the tunnel face, so the possible Q-values thereby corresponded to a range of possible behavior. However, the probability that the rock support and grouting would be within the normal behavior (class 1–3, Table 1) was not assessed. Thus, it was not known in the design stage how difficult and costly it would be to handle large areas of very poor rock and/or reduce high inflow of water to acceptable levels, had they occurred. Notably, this is a matter of cost rather than structural safety as long as it is possible to undertake the contingency actions more extensively than expected (see Spross et al. 2016). Spross & Johansson (2017) and Spross & Gasch (2019) discussed how this "acceptable probability" can be calculated if threshold values are established with reliability-based methods. Such calculations would, however, be rather challenging for the thresholds in this case. We note here, however, that not analyzing the probability that the actual behavior will be within the acceptable limits does imply a considerable economic risk for the risk owner, which for the Hvalfjörður project was the contractor due to the turn-key contract.

— *"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 monitoring plan was established by the joint-venture before the start of the excavation of the tunnel. The monitoring included deformation measurements and the indicators in Table 1. The monitoring had sufficient response time.

— *"a plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits."*

A plan of contingency actions was devised before the start of the excavation of the tunnel. In case a threshold value was exceeded (e.g., too much inflow of water into the tunnel), the senior geologist would contact the senior hydrogeologist, the senior rock engineer and the project manager, who would then decide where, how, and to what extent the contingency actions would be undertaken, as detailed in Table 1. The fact that the extent of the action was not predetermined deviates from the Eurocode, which requires detailed planning in advance.

7.1.3. The construction phase

For the construction phase, Eurocode 7 states:

"(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."

The monitoring was carried out mainly according to the planning, and contingency actions were undertaken at some locations, as described in section 6.3.3. Note that the continuous adjustment of the support based on support classes can formally be interpreted as a use of contingency actions as soon as class 1 is not used, which here was very common. The term "contingency action" can therefore be misleading for this type of application.

7.2. Contractual Considerations

The uncertainties involved in projects adopting the observational method implies difficulty being able to describe the geotechnical behavior and, consequently, estimate the cost and time schedule of the project. This is an economical risk to either the client or the contractor depending on the contractual framework. When using the observational method, the contractual framework needs to be both adapted to the specific problem at hand, e.g., if the work could be described as series or parallel works, and flexible enough to be able to handle changes in design and execution.

If the client wants to reduce the risk exposure, a design-and-build, turnkey, or build-own-transfer contract may be used since most of the risks are owned by the contractor in such contracts (Palmström & Stille 2015). However, Ward et al. (1991) argue, based on insurance law and practice, that a contractor should not be expected to price risk that is very difficult to quantify accurately. Instead they recommend that price should be based either on actually encountered conditions or possibly on a contractor's risk premium estimated based on the client's supplied in-depth risk analysis. While large allocation of risk to the contractor makes bidding a challenge, it gives, as discussed by Tidlund (2021), the contractor an opportunity to ensure safe and cost-effective design and execution by using the observational method, since the contractor becomes responsible for both of these project phases. However, if the client transfers too much of the risks to the contractor, and the contractor realizes itself being unable to manage such large risks, there is a possibility that the contractor will choose not to submit a tender. According to Ward et al. (1991), this may in the long run decrease the competition, encouraging low-quality tenders that do not account for the risk accurately. For further general discussions of the effects of different risk allocation strategies in construction contracts, we refer to, e.g., Hanna et al. (2013) and Zhang et al. (2016); however, the amount of research on risk allocation in underground construction projects specifically is very limited and remains an issue for future studies.

In the Hvalfjörður project, the contract was a turn-key contract where the contractor guaranteed the financing of the project during the construction period, and the tunnel works were paid with a lump sum payment, with a minor remeasurement payment made related to the rock support and grouting. Thus, a considerable part of the risks, such as the construction risks related to the excavation of the tunnel, was owned by the contractor. However, the turn-key contract provided the contractor with the possibility of fully adopting the observational method and to implement the planned contingency measures when necessary without permission from the client, as long as the functional requirements in the tender documents were fulfilled. The project was completed within budget and ahead of schedule, partly due to better geotechnical conditions than expected. It can only be speculated about what would have happened if the geotechnical conditions were worse than expected, but the contractor would certainly have tried to get compensation for the associated extra costs and an extended time schedule. Unfair or unreasonable risk allocation is likely only debated when the ground conditions are poorer than expected; for such instances it is quite likely that the involved parties will interpret the contract differently (Hartman & Snelgrove 1996). Regardless, in a turn-key contract like this, the client benefits very little from the unexpectedly good conditions and still likely has to pay a considerable risk premium to the contractor.

8. Concluding Remarks

The risk management process and its use of the observational method had an important role in the design and execution of the tunnel under the Hvalfjörður fjord, due to the project team's limited knowledge and experience of subsea tunneling in Iceland and known failures in similar tunnel projects. The observational method's monitoring of geotechnical hazard indicators ensured safe and cost-effective execution of the project.

Continuous probe drilling, grouting ahead of the tunnel face, and systematic geological mapping resulted in flexible and efficient execution of the tunneling work.

