THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Managing hydrogeological risks in underground construction

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Cover:
Event tree illustrating the cause–effect chain for several examples of effects and consequences caused by leakage into an underground facility, developed in Merisalu et al. (2021).

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ABSTRACT

Groundwater leakage into underground constructions can cause groundwater drawdown and subsequently costly damages to objects impacted by changes in groundwater conditions. In order to reduce the damage risk, risk-reducing measures can be implemented. When implementing measures, society’s limited resources must be carefully managed by balancing the costs and the benefits (e.g. reduced risk) of the measures. Decisions regarding risk-reducing measures must always be taken under uncertainty since the conditions of the hydrogeological system cannot be fully known. In this thesis, a generic framework for management of hydrogeological risks in underground construction is presented (Paper 1). This framework constitutes a structured and transparent approach to the decision process for implementation of risk-reducing measures for groundwater control in underground construction. The framework uses a stochastic and iterative approach for managing the changing level of uncertainty inevitably associated with underground construction. The different modules that constitute the framework are also exemplified by application in a case study (paper 2). The case study focuses on the risk of subsidence damages to the built-up environment (buildings, paved surfaces and pipes) and risk-reducing measures in the form of sealing, artificial recharge and reinforcement measures to houses. The framework and methods used within the framework for the risk analysis and risk evaluation have proven useful as decision support for management of hydrogeological risks. The framework has also proven to be an efficient tool in communication of risks both internally in a project but also between the project owner and stakeholders in the society.

Keywords: risk management; groundwater drawdown-induced damages; uncertainties; decision support; cost–benefit analysis

LIST OF PUBLICATIONS

This thesis contains the following publications appended to the thesis:

I. Merisalu, J., Sundell, J., & Rosén, L. (2021). A Framework for Risk-Based Cost–Benefit Analysis for Decision Support on Hydrogeological Risks in Underground Construction. *Geosciences*, *11*(2), 82. https://doi.org/10.3390/geosciences11020082
II. Merisalu, J., Sundell, J., & Rosén, L. (2021). Cost-benefit analysis of hydrogeological risk mitigation in underground construction. Submitted manuscript.

Division of work between the authors:

Paper I: Conceptualization, J.M., J.S., and L.R.; Funding acquisition, J.M. and L.R.; Supervision, J.S. and L.R.; Project administration, L.R.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review and editing, J.M., J.S., and L.R. All authors have read and agreed to the published version of the manuscript.

Paper II: Conceptualization, J.M., J.S., and L.R.; Funding acquisition, J.M. and L.R.; Supervision, J.S. and L.R.; Methodology, J.M., J.S., and L.R.; Software, J.M.; Formal analysis, J.M.; Investigation, J.M., and J.S.; Visualization, J.M.; Writing—original draft, J.M.; Writing—review and editing, J.M., J.S., and L.R.; Project administration, L.R. All authors have read and agreed to the published version of the manuscript.

Other work and publications not appended to this thesis:

Merisalu, J., Sundell, J., & Rosén, L. (2020). *Kostnads-nyttoanalys av skyddsåtgärder för hantering av hydrogeologiska risker vid undermarksbyggande.* Tech. Rep. No. ACE 2020: 12. Gothenburg: Chalmers University of Technology. https://research.chalmers.se/publication/517667/file/517667_Fulltext.pdf

Merisalu, J., & Rosén, L. (2020). *Villkorsutformning för grundvattenbortledning vid undermarksbyggande*. Tech. Rep. No. ACE 2020: 11. Gothenburg: Chalmers University of Technology. https://research.chalmers.se/publication/516949/file/516949_Fulltext.pdf

Merisalu, J., & Rosén, L. (2020). *Villkorsutformning för grundvattenbortledning vid undermarksbyggande*. Oral presentation at the Swedish transport administrations research and innovation day (Trafikverkets FoI-dag), Digital presentation.

Merisalu, J., Sundell, J., & Rosén, L. (2020). Kostnader och nyttor av riskreducerande åtgärder vid grundvattenbortledning. Oral presentation (Webinar) for the Swedish geotechnical society (SGF), digital presentation. http://www.sgf.net/web/page.aspx?refid=7004

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Johanna Merisalu

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1 Introduction

The first chapter of the licentiate thesis provides a brief background of the research and presents the research aim and the main objectives. It also lays out the scope of work followed by clarifying some limitations.

1.1 General background

With increasing global urbanization follows a land-use conflict which results in a higher demand for locating infrastructure such as roads and rails below the ground surface (Huggenberger et al., 2011). Constructing below the ground surface and below the groundwater table are often associated with groundwater leakage into the construction. In order to ensure dry working conditions in the facility, the leakage must be pumped which subsequently may result in groundwater lowering in the surrounding areas. Groundwater lowering measures may also be necessary outside excavation shafts in order to ensure secure working conditions and to avoid e.g. bottom destabilization and bottom heave (Cashman & Preene, 2001). Dewatering of groundwater resources induced by leakage into the underground construction is known from several underground projects around the world, see e.g. (Kværner & Snilsberg, 2013; López-Fernández et al., 2012). Groundwater drawdown induced by leakage can affect large areas surrounding the underground facility (Burbey, 2002; Gustafson, 2012). The groundwater drawdown may subsequently cause severe economic, cultural and environmental impacts. Example of consequences from groundwater drawdown are impacts on groundwater dependent ecosystems such as peatlands, streams, springs and lakes (Attanayake & Waterman, 2006; Kværner & Snilsberg, 2008; Mortellaro et al., 1995), damages to groundwater dependent building foundations (Vatovec & Kelley, 2007), and land subsidence which subsequently may damage buildings and other facilities (Boone, 1996; Lindskoug & Nilsson, 1974; Persson, 2007). Other risks associated with groundwater lowering are changes to groundwater chemistry (Mossmark et al., 2017; Mossmark et al., 2008), changes in flow patterns and mobilization of contaminants (Hernández-Espriú et al., 2014) and crop yield losses (Graffner, 2007; Lewan & Linnér, 2008).

The relationships between leakage and various effects and their consequences can be described by a chain of events that need to occur for the leakage to cause damage (see Figure 1). The nature and severity of the consequences of damage are determined by the dynamic interaction between the different components in the cause–effect chains (illustrated with functions and probability-density functions within the circles in the figure). Consider the example of damages to buildings caused by subsidence in the figure. The chain of events is first initiated with a leakage of groundwater into the underground facility. The magnitude of the leakage depends on the transmissivity of the surrounding bedrock or soil, the pressure gradient of the groundwater, and the sealing design of the tunnel.

Depending on the size and duration of the leakage, and the conditions of the hydrogeological system, the groundwater level in the surrounding aquifers may decline. The magnitude of the groundwater drawdown depends on the hydraulic properties of the aquifers, the boundary conditions of the system and the water balance. As an example, an aquifer can be located next to a river that continuously recharge the aquifer and a large leakage will not have any impact of the groundwater levels. The opposite is true if the aquifer has boundaries where no or little water can flow. At such conditions even a small leakage may cause large impacts on the groundwater levels. The magnitude of the groundwater drawdown is thus to a higher degree dependent of the conditions in the groundwater system compared to the magnitude of the leakage. If the aquifer is overlain by a layer of clay, the pore pressure of the clay may be reduced due to the lowered groundwater levels. Reduction of pore pressure is a slow process, and the speed is mainly dependent on the permeability of the clay, thickness and the hydraulic gradient between the clay and the underlying aquifer. The duration of the groundwater lowering is thus decisive for the change of pore pressure in the clay. The lowered pore pressure can initiate a process of subsidence of the clay. Whether it is initiated or not depends on the historical consolidation of the clay which in turn controls the consolidation properties of the clay. The subsidence can subsequently lead to damages on objects such as buildings, pipes and other installations. The magnitude of the damage depends on the sensitivity of the objects of risk. As an example, the foundation of a building may or may not be sensitive to subsidence. Finally, the damages give rise to costs for reparation and thus reimbursement costs (Sundell, 2018). These dynamic characteristics of the cause–effect chains imply that it is not relevant to define risk as a traditional binary failure–no-failure situation. Risk should rather be defined as an integrated process where the total risk is the integral sum of a number of possible situations with varying probabilities and consequences ranging from those with large probabilities and little-to-no consequences to those with small probabilities and large-to-catastrophic consequences.

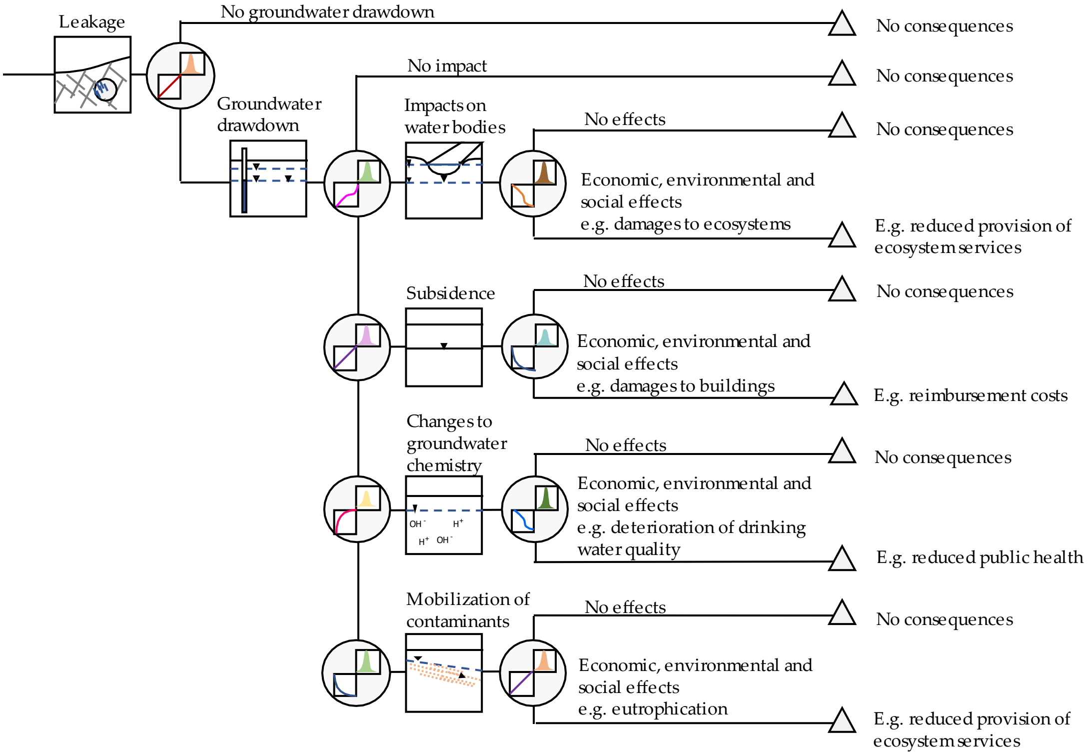

Figure 1. Event tree illustrating the cause–effect chain for several examples of effects and consequences caused by leakage into an underground facility. The circles represent the complex nonbinary relationship between the different events of the chain. The events can have economic, environmental, and social effects, which in turn result in consequences. The figure is published in paper 1.

To reduce the damage risk, the project owner must often implement risk-reducing measures. When deciding on which risk-reducing measure to implement there is always a trade-off between the benefits in the form of reduced damage risk and the implementation costs. From an economic perspective, there are two risks for making erroneous decisions associated with the implementation of risk-reducing measures:

1. The risk of not implementing necessary measures resulting in damages and damage costs for the project owner, the society and the environment, and
2. The risk of implementing unnecessary measures resulting in unnecessary costs.

These risks and their relationship to implementation costs and damage costs can be described in accordance with Figure 2 where the x-axis represents increasing risk-mitigation strategies and the y-axis represents costs, both costs for implementing measures and damage costs. Risk type 1 dominates the left part of the graph and risk type 2 dominates the right part of the graph. If these two risks are optimally balanced, an optimal risk level is reached.

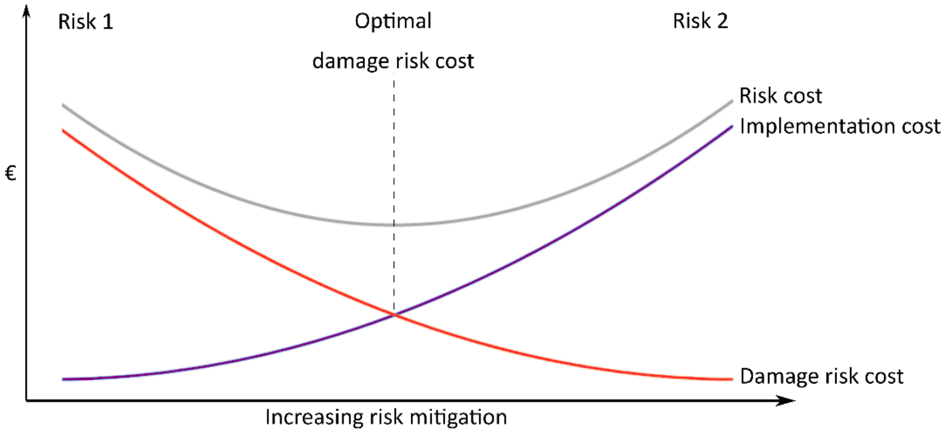

Figure 2. The principles of the relationship between implementation costs, damage costs and the total cost (risk level) for the two risks (Risk 1 and Risk 2) for making erroneous decisions. The figure is published in paper 1.

To balance risk type 1 and risk type 2 and thus find the optimal risk level where the society's limited resources are used efficiently, it is necessary that risk-reducing measures' positive and negative consequences are considered and compared. From a socioeconomic perspective, this is preferably done using cost–benefit analysis (CBA) (Boardman et al., 2017; Johansson & Kriström, 2015). The result from a CBA describes whether a risk-reducing measure is economically profitable or not to society and can thus be used as support when deciding whether to implement the risk-reducing measure or not. For the result to be relevant for societal decision-making, the project´s internal economic consequences as well as the external environmental and societal consequences must be considered. The project's internal costs relevant for hydrogeological risk-reducing measures in underground construction include investment costs, operation, and maintenance costs and costs for reinvestment in the measure after its lifespan. External consequences that need to be considered are of economic, social, and environmental character. Examples of external costs are risks of accidents associated with the measure, costs for reduced accessibility, reduced provision of ecosystem services, and costs for emissions. The project's internal benefits of implementing a measure includes reducing the risk for penalties and delays due to violation of terms and conditions and reduced reimbursement costs of damaged objects such as a buildings, wells, or pipings. External benefits include reduced damage risk to objects such as groundwater-dependent ecosystems, buildings, and other installations, e.g., water supplies, archeological remnants, or underground storage facilities. If possible, consequences are monetized. However, not all consequences can be expressed quantitatively in monetary units. To make sure that these consequences are not overlooked, they must instead be described qualitatively, and their effects on the overall result must be evaluated.

There are several methods available for assessment of the individual parts of the cause effect chain e.g. prediction of leakage (Kitterød et al., 2000; Panthi & Nilsen, 2010; Zhang & Franklin, 1993), prediction of groundwater drawdown (Molinero et al., 2002; Sundell et al., 2015), prediction of subsidence due to pore pressure decrease(Griffiths & Fentont, 2007; Sundell et al., 2017; Yoo et al., 2012), and damaging impacts (Lewan & Linnér, 2008; Mortellaro et al., 1995; Sundell et al., 2019a). However, in order to assess the damage risk, models covering all parts of the cause effect chain must be used and copuled.

There exists no comprehensive list of which internal and external consequences to include in the risk evaluation of risk-reducing measures. This calls for guidance on how the damage risk of leakage can be assessed by coupling models representing the various steps in the cause-effect chain together with guidance on what consequences to include in the evaluation of risks from risk-reducing measures.

1.2 Aim and objective of the PhD project

The overall aim of this PhD-project is to:

> *Develop a comprehensive and systematic procedure for management of hydrogeological risks in underground infrastructure projects by considering the whole chain of events from leakage to damage in the risk analysis, and by using a cost-benefit analysis approach considering both the economic, environmental and social effects of risk-mitigation measures in the risk evaluation process.*

To meet the overall aim, there are four specific objectives:

- *Develop a comprehensive framework for management of hydrogeological risks*
- *Develop methods for coupling of models representing the various events in the cause-effect chain.*
- *Identify and economically value the project internal and the external consequences of risk mitigation measures*
- *Apply this framework on a case study to exemplify its usage*

1.3 Scope

Achieving the objectives of this thesis required a multi-disciplinary approach. To understand the relevant topics and to establish the context within which this work has been carried out, the thesis starts with a literature review of the concepts and methods, presented in chapter 2.

Chapter 3 presents a summary of the publications appended in this thesis. The first paper constitutes the developed framework for management of hydrogeological risks. The second paper constitutes a case study in which the developed framework was applied. This paper also presents methods for coupling models representing the various events in the cause effect chain and the identification and valuation of consequences of implementing risk-reducing measures.

Chapter 4 constitutes a discussion of the thesis with focus on the developed framework and its application. The appended papers have been reflected upon, required further investigations have been identified and further work and potential studies have been put forward.

1.4 Limitations

The limitations of this thesis are as follows:

- As it is a multidisciplinary research, the focus has been on linking different fields of interest rather than an in-depth exploration of each topic. Thus, the thesis provides a limited investigation of relevant methods and concepts.
- The chapter covering environmental legislation and legal permits only focuses on a Swedish context. The legal context for groundwater dispersion in other countries may differ.

2 Literature review of concepts and methods

In this section, a literature review of the concepts and methods used so far in this PhD-project are presented. First, the concept and definition of risk is introduced. Second, the risk management process according to the international standard organization (ISO, 2018) is presented with focus on how it relates to hydrogeological risks associated with underground construction. Third, the difficulties associated with uncertainties in underground construction as well as the concept of stochastic modeling for quantifying uncertainties are presented. Fourth, the method of cost-benefit analysis is presented with focus on valuation of consequences is introduced. Finally, the legal framework to which underground constructions in Sweden must abide is covered.

2.1 The risk concept

There are several definitions of risk. One commonly used definitions was presented by Kaplan and Garrick (1981) where risk is defined as the combination of the probability for an event to happen and the consequences of that event. The risk is defined by the questions: What can happen; How likely is it to happen; and What are the consequences if it happens? Another definition is given in the ISO 31000 standard. Here, risk is defined as the effect of uncertainties on objectives (ISO, 2018). Within the framework of this PhD project, risk is defined in an economic context as a function of probability and economic consequence. The risk R_i is expressed in monetary terms as the expected value of damage cost and can mathematically be calculated using the probability-density function of an event, f_i, and a function representing the consequences of that event, C_i, as follows:

$$R_i = \int C_i f_i \, ds \tag{1}$$

For example, the risk of damage to buildings due to subsidence induced by leakage can be described as the economic risk of damage induced subsidence, R_s, which is given by the economic cost of damage, C_s, and the probability of a damage to occur, f_s. The total risk is given by summing R_s for all buildings within the impact area of the tunnel.

As illustrated by Figure 3a, the risk function includes events with both high-probability–low-consequence risks (illustrated to the left in the graphs) and low-probability–high-consequence risks (illustrated to the right in the graphs). To calculate the total risk, all possible (imaginable) events must be included in the risk analysis. However, in practice, it is difficult or often not feasible to describe all these events. To overcome this difficulty, a staircase function of the identified risk categories (illustrated as I-V in the graphs) can be defined. In the example of damage costs to buildings, the continuous function can be simplified by defining a staircase function where each step represents a damage category, e.g., esthetical damages, functional damages, and stability damages (Sundell et al., 2019a). The graph in Figure 3a illustrates the risk at a time when uncertainties are large, and when risk-reducing measures has not yet been implemented. In Figure 3b, the graph illustrates how the uncertainty decreases when new information is collected as the project progresses. In Figure 3c, a risk-reducing measure has been implemented with a reduced risk for high-consequence events and a reduced total risk as a result. For the example of damage costs on buildings, a risk-reducing measure, e.g., extra sealing measures to reduce leakage, has been implemented resulting in lower probability of high-consequence damages such as stability problems.