Our analysis of the Hvalfjörður project indicates that the contractor was allocated a considerable amount of risk due to the turn-key contract. This puts a significant burden on the contractor to be extremely careful in the analysis of the uncertainty of the ground conditions so that a fair risk premium can be added to the tender. In our opinion, it should in most cases be more favorable for the client to share some risks related to the ground conditions, rather than allocating them to the contractor and risking disputes or, in a worst-case scenario, the contractor's bankruptcy before completion of the project.

Regarding technical planning and execution, we believe that the Hvalfjörður project is a good example of how the observational method can be applied to tunnel projects with substantial geotechnical uncertainty. Although it can be argued that the Hvalfjörður project was completed within budget and ahead of schedule only due to better geotechnical conditions than expected, we believe that the organization of the project was an important factor for its success. We would here specifically like to highlight the well-thought-out risk management process, the good cooperation between the actors involved, and the systematic planning and undertaking of the monitoring and contingency actions during its design and execution.

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References

Ang A H S & Tang W H, 2007, *Probability Concepts in Engineering: Emphasis on Applications to Civil and Environmental Engineering*, Wiley, Hoboken, NJ.

Bjureland W, Spross J, Johansson F, Prästings A & Larsson S, 2017, Reliability Aspects of Rock Tunnel Design with the Observational Method, *International Journal of Rock Mechanics and Mining Science 98*, pp. 102-110.

Brantmark J, Taube A & Stille H, 1998, Excavation Of a Sub-Sea Road Tunnel at Hvalfjördur, Iceland, In: *Hungr O, Moore D (eds), Proceedings of the 8th International IAEG Congress: Engineering Geology, a Global View from the Pacific Rim*, CRC Press: Boca Raton, pp. 3 685-3 691.

CEN, 2004, *EN 1997-1:2004 Eurocode 7: Geotechnical Design – Part 1: General Rules,* European Committee for Standardisation. Brussels, Belgium.

CEN, 2018, *ISO 31000 Risk Management – Guidelines*, European Committee for Standardisation. Brussels, Belgium.

Clayton C R I, 2001, Managing Geotechnical Risk: Time for Change? In: *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering, vol. 149, issue 1*, pp. 3-11.

Duncan J M & Brandon T L, 2019, Use of the Observational Method as the Sole Basis for Design. In: *Proceedings of Geo-Congress 2019: Data, Software, Education, and a Tribute to Ralph Peck*, Reston, VA: American Society of Civil Engineers, pp. 107-116.

Fuentes R, Pillai A & Ferreira P, 2018, Lessons Learnt from a Deep Excavation for Future Application of the Observational Method, *Journal of Rock Mechanics and Geotechnical Engineering, vol. 10, issue 3*, pp. 468-485.

Guba E G, 1981, Criteria for Assessing the Trustworthiness of Naturalistic Inquiries, *Educational Communication and Technology Journal, vol. 29, issue 2*, pp. 75–91.

Hanna A S, Thomas G & Swanson J R, 2013, Construction Risk Identification and Allocation: Cooperative Approach, *Journal of Construction Engineering and Management, vol. 139, issue 9*, pp. 1 098-1 107.

Hartman F & Snelgrove P, 1996. Risk allocation in Lump-Sum Contracts—Concept of Latent Dispute. *Journal of Construction Engineering and Management, vol. 122, issue 3*, pp. 291-296.

Lacasse S & DiBiagio E, 2019, Two Observational Method Applications: An Ideal Solution for Geotechnical Projects with Uncertainty, In: *Proceedings of Geo-Congress 2019: Data, Software, Education, and a Tribute to Ralph Peck*, Reston, VA: American Society of Civil Engineers, pp. 117-128.

Nicholson D, Tse C M, Penny C, O Hana S & Dimmock R, 1999, *The Observational Method in Ground Engineering: Principles and Applications, vol. 185*, London: Construction Industry Research and Information Association.

Palmström, A & Stille H, 2015, *Rock Engineering*, 2nd edition. London: ICE Publishing.

Peck R B, 1969, Advantages and Limitations of the Observational Method in Applied Soil Mechanics, *Géotechnique, vol. 19, issue 2*, pp. 171-187.

Powderham, A & O'Brien A, 2020, The Observational Method in Civil Engineering: Minimising Risk, Maximising Economy, Abingdon: CRC Press.

Prästings A, Müller R, & Larsson S, 2014, *The Observational Method Applied to a High Embankment Founded on Sulphide Clay*, Engineering Geology, vol. 181, pp. 112-123.

Spross J, Bergman N & Larsson S, 2021a, Reliability-Based Verification of Serviceability Limit States of Dry Deep Mixing Columns*, Journal of Geotechnical and Geoenvironmental Engineering, vol. 147, issue 3,* pp. 04020183-1-9.

Spross J & Gasch T, 2019, Reliability-Based Alarm Thresholds for Structures Analysed with the Finite Element Method, *Structural Safety, vol. 76*, pp. 174-183.