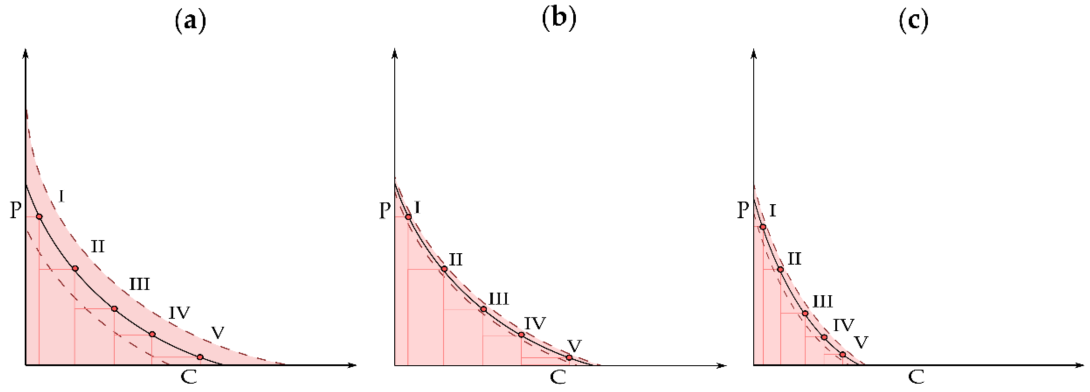

Figure 3. Schematic description of staircase and continuous risk functions indicated by red circles and black solid line together with an interval for uncertainty indicated by dashed lines. “P” and “C” indicate probability and consequence, respectively. (a) the risk curve in an early stage before any risk-reducing measures have been implemented; (b) the risk curve after retrieval of more information resulting in less uncertainty, and (c) the risk curve after implementation of risk-reducing measures resulting in reduced total risk. The figure published in paper 1.

2.2 The risk-management process

The risk management process includes both the prevention and mitigation of risks. Risk management is defined as *coordinated activities to direct and control an organization with regard to risk*, in the ISO 31000 standard (ISO, 2018). The risk management process should include the establishment of context (definition of goals and delimitation), identification and analysis of risks, evaluation of risks, risk treatment (implementation of risk-reducing measures), and consultation, communication, monitoring and review (Figure 4).

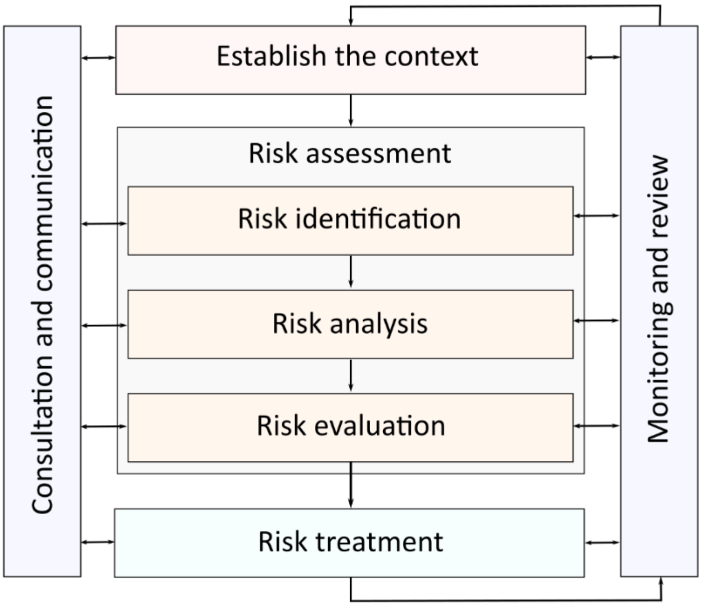

Figure 4. The risk management process (ISO, 2018)

2.2.1 Consultation and communication

One of the most important parts of the risk management process is the communication and consultation with stakeholders affected by the measure. According to Fischhoff (1995), “*communication is like an insurance policy. It is a fixed cost that can prevent larger damage*”. Risk communication within the organization is as important as communication between stakeholders. Risk communication includes all activities that aims at increasing the understanding of the present risks and that includes involvement of stakeholder in the risk management process. Stakeholders affected by the decisions on hydrogeological risks in underground constructions includes the project owner, the contractors, authorities, landowners, owners of buildings and other facilities, interest groups and residentials living in the area surrounding the facility. The perception of risk is highly subjective and it is a product of beliefs, values and past experiences (Kasperson et al., 1988; Slovic, 1987). This means that it is likely that different stakeholders have considerably different perception of risk. Communication between stakeholders should be a two-way communication (ISO, 2018). A key to a successful risk communication is building trust between the stakeholders (Slovic, 1993).

2.2.2 Establish the context

This part of the risk management process aims at defining the aim or the purpose of the risk management and thus the possible decision problems. In this part, the system is also defined setting the level of ambition for the risk management. In hydrogeological risk management in underground construction as outlined in this study, the decision problem regards what risk-reducing measure to implement to manage groundwater leakage into the construction. This part also includes defining the criteria for the decision problem. The criteria can be formulated in several ways. As an example, the criteria can be that the risk-reducing measure with highest social economic profitability should be implemented. The criteria can also be based on ethical values on legal requirements. In Sweden, the project owner must often abide the terms and conditions from the legal permit which limits how the criteria can be formulated (see section 2.6).

2.2.3 Risk identification

The risk identification is the foundation of the risk analysis. This step aims at listing all possible risks (ISO, 2018). Risk identification constitutes inventory and identification of risk objects and objects at risk. Risk objects are the underground facility or the activity that causes the risk. The object at risk is the receiver of the risk such as groundwater dependent ecosystems or buildings that are affected by the leakage and the subsequent groundwater drawdown.

2.2.4 Risk analysis

The risk analysis includes the consideration of the causes and sources of the risks and the positive and negative consequences. The causes and sources of risks can e.g., be described through a cause-effect chain. The risk level for the identified risks is determined in a quantitative, semi-quantitative or qualitative manner, depending on the circumstances. Hydrogeological risks in underground construction can as an example be expressed as costs for reimbursement of a damaged well, delays of the project in days or injuries and fatalities (Wladis & Rosén, 2018), all of which are as far as possible expressed in monetary units if the risk assessment is performed in an economic context. The level of detail may also vary depending on the risk, the purpose of the analysis and the available input resources. The probability of a consequence to occur can be estimated using e.g. expert judgement, process-based models and simulations or by extrapolating from experimental studies and available data (ISO, 2018).

2.2.5 Risk evaluation

Risk evaluation means that the risks are weighted in relation to the perceived risk of individuals and representatives for the society. In this step, the risks can be evaluated based on the risk acceptability criteria defined early in the risk management process. The purpose of this process is to identify which risks that need treatment and which risks that needs to be prioritized for treatment implementation (ISO, 2018). If acceptability criteria are used, a cost-effectiveness analysis (CEA) is one approach to determine what measure alternative to implement. A CEA determines which one of several alternative measures that meets the criteria at the lowest cost (STA, 2020). Another approach is to use a cost-benefit analysis

(CBA). The CBA compares the costs (implementation costs) and benefits (risk reductions and other potential benefits) of one or several measure alternatives against a reference alternative without considering any acceptability criteria (Johansson & Kriström, 2015). In many real-world applications of CBA, the analysis may be at least partly bounded by acceptability criteria. The reference alternative is often, but not always, defined as not implementing any measure. CBA is covered in more detail in section 2.5. The risk evaluation step provides support for decisions on which risk-reducing alternative, if any, to implement.

2.2.6 Risk treatment

In this step, the risks are treated by implementing risk-reducing measures. The measures can be directed both towards eliminating the risk by removing the source/cause or towards reducing the risk by reducing the likelihood that a risk occurs or its consequences. The acceptability criteria and the cost and benefits of the risk treatment should be considered when choosing what treatment to implement (ISO, 2018).

2.2.7 Monitoring and review

The monitoring and reviewing are essential parts of a successful risk management. It provides new knowledge and can detect changes that are necessary to consider. The new knowledge should be used iteratively in the risk management process for updating the risk analysis and the risk evaluation as new information becomes available.

2.3 Uncertainties

One of the greatest challenges with underground construction is that, regardless of the location, the construction material and the groundwater conditions are given from the start and cannot be replaced (Lundman, 2011). Uncertainty is therefore always a distinctive characteristic of underground construction and it is present in both the planning and design as well as in the assessment of environmental impacts and it must always be considered (Einstein & Baecher, 1983; Sturk, 1998). Uncertainty can be defined as any deviation from the unachievable ideal of complete deterministic knowledge of the relevant system (Walker et al., 2003). As described with the cause-effect chain presented above, there are several processes that interact for leakage of groundwater to cause damages. Even if the different events of the cause-effect chain are known, the interaction between the events are associated with large uncertainties.

The level of uncertainty in an underground project is not constant over time (Lundman, 2011). As illustrated by Figure 5, the uncertainty, the accumulated costs, and the possibility to influence the project outcome change with time as the project progresses. In the beginning of a project, uncertainties are typically large and as the project progresses and more information is collected, uncertainties decrease. The spent resources, i.e. the accumulated costs, increase as the project progresses. The room for changes and adjustments in the project are larger in the planning and feasibility phase, before the exact location of the facility is determined. This can be compared with the construction phase when there is little or no room to change the location. The changing level of uncertainty throughout a project must be considered when planning for risk-reducing measures. Some risk-reducing measures has higher potential of succeeding if they are implemented before the conditions are fully known. One example of such measure is grouting where pregrouting (implemented before excavation) often is more successful in reducing leakage than postgrouting (implemented after excavation) (Garshol, 2003). The possibility of influencing the success in reducing leakage is therefore higher before excavation when the uncertainties are large. This implies that for some measures there exist critical windows in time (indicated by the colored area in the figure) where the measures must be implemented to be successful. For the example with grouting for sealing, the critical window for succeeding with pregrouting constitutes the time before excavation which occurs at time t_x.

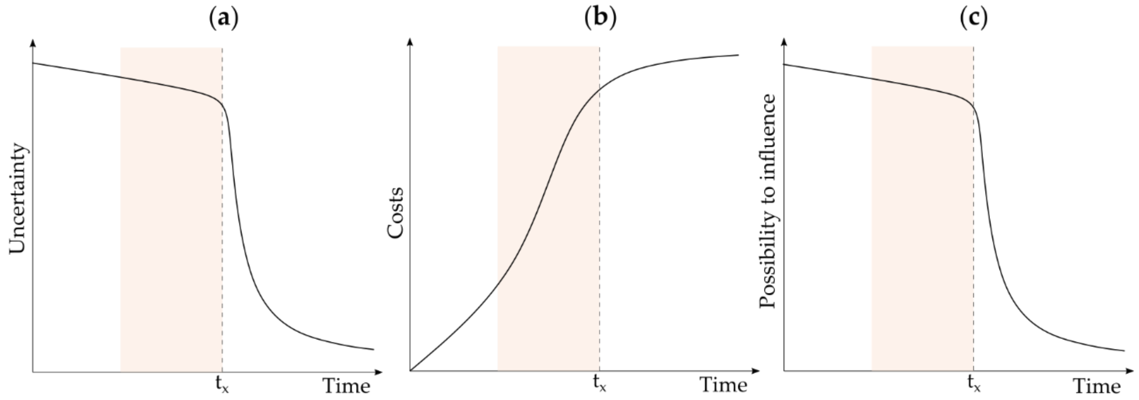

Figure 5. (a) level of uncertainty, (b) accumulated costs, and (c) the possibility to influence the outcome of the project in relation to the progress of the project in time. The colored area indicates the critical window where measures can be successfully implemented. At time tx, the project reaches a state where the room to maneuver and the chance to succeed with measures decrease. Modified from Lundman (2011). The figure is published in paper 1.

2.3.1 Models and uncertainties

Since it is impossible to describe the reality in full detail, models are often used to predict future behaviors given certain conditions. According to Walker et al. (2003) the model uncertainties can be divided into three categories: the location of uncertainty, the level of uncertainty and the nature of uncertainty.

The location of uncertainty describes where the uncertainty appears within the model complex. The locations for uncertainty are: context, model, inputs, parameters and model outcome. Context includes uncertainties regarding the boundaries of the model and thus the economic, environmental, political, social, and technological situation that forms the context for the problem being examined. Model uncertainty constitutes uncertainties regarding lack of understanding of the system and thus the ability of the model to represent the system. These uncertainties can only be reduced by an improved understanding of nature and an update of the conceptual, physical or mathematical model. Models are also always simplification of the reality, both because the inherent uncertainty makes it impossible to describe the reality in an exact manner and because simplifications often are made deliberately in order to make the model usable with regards to e.g. computation time (Burgman, 2005; Sturk, 1998). Inputs uncertainties constitute the description of the current (reference) system and the forces influencing this. Parameter uncertainty is uncertainty about the constants used in the model. Model outcome uncertainty is the accumulated uncertainty from all other categories of uncertainty.

The level of uncertainty describes where the uncertainty manifests itself. It can be divided into following uncertainties: statistical, scenario, recognized ignorance, and total ignorance. Statistical uncertainties are any uncertainty that can be described and handled statistically. Scenario uncertainty describes that there can be many plausible descriptions of the system. This uncertainty is often handled with scenario analysis. Recognized ignorance describes that there is a fundamental uncertainty regarding mechanisms and functional relationships being studied. Total ignorance implies a deep level of uncertainty regarding both scenarios, and the mechanisms and functional relationships being studied.

The nature of uncertainty can be divided into two categories: 1) the aleatory uncertainty from nature’s inherent variability, and 2) the epistemic uncertainty from our lack of knowledge about nature’s variability (Aven, 2012). One example of aleatory uncertainties is the spatial heterogeneity of different geological properties. The natural variability, and thus the aleatory uncertainty, cannot be reduced. In contrary to the aleatory uncertainty, the epistemic uncertainty can be reduced by gathering more information. As an example, the knowledge regarding the geological heterogeneity can increase by conducting borings and other field tests. The epistemic uncertainty can thus be reduced by collecting more data. However, detailed investigations of the total geological and hydrogeological conditions at a site before construction is, due to financial limitations, most often not possible and limited amounts of data must form the basis for the hydrogeological prognoses (Kadefors & Bröchner, 2008).

Uncertainties must be accounted for, and models that are accessible and transparent for both policy makers and stakeholder should be the aim (Saltelli & Funtowicz, 2014). There are mainly two approaches used for handling the uncertainty in underground projects: the deterministic approach and the stochastic approach (Sturk, 1998). The deterministic approach is the most traditional. The deterministic approach uses data from measurements and properties at unsampled locations are often determined by interpolating the data. The deterministic approach usually deals with uncertainty by adding a safety margin or a factor of safety (Alén, 1998; Freeze et al., 1990). There are two major criticisms to this approach: first, the regionalized variables (or variables of interest) can vary irregularly in space and can thus not be determined by interpolation, second, values at unsampled locations are subjected to uncertainty (Dagan, 1982). Within the work of this PhD project, uncertainties are mainly accounted for by stochastic modeling. The stochastic approach or the reliability approach use probability theory to quantify the uncertain parameters within a model. Stochastic models aim at given prognoses for all possible outcomes and to assess the probability for these. With this approach, the input parameters to the model are represented by probability density functions instead of deterministic values. If an input parameter to a model is associated with uncertainty and is specified as having a distribution of probability, then the analysis requires a stochastic approach that can generate a result with a distribution of probability (Bedford & Cooke, 2001; Freeze et al., 1990). The uncertainty analysis is carried out by representing all input variables with probability distributions and by running the model with Monte Carlo simulations (Figure 6). Monte Carlo simulations facilitates the result being simulated with many iterations, thus the result is calculated many times. For each calculation, a random value from each input distribution is drawn resulting in an output variable including probabilities, and thus quantified uncertainties.

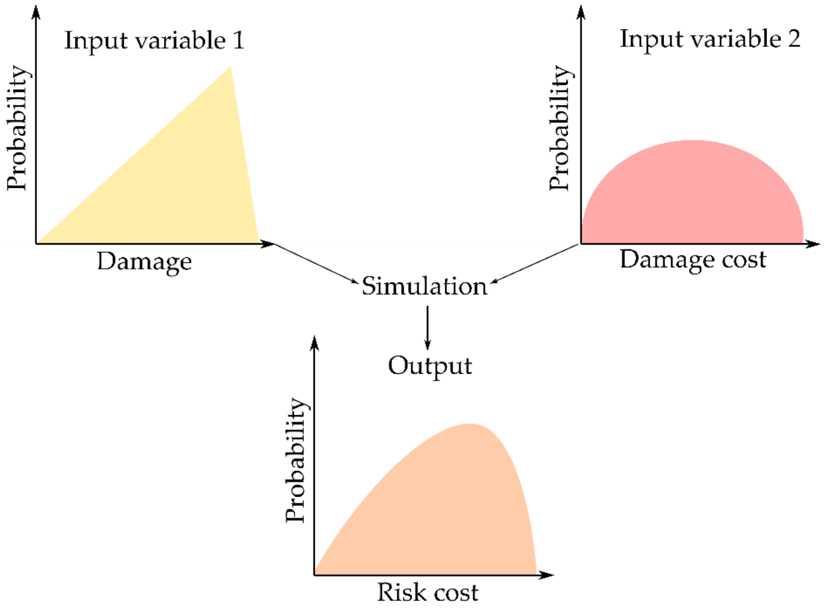

Figure 6. Principle description of stochastic simulation where uncertainties in the input parameters result in uncertainties in the output. The figure is published in paper 1.

2.3.2 Sensitivity analysis

Some input parameters to the model can have a large effect on the output variable. When prioritizing further studies to collect more data, it can be beneficial to know which parameters to focus on since reducing the uncertainty of such parameter can have a large impact on the overall uncertainty of the model output. What parameters that has the largest impact on the model output can be investigated y performing a sensitivity analysis. A sensitivity analysis can be performed both locally (specific parameters being analyzed) or globally (all parameters are analyzed). If possible, it is recommended to conduct a global analysis (Saltelli et al., 2006). A common global approach is to calculate Pearson correlation coefficients for the input and output variables (Hamby, 1994). This approach assumes a linear relationship. If the model is nonlinear, the data can be ranked using the Spearman rank (Iman & Conover, 1979). What method to choose depends on the level of ambition, the computational power available, and the model properties.

2.4 Risk-reducing measures

The most common measure for reducing leakage into the underground facility is sealing measures. Sealing measures for facilities located in bedrock is most often a large part of the overall project budget (Werner et al., 2012). Grouting or concrete lining of the tunnel walls, floor and roof are the most common sealing measures for bedrock facilities. Grouting means that the fractures and openings in the bedrock is filled with grout through pressure injection (Butrón et al., 2010). Grouting can be performed both before and after excavation but pre-excavation grouting is the most common and efficient approach (Stille, 2015; Zetterlund et al., 2011). Pre-grouting is both an expensive and time consuming process (Strømsvik, 2019). In 2012, Grøv and Woldmo (2012) investigated the cost of pre-grouting in relation to leakage into the tunnel in Norwegian tunnels. The result from their study is shown in Figure 7. The rock is most often of high quality in Sweden and concrete lining is therefore seldom used. There are however exceptions, e.g., in areas of low rock quality or when the tunnel roof thickness is too low.

Another common measure is artificial recharge of groundwater which can be used to avoid or limit groundwater drawdown and to maintain stable groundwater levels. Water can be infiltrated directly into the soil and bedrock aquifers via infiltration wells. It is of high importance that the hydraulic conductivity of the aquifer is high for the infiltration to be successful. For infiltration into a bedrock aquifer, it is important that the well screen is located in such a way that the active fracture zones in the rock are utilized. Locating these zones can be difficult and requires knowledge regarding the hydrogeological conditions, especially in areas with multiple aquifers (Andersson & Sellner, 2000). The groundwater level is often increased around the infiltration well. This local high groundwater level may result in risks for flooding of low-lying facilities such as basements. Infiltrating oxygen-rich water may also start a degradation process of wooden foundations (Vatovec & Kelley, 2007).

Risk-reducing measures that reduce leakage or groundwater drawdown both aim at reducing the probability of damage that may be induced by groundwater drawdown. Measures can also be directed directly towards the object at harm with the purpose to reduce the consequences of groundwater drawdown. As an example, the foundations of subsidence sensitive buildings may be reinforced so that no damage can occur due to groundwater lowering. The measures described above can be both proactive and reactive. Examples of proactive measures are pre-excavation grouting with the purpose to reduce leakage, stand by infiltration wells that can be activated in case of groundwater drawdown, or reinforcement measures of building foundations before the start of activities that has the potential to impact the groundwater levels. Examples of reactive measures are extra grouting after excavation, installation of new infiltration wells after groundwater drawdown has occurred, and reinforcement of buildings and/or reimbursement for damages.