Spross J & Johansson F, 2017, When is the Observational Method in Geotechnical Engineering Favourable? *Structural Safety, vol. 66*, pp. 17-26.

Spross J, Johansson F, Uotinen LKT & Rafi J, 2016, Using Observational Method to Manage Safety Aspects of Remedial Grouting of Concrete Dam Foundations, *Geotechnical and Geological Engineering, vol. 34,* pp. 1 613–1 630.

Spross J, & Larsson S, 2021b, Probabilistic Observational Method for Design of Surcharges on Vertical Drains, *Géotechnique, vol. 71, issue 3,* pp. 226-238.

Spross J, Olsson L & Stille H, 2018, The Swedish Geotechnical Society's Methodology for Risk Management: A Tool for Engineers in Their Everyday Work, *Georisk. vol. 12, issue 3*, pp. 183-189.

Spross J, Olsson L, Stille H, Hintze S & Båtelsson O, 2021c, Risk Management Procedure to Understand and Interpret the Geotechnical Context, *Georisk* (In press).

Spross J, Stille H, Johansson F & Palmstrøm A, 2020, Principles of Risk-Based Rock Engineering Design, *Rock Mechanics and Rock Engineering, vol. 53, issue 3,* pp. 1 129-1 143.

Stake R E, 2005, Qualitative Case Studies, In: *Denzin N K & Lincoln Y S (Eds.), The Sage Handbook of Qualitative Research*, Thousand Oaks: Sage, pp. 443-466.

Stille H, 1986, Experiences of Design of Large Caverns in Sweden, In: *Proceedings of the International Symposium on Large Rock Caverns, Helsinki, 25-28 August 1986*, Oxford, UK: Pergamon Press, pp. 231-241.

Stille H, 2017, Geological Uncertainties in Tunnelling–Risk Assessment and Quality Assurance, In*: ITA-AITES World Tunnel Congress 9-15, June 2017, Paris,* The International Tunnelling and Underground Space Association.

Tidlund, M, 2021, Geotechnical Risk Management Using the Observational Method, Doctoral thesis, *TRITA-ABE-DLT-2123*, KTH Royal Institute of Technology, Stockholm, Sweden.

van Staveren M T, 2006, *Uncertainty and Ground Conditions: A Risk Management Approach*, Oxford: Butterworth Heinemann.

van Staveren M T, 2013, Geotechnics on the Move: Guidance for a Risk-Driven Way of Working, *Georisk, vol. 7, issue 3*, pp. 225-236.

Ward S C, Chapman C B & Curtis B, 1991, On the Allocation of Risk in Construction Projects, *International Journal of Project Management, vol. 9, issue 3*, pp. 140-147.

Yin R K, 2018, *Case Study Research and Applications: Design and Methods*, 6th edition, Thousand Oaks: Sage

Zhang S, Zhang S & Gao Y, 2016, Contractual Governance: Effects of Risk Allocation on Contractors' Cooperative Behavior in Construction Projects, *Journal of Construction Engineering and Management, vol. 142, issue 6*, pp. 04016005-1-11.

Paper A appendix: Interview instrument

Introduction:

Present yourself, describe the purpose of the study and that the interviewee will by anonymous.

General questions:

- Which were the key characteristics of the project?
- Which were the main challenges?
- From your point of view, what is risk management?
- Did you participate in the risk management process in the tender phase?
- Did you participate in the risk management process after the contract was awarded?
- How important is risk management compared to your other daily tasks?

The risk management process in the tender and design phase:

- Which geotechnical risks were included in the tender documents?
- How were the geotechnical risks presented in the tender documents?
- How were the risks allocated between the contractor and the client?
- In your opinion, which techniques are useful to perform risk identification, risk analysis and risk evaluation?
- How were the risks identified?

- How were the risks analyzed?
- How were the risks evaluated?
- Which geotechnical risks were considered to be most crucial?
- Which risk treatment actions were identified?
- How was the risk information documented and communicated to the construction phase?
- Were there any obstacles that hindered the management of geotechnical risks?
- How do you think the geotechnical risk management process in the tender and design phase can be improved?

The risk management process in the construction phase:

- Describe the method of risk management that was adopted.
- Which geotechnical risks were considered as the most critical?
- Who was responsible for the decisions regarding the implementation of the risk treatment actions?
- Who was responsible for the implementation of the risk treatment actions?
- Which geotechnical risks were realized?
- Were there any “new” (unidentified) geotechnical risks?
- How was it decided when risk management measures were to be implemented?
- Which geotechnical risk treatment actions were implemented?
- What was the result of the risk treatment actions?
- Were there any obstacles that hindered the management of geotechnical risks?

- How do you think the geotechnical risk management process in the construction phase can be improved?

Project management: (project manager only)

- Describe the project management method/model in the project.
- Which factors were critical to the outcome of the project?
- How was the work with geotechnical risk management incorporated into the other project activities?

Ending:

- Are there any other observations?
- Anything we have not covered?
- Any relevant observations with regards to your specific perspective in the project?

Finish with a brief summary, thank the interviewee, and ask if it is ok to come back with questions afterwards.