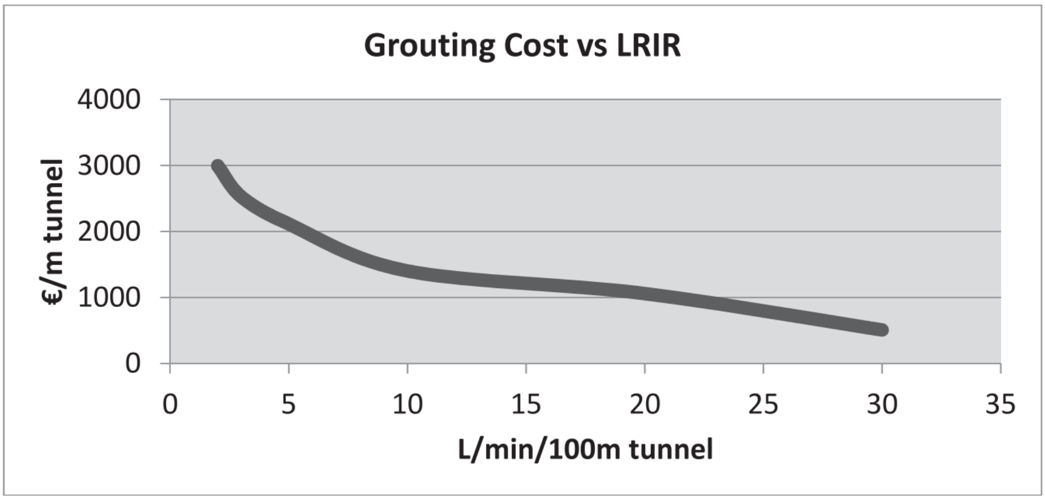

Figure 7. Costs per meters of tunnel in relation to allowable inflow rate in l/min per 100 meters of tunnel (Grøv & Woldmo, 2012).

2.5 Cost-benefit analysis

A cost-benefit analysis (CBA) provides support for decision makers and the result from a CBA cannot be confused with the decision itself. CBA is based on an identification of the positive and negative consequences of a project (e.g., implementing a measure) in the society and aims at comparing these consequences in order to determine if the positive consequences are larger than the negative or the other way around (Figure 8). The analysis is carried out by valuing the positive effects (marginal benefits) and the negative effects (marginal costs) relative a reference alternative. All consequences possible to value are expressed in monetary units. It is important that the costs and benefits are based on the same conditions for the assessment to be correct. As an example, the cost and benefits must be determined using the same reference alternative and be expressed in the same preparatory price. The effects that cannot be expressed in monetary units must as far as possible be described qualitatively and their potential effects on the overall result must be evaluated. CBAs as a method is described in many textbooks and articles such as Boardman et al. (2017) or Johansson and Kriström (2015).

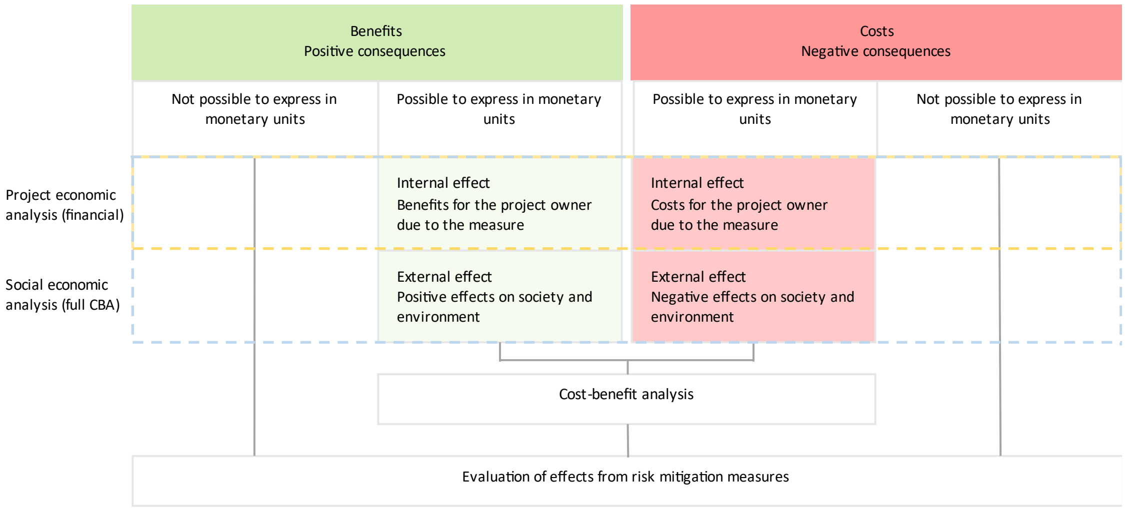

Figure 8. The evaluation procedure of positive and negative effects from risk-mitigation measures. The effects possible to express in monetary units are evaluated using cost–benefit analysis. The effects that are not possible to express in monetary units are described qualitatively. The figure is modified from figure published in paper 1.

A cost-benefit analysis can mathematically be expressed as an objective function that determines the difference between benefits and costs. The objective function for risk-reducing measure alternative *i* can be described as:

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} [B_{i,t}] - \sum_{t=0}^{T} \frac{1}{(1+r_t)^t} [C_{i,t}] \qquad (2)$$

where NPV_i = net present value, which constitutes the present value of the net benefit (in other words, benefits minus costs) of implementing the measure *i*, *T* = time horizon in the number of years *t*, B_t = the benefits of implementing the measure *i* during year *t*, C_t = costs of implementing the measure *i* during year *t*, and *r* = discount rate.

As expressed in the equation for the CBA, the present value of all costs and benefits can be calculated for the decided time horizon. The present value is calculated by a conversion of the costs and benefits by a discount rate. This is carried out in order to consider that costs, and benefits may occur at different times.

A risk-reducing measure alternative is socio economically profitable if the value of the objective function, thus the *NPV*, is positive. The higher the *NPV*, the more profitable. The alternatives are valued in relation to a reference alternative, thus costs and benefits represents positive and negative *changes* in relation to the reference alternative. The reference alternative is often, but not always, defined as not implementing any measure. It is important to be aware that there are several factors that are not considered and thus neglected in the utilitarian framework of a CBA (Aven, 2012). Example of such a factor is laws and norms. In an underground construction context, the project owner is often forced to submit to rules and regulations or terms and conditions. Therefore, practical application of CBA is therefore typically associated with boundary conditions with respect to e.g. legal requirements or risk tolerability criteria.

The CBA for evaluation of profitability of implementing risk-reducing measures can also be complemented with an analysis of the value of additional information i.e., value of information analysis (VOIA) (Back, 2006; James & Freeze, 1993; McNulty et al., 1997; Sundell et al., 2019b; Zetterlund, M. S. et al., 2015). A VOIA is a CBA that compares the cost of collecting more data (information) to the reduced risk of making an erroneous decision when making the choice of what risk-reducing measure alternative to implement. In a VOIA, additional information is only valuable if it changes the preferred decision. Thus, from a strict economic perspective, the collection of more data should only be carried out if the retrieved information is more valuable than the cost of collecting it (Zetterlund et al., 2011).A VOIA can mathematically be expressed as follows:

$$EVI_i = \Phi_{preposterior_i} - \Phi_{prior_i} \qquad (3)$$

where the EVI_i = the expected value of information of the data-collection program *i* expressed in monetary terms; $\Phi_{preposterior\,i}$ = is the calculated net present value (calculated with Equation 2) based on the information that is expected from the new data-collection program *i*; and $\Phi_{prior\,i}$ = is the net present value calculated similarly but based on the present stage of knowledge. The EVI should be compared with the cost of performing the investigation to calculate the expected net value (ENV).

2.5.1 Valuation of consequences

In order to be able to account for all effects of risk mitigation measures, both the project-internal and external consequences must be considered for the CBA. If possible, consequences should be monetized.

There are several methods available for economic valuation of consequences, both market goods and non-market goods. What method to choose for each identified consequence depends on the available data and the possibility to collect data (Freeman et al., 2014). One time saving approach for valuation of consequences constitute the usage of standard values. One example of such values is the Swedish ASEK-system that are used for decisions on investments in the transport sector (STA, 2020). However, it is often the case that such values are not available, then valuations from already existing studies can be used via benefit transfer (Boutwell & Westra, 2013; Boyle & Bergstrom, 1992). Benefit transfer is most often used if it is difficult to conduct primary valuation studies due to time, funding, or data constraints (Johnston et al., 2015). Another approach is to use expert elicitation (Gosling, 2018; O'Hagan et al., 2006). Conducting primary valuation studies is another option. Primary valuation studies include market price-based approaches (see for example the developed damage-cost model in Sundell et al. (2019a)), production function-based approaches, revealed-preference methods, and stated-preference methods (Freeman et al., 2014). Not all consequences can be expressed quantitatively in monetary units. To make sure that these consequences are not overlooked, they must instead be described qualitatively, and their effects on the overall result must be evaluated.

2.5.2 Discounting

Discounting is a concept that is used in all socio-economic calculations. It means that the costs and benefits are recalculated with an interest rate in order to account for the fact that different consequences may occur at different times. The discount rate is used to recalculate all the costs and benefits to a net present value. There are mainly two approaches for discounting: the descriptive approach and the prescriptive approach. The descriptive approach bases the discount rate on how people are behaving justifying the usage of market interest rates from capital markets. The prescriptive approach instead argues that capital markets are not perfect and therefore unsafe to use. With this approach the discount rate is instead based on ethical principles of e.g., not favoring present generations over future ones. In general, the prescriptive approach favors a lower discount rate than the descriptive approach (Söderqvist, 2006). The discount rate can significantly influence the result of a CBA both regarding the net present value and the ranking of the alternatives. What discount rate to choose depends on the values and principles within the framework in which the CBA is performed. It can be beneficial to calculate the *NPV* with several discount rate in order to analyze how sensitive the *NPV* is to a changing discount rate (Johansson & Kriström, 2015).

The Swedish transport administration recommend a discount rate of 3.5 % for socio-economic calculations within the field of transport. This value is based on studies of market interests and productivity in the society (STA, 2020). The so-called Stern-report (Stern, 2007) recommends a discount rate of 1.4 % for socio-economic calculations of climate effects and measures against climate change. Low, and sometimes falling rates over time is sometimes recommended when moral aspects of future generations are considered or when there are large uncertainties regarding the future conditions. Different discount rates can also be used depending on the time frame of the project where discount rates based on the market interest can be used for shorter time frames while lower interest rates are used for longer time periods (Söderqvist, 2006).

2.6 Environmental legislation and legal permits

Water operations is a legal concept that includes construction in water, water utilities, dewatering of groundwater resources and any water level changing operation. Water operations are covered under Chapter 11 in the Swedish environmental code. Groundwater diversion and thus underground constructions are as a rule obliged to apply for a permit (Chapter 11, 9§) (Naturvårdsverket, 2008). There is however an exception to the requirements regarding permits. Chapter 11, paragraph 12 states that “Permits referred to in this Code shall not be required where public or private interests are manifestly not harmed by the impact of water operations on water conditions." (Lewis et al., 2013). Conducting any water operation without a permit when needed is an offense. A permit also protects the project from new requirements in the future.

The permit is obtained through the Land- and Environmental court. Several of the requirements in the environmental code must be fulfilled in order for the operation to obtain a permit (Michanek & Zetterberg, 2012). Unlike many other legal procedures, the burden of proof is inverse for environmental cases. This means that the project owner must provide the evidence needed for the processing of the application. In the proceedings, the overall goal of the environmental code in chapter 1 is considered together with the rules of considerations in chapter 2 and the management provisions in chapters 3 and 4.

Terms and conditions are most often included in the permit in order to ensure that the project meets the goals and requirements of the environmental code (Chapter 16, 2§). Both the permit and its terms and conditions aim at limit harmful impact on humans and the environment. For groundwater diversion in urban environments, the damage risk is in focus. The design of the terms and conditions may have a significant impact on the possibility to pursue an efficient supervision, to objectively determine whether a violation has occurred, and for the project owner to follow the project (Prop. 1997/98:45 part 1, p.171). The terms and conditions can be separated in to two categories: the general and the specific. De general terms and conditions bind the project owner to the commitments stated in the permit application. The specific terms and conditions are commonly formulated as limits, e.g. maximum allowed leakage (Michanek & Zetterberg, 2012).

The most common types of terms and conditions for underground constructions in Sweden are limitations for leakage and groundwater drawdown. It is also common to have a term stating that the project owner should artificially recharge water into the aquifers in order to reduce the risk of damaging environmental impacts. The terms and conditions for leakage and drawdown are often formulated stricter for the operation phase compared to the construction phase. In this way, the project owner has some flexibility in fulfilling the terms without being forced to stop the construction. The division of requirements for the construction phase and the operational phase is also due to the reduced uncertainties in the operational phase once the whole tunnel is excavated. It is most common to have a combination of several terms and conditions (Merisalu & Rosén, 2020).

What risk-reducing measures that may be possible to implement in order to fulfill the terms and conditions depends on the formulation of the these. In order to comply with a condition formulated as a maximum allowed leakage into the underground facility, the project owner must invest in sealing measures. In order to comply with a condition formulated as maximum allowed groundwater drawdown, the project owner can invest in both sealing measures and infiltration wells. for terms formulated as the project owner is obliged to implement measures to avoid damages, the project owner can invest in both sealing measures, infiltration wells and reinforcement measures. How the terms and conditions are formulated is thus affecting the project owners' options for risk-reducing measures.

According to Chapter 2, paragraph 7 in the Swedish environmental code, when the proportional principle shall be applied, a measure's ability to prevent or limit damages or inconveniences shall be weighed against the cost for implementing the measure. The cost for fulfilling the rules of consideration in Chapter 2 shall be motivated from an environmental point of view. This means that the proportion of the benefits for human health and the environment that comes from implementing the measure and the resulting implementation cost must not be unreasonable (prop. 1997/98:45, part 2, p.24–25). The same proposition also states that it is the project owner's responsibility to show that the cost for implementing a measure is unreasonable or unmotivated from an environmental point of view. There are two main factors that should be considered for the application of the proportional principle. The first one is the character of the inconvenience such as the level of danger or the extent. The other one is the sensitivity of the area affected by the project (prop. 1997/98:45, part 2, p.25). For underground constructions in urban environments, the sensitivity of the area can e.g., be dependent on the cultural and economic value of the subsidence sensitive buildings within the area of influence of the tunnel.

There is no guidance in the proposition for the environmental code regarding how the proportional principle should be applied. Therefore, it is up to each court to interpret the law text when applied. According to Söderqvist et al. (2015), the proportionality principle is often not applied in a structured manner in cases for an environmental permit. When applied, it is not always transparent in the written verdict how it has been applied. The same is true for permit cases for underground construction and thus groundwater diversion (Merisalu & Rosén, 2020).

In 2017, the Swedish environmental protection agency published a report written by Nordzell et al. (2017) on the topic on how to apply the proportionality principle in environmental cases. In order to investigate whether a measures implementation cost is reasonable, the writers suggest that the cost is investigated in two steps. In the first step, the measures' socio-economic costs and benefits should be assessed. This step aims at investigating if a measure is socio-economically profitable to implement or not. A cost-benefit analysis (CBA), that expresses both the costs and benefits in monetary units is recommended for this assessment. For step 2, a business-economic proportionality assessment is carried out from an industry perspective. The focus in this step is to determine how the cost for the measure is distributed among actors in the society and to what degree these actors can manage the costs. Whether a measure is reasonable to implement can e.g., be dependent on how large part of the production cost that the measure constitutes and to what degree the costs for the measure is distributed among the project owner costumers and contractors. The result from step 1 and 2 should both be weighted together when applying the proportionality principle.

3 Summary of appended papers

In this section, the two papers (one published and one manuscript) written within this PhD project so far will be summarized.

3.1 Paper 1

The first paper (Merisalu et al., 2021) presents a comprehensive description of the challenges associated with decisions on hydrogeological risk mitigation in underground construction together with commonly used approaches and methods for handling these challenges. Finally, the paper presents a novel framework for probabilistic risk-based cost–benefit analysis (CBA) for decision support on the mitigation of hydrogeological risks in underground constructions where the presented methods are combined and incorporated for a sustainable and economically efficient risk management process. The framework uses the ISO standard framework (ISO, 2018) as a point of departure. The developed framework handles the complex nature of environmental impact in the surrounding of the facility as well as the evaluation of risk-reducing measures. Additional novelty, compared to e.g. Sundell et al. (2015), constitutes the usage of a full CBA where both the project's internal costs and benefits as well as the economic, environmental, and social externalities of implementing risk-reducing measures are included. Furthermore, the framework accounts for the inevitable and changing uncertainties associated with underground constructions by incorporating an iterative process of continuous updating of the risk analysis and the risk evaluation models as new information is retrieved.

The framework (Figure 9) starts with defining the scope and criteria for the project. The next step is to identify all possible risks that leakage into the underground construction may give rise to. Once all risks have been identified, risk-reducing measure alternatives relevant for preventing or reducing these risks are defined. The risk is in a next step estimated by means of data, models, simulations, an expert elicitation, for all defined risk-reducing measures. This is followed by the risk evaluation, which by means of CBA evaluates the positive and negative consequences of the risk-reducing measure alternatives. In order to evaluate what input parameters to the model that has the largest impact on the result, a sensitivity analysis is carried out. In a following step, the CBA may be updated by means of VOIA in order to evaluate whether to implement a risk-reducing measure alternative or collect more data and thus postpone the decision on implementing a measure. Whatever decision is made, more data are continuously collected and processed and used to update the models. This loop of risk analysis, risk evaluation, decision making, and monitoring will continue throughout the project allowing for continuous updating of the models.

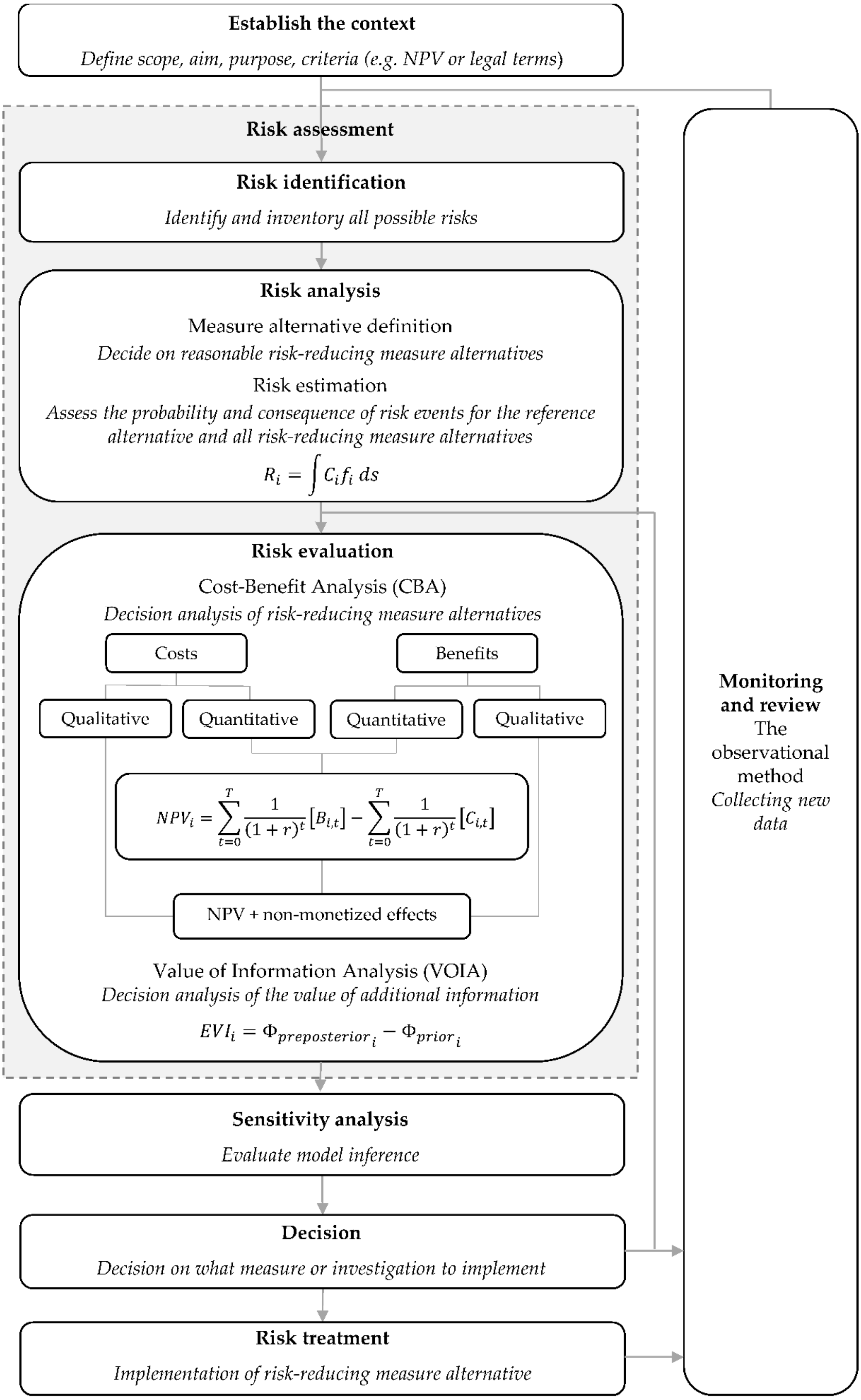

Figure 9. The hydrogeological risk-management framework for decision support on risk-reducing measure alternatives.

3.2 Paper 2

In this paper, the framework presented in the first paper is applied on a case study. The case study constitutes the road tunnel Bypass Stockholm located in Stockholm, Sweden (Figure 10). The tunnel was under construction when the case study was carried out. The hydrogeological conditions in the area can be simplified as three main aquifers: a lower confined aquifer in the fractured gneiss bedrock, a lower confined aquifer in glacial till or glaciofluvial material located on top of the bedrock and below a layer of clay, and an upper unconfined aquifer in course material (often filling in the built-up areas). The objects at risk within the tunnel's area of influence mainly constituted facilities sensitive to subsidence. The risk analysis therefore focused on subsidence damages on buildings, garden areas, paved surfaces, and pipes.

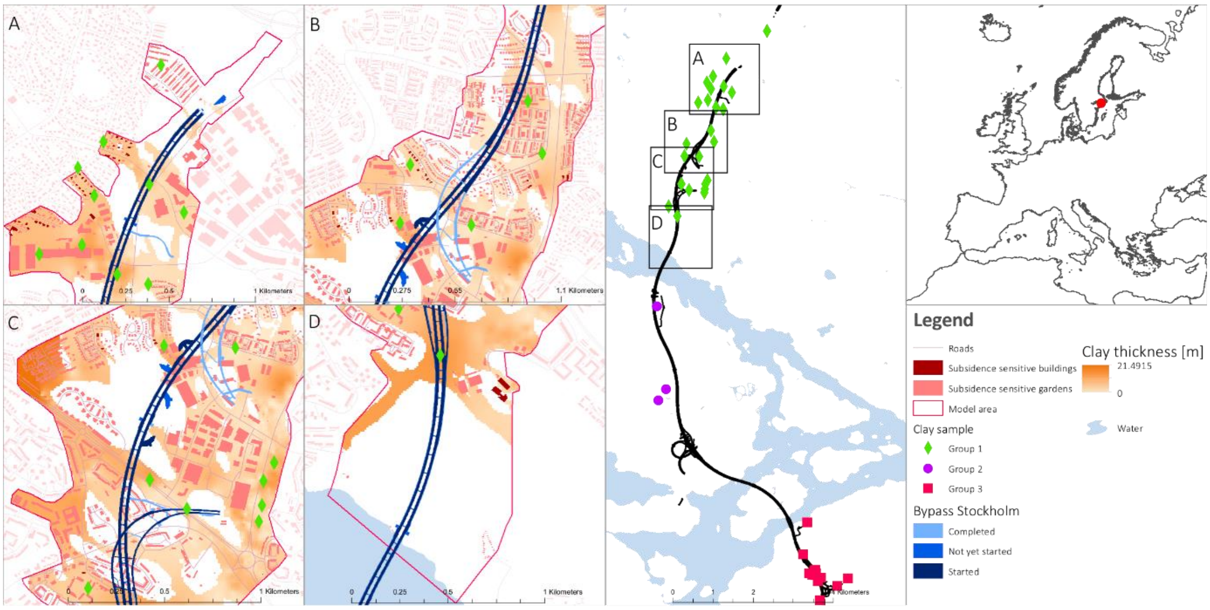

Figure 10. Map of the model area, including the location of the tunnel in three blue colors representing the status of the project (completed, not yet started, and started) at the time of the study. The location of subsidence sensitive buildings, buildings with subsidence sensitive garden areas, and roads, are also indicated. The DEM of the clay thickness as well as the location of the oedometer tested clay samples used as input for the subsidence calculations are also displayed. The figure is included in paper 2.

The main scope of the study was to provide support to decision makers in the tunnel-project for decisions on hydrogeological risk-reducing measures. for this purpose, five risk-reducing measure alternatives (including one reference alternative) The alternatives are all based on different combinations of sealing-, artificial recharge-, and reinforcement strategies. Two sealing strategies were considered relevant for this study. The first sealing strategy (Original) is based on the original sealing strategy specified by the project owner in the planning phase of the project. The second sealing strategy (Modified) constitutes a sealing design assessed necessary to implement to fulfill the leakage criterion in the legal permit. The first sealing strategy was based on the accumulated knowledge of the hydrogeological conditions in the bedrock from the planning phase of the project, before excavation started in 2018. The second strategy was based on knowledge regarding the conditions that was revealed during excavation and thus constituted the accumulated knowledge from the planning phase and the excavation phase until autumn 2019 when this study was conducted. The artificial recharge is divided into no recharge (No recharge) or recharge necessary to counteract groundwater drawdown (Recharge). One alternative did also include reinforcement measures on subsidence sensitive buildings.

The cost (implementation costs) and benefits (here reduced damage risk) were evaluated. With a cost-benefit analysis. Three discount rates were used, 0%, 1.4% and 3.5%, respectively. The 0% discount rate was chosen to reflect the ethical principles of not at all favoring present generations over future ones, the 1.4% reflects the average discount rate used in the Stern Review on Climate Change (Stern, 2007), implying a relatively strong recognition of inter-generational equity, and the 3.5% rate suggested in the Swedish Transport Administration Guidelines for cost-benefit analysis (STA, 2020), based on productivity in society. Some of the risk-reducing measure alternatives include measures with reoccurring costs during the life expectancy of the tunnel, e.g. artificial recharge. The time horizon used for these measures was set to 120 years. Several models (groundwater drawdown, subsidence, implementation costs) and methods (data and expert elicitation) for valuation of consequences were used in combination to calculate the net present value (*NPV*) of the different alternatives.

The costs, benefits and the net present value (*NPV*) for the discount rate 0, 1.4 and 3.5 % are presented for the 5th, 50th and 95th percentile in Figure 11. The benefits are highest for alternative 2 and 3 (median value around 165 MSEK). This is due to the artificial recharge in both these alternatives that maintain stable groundwater levels subsequently resulting in no subsidence damages. The choice of discount rate does not have a large impact on the benefits indicating that the subsidence occurs shortly (within a few years) after the initiated groundwater drawdown. This corresponds well with the measurements of subsidence performed continuously as a part of the environmental monitoring program of the project. The investment cost is highest for risk-reducing measure alternative 3 (median value around 7000 MSEK). Followed by alternative 1 (median value around 1700 MSEK) and 2 (median value around 660 MSEK) and last 4 (median value around 4 MSEK). The discount rate impact the costs for both alternative 2 and 3 due to the recurring costs for artificial recharge included in both alternative 2 and 3 ($T=120$).The *NPV* is highest (median value around 0 MSEK) for alternative 4 followed by alternative 2 (median value around -630 MSEK), 1 (median value around -1692 MSEK) and last 3 (median value around 7140 MSEK). It is important to notice that alternative 3, which has the lowest *NPV*, is the only alternative that fulfills the leakage requirement and cause no damaging impacts.

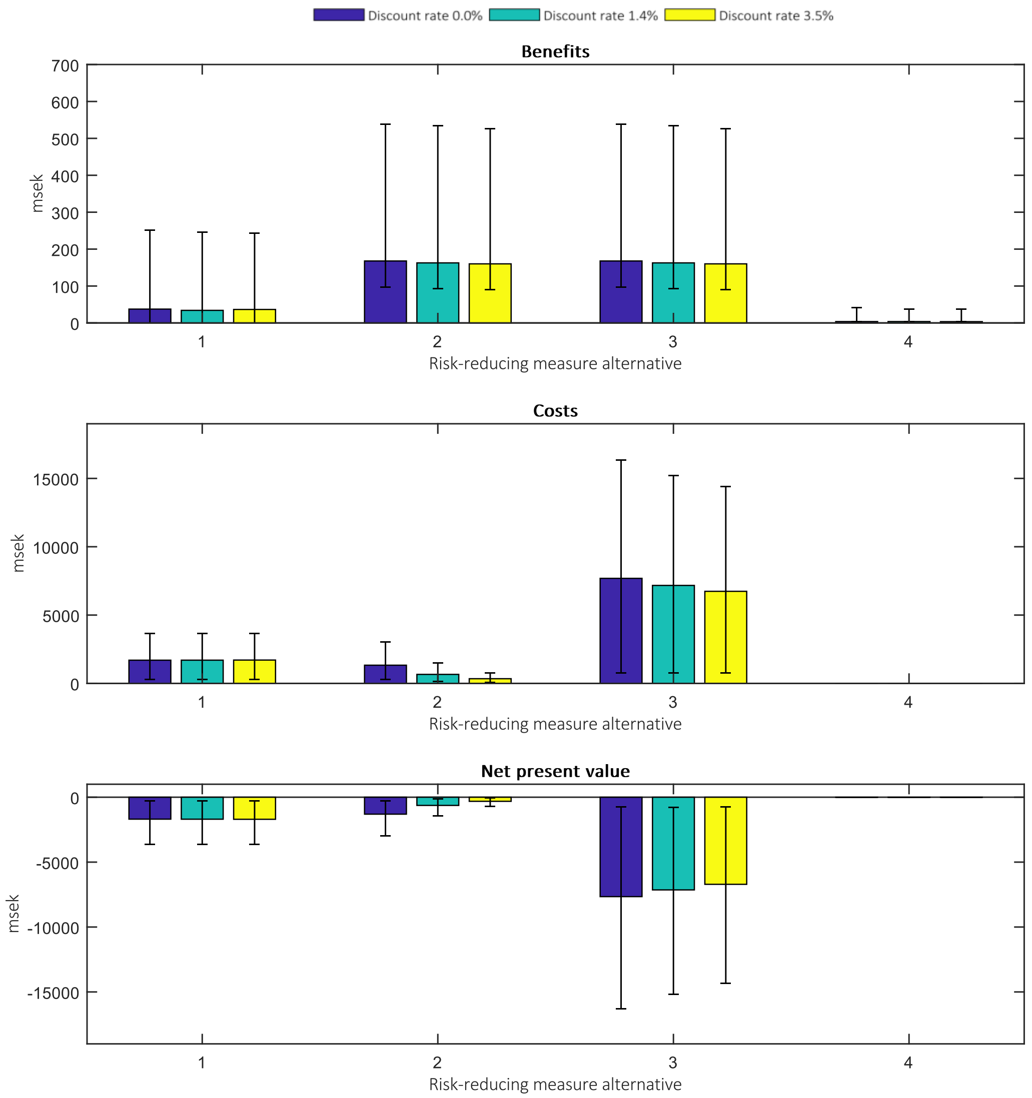

Figure 11. The benefits, costs and NPV in million SEK for the risk-reducing measure alternatives 1-4 and for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile. The figure is included in paper 2.

The main conclusions of this study were:

- The usage of expert elicitation in combination with data and empirical models enables the cost-benefit analysis of risk-reducing measure alternatives when data is limited.
- The CBA in the case study showed that the net benefits in the form of reduced economic damage-risk is small relative the implementation costs for risk-reducing measures due to the few objects at risk and the large implementation costs that sealing measures entails.
- The cost of implementing the risk-reducing measure alternative 3 that fulfills the legal requirements and prevent damages (7000 MSEK) are not proportional to the benefits obtained (165 MSEK). Billions of SEK taxpayers' money are spent on unnecessary expenses to fulfill legal requirements without societal benefits.
- The result is only representative for this case study, its benefits and costs are thus contextual. In another context, with e.g. more or other objects at risk, the result could be different.

4 Conclusions and further work

This chapter of the thesis first presents a summary on the work so far with respect to the aim and objectives. Major conclusions are then provided regarding output and limitations as well as some broader implications concerning application of the developed risk management framework. Finally, further work within the PhD project is also described.

4.1 Meeting aim and objectives

This thesis presents a literature review of the research area *Hydrogeological risks in underground construction* and a summary of the two papers produced up to date in this PhD-project. The overall aim of the research project is to develop the methodology for assessment of hydrogeological risks in underground infrastructure projects, considering the whole chain of events from leakage to damage, and considering both the economic, environmental, and social effects of risk-mitigation measures in the risk evaluation process. The overall aim has so far been partly fulfilled through four different objectives.

The first objective was to develop a comprehensive framework for management of hydrogeological risks. The resulting framework was presented in paper 1. This framework embraces the whole cause-effect chains from leakage to damage. It also addresses the spatial difficulties associated with large scale (km^2) groundwater impacts from leakage into underground constructions as well as the time-dynamic conditions with different level of uncertainty throughout a project.

The second objective was to develop methods for coupling of models representing the various events in the cause-effect chain. The second paper fulfills the second objective by the development and demonstration of application of models for analysis of the events in the cause-effect chain. The paper also demonstrates methods for how these models must be coupled for the risk analysis and risk evaluation.

The third objective was to identify internal and external consequences of risk mitigation measures and the fourth objective was to apply this framework in a case study to exemplify its usage. The second paper partly fulfills the third objective and fulfills the fourth objective. Paper two presents a case study in which the framework presented in paper 1 is applied. Consequences of risk mitigation measures are identified and valued economically. However, the case study only focuses on risks associated with groundwater induced subsidence and does not cover any other risks that may arise due to groundwater drawdown, e.g., damages to groundwater dependent ecosystems or crop yield losses. There are several limitations associated with the models used for subsidence calculations in this study. First, the model for groundwater drawdown is based on groundwater level data from the monitoring program of the project and expert elicitation. Second, the subsidence is calculated with a simple one-dimensional elasto-plastic compression model developed by Sundell (2018). In a more detailed study, the groundwater drawdown model and the subsidence calculations may be updated to numerical models. A more advanced subsidence model, based on numerical calculations and systematic sensitivity studies, is now being developed at the Division of geology and geotechnics at Chalmers University of Technology and may be used for the risk analysis of subsidence damage in future studies. Another limitation is that this study only accounts for project internal consequences from the risk mitigation measures e.g., investment costs for sealing measures and maintenance costs. In order to fully cover both the economic, environmental, and social effects of mitigation measures, both the project internal and the external consequences must be considered, as indicated in Figure 8. Examples of external consequences are CO_2 emissions from sealing measures.

4.2 Main conclusions

The main conclusions from this PhD-project are:

- Groundwater drawdown induced by leakage into underground constructions can result in a wide variety of risks. These risks as well as the consequences of implementing measures to reduce these risks must be considered for decisions on implementing mitigation measures.
- The developed framework facilitates risk management of impact from leakage into underground facilities that considers both the project's internal costs and benefits as well as the economic, environmental, and social externalities of implementing risk-reducing measures.
- The application of the developed framework on a case study helped to demonstrate the applicability of the framework and to identify and highlight the issues that need further investigation and development for comprehensive management of hydrogeological risks in underground constructions.
- Future research on implementing the framework in various hydrogeological settings with different types of objects at risk is needed to evaluate and develop the framework further.
- Relevant models that represent all parts of the cause-effect chain of leakage to damage must be adapted, integrated, and developed in order to enable better predictions of the hydrogeological system's response to leakage and thus improve the risk analysis.
- A major value of applying the risk management framework presented here is that it introduces a holistic process that requires that risks and other conditions that otherwise may have been ignored are acknowledged. That process may be just as important as the quantitative results from the risk analysis and risk evaluation steps.

4.3 Further work

The next study that will be carried out within this PhD-project will cover the identification and economic valuation of external consequences of illegal groundwater disturbances in an urban underground project. The rail tunnel Västlänken with focus on the station area Haga will be used as a case study. This area is densely populated and contains both residential and commercial buildings. Both roads, bicycle lanes, pedestrian paths and tram rails run through the area. Parts of the tunnel and station will be built in an open shaft. The traffic in the area must be redirected while the construction in the open shaft is ongoing. The consequences will be identified through a workshop with experts in underground construction and city planning. The valuation of the consequences will be carried out in collaboration with environmental economists. Within the framework for this study, the possible measures to reduce the risk of causing illegal groundwater disturbances will also be identified, also using expert elicitation. A similar approach as the method presented in paper 2 will be used but the risk evaluation will be more comprehensive due to the inclusion of external consequences.

The second study within this PhD-project will cover the topic of Value Of Information Analysis (VOIA). The focus will be on information that can improve the hydrogeological prognoses in underground construction. Examples of such information are: borehole logs and rock classifications, soils samples and pumping tests in rock and soil. The developed framework in paper 1 is used here with emphasis on the updating of the models with new information. A case study will also be used for this study.

A third study in this PhD-project will use the developed framework to evaluate the cost and benefits of risk-reducing measures in a rural area containing other objects at risk compared to the previous studies performed in urban areas. The objects at risk in this study will constitute groundwater dependent ecosystems and agricultural areas. Groundwater modelling will be used as an important step in this analysis to assess the probability of damaging groundwater drawdown. A case study will also be used in this study.

A fourth study in this PhD-project relates to the uncertainty in the hydrogeological predictions. In order to get a valid result from flow models and thus subsequently risk estimations, a geological model that represents the architecture and heterogeneity of the subsurface must be used as an input. Several geostatistical methods have been developed to estimate and simulate the soil strata at unsampled locations. In complex geological environments where the stratigraphy cannot be simplified into continuous layers, category-based methods, e.g., indicator kriging, transitions probability geostatistics and multiple point statistics, must be used. However, what method to choose is not always clear. The purpose of this study will therefore be to exemplify the positive and negative aspects with these methods and also present a method for validation of the models. This work has started and the methods will be evaluated based on their performances in a case study where the geology consists of several interbedded isolated and connected permeable layers within glaciomarine clay deposits.

5 References

Alén, C. (1998). *On probability in geotechnics. Random calculation models exemplified on slope stability analysis and ground-superstructure interaction.* (Doctoral thesis), Chalmers University of Technology, Gotenburg.

Andersson, P., & Sellner, A. (2000). *Tätning av bergtunnlar–förutsättningar, bedömningsgrunder och strategi vid planering och utformning av tätningsinsatser*. Retrieved from https://trafikverket.ineko.se/Files/sv-SE/10421/RelatedFiles/2000_101_tatning_av_bergtunnlar.pdf

Attanayake, P. M., & Waterman, M. K. (2006). Identifying environmental impacts of underground construction. *Hydrogeology Journal, 14*(7), 1160-1170.

Aven, T. (2012). *Foundations of risk analysis*: John Wiley & Sons.

Back, P.-E. (2006). *Value of information analysis for site investigations in remediation projects.* (Dissertation/Thesis), Chalmers University of Technology,

Bedford, T., & Cooke, R. (2001). *Probabilistic risk analysis: foundations and methods*: Cambridge University Press.

Boardman, A. E., Greenberg, D. H., Vining, A. R., & Weimer, D. L. (2017). *Cost-benefit analysis: concepts and practice*: Cambridge University Press.

Boone, S. J. (1996). Ground-movement-related building damage. *Journal of geotechnical engineering, 122*(11), 886-896.

Boutwell, J. L., & Westra, J. V. (2013). Benefit transfer: A review of methodologies and challenges. *Resources, 2*(4), 517-527.

Boyle, K. J., & Bergstrom, J. C. (1992). Benefit transfer studies: myths, pragmatism, and idealism. *Water resources research, 28*(3), 657-663.

Burbey, T. J. (2002). The influence of faults in basin-fill deposits on land subsidence, Las Vegas Valley, Nevada, USA. *Hydrogeology Journal, 10*(5), 525-538.

Burgman, M. (2005). *Risks and decisions for conservation and environmental management*: Cambridge University Press.

Butrón, C., Gustafson, G., Fransson, Å., & Funehag, J. (2010). Drip sealing of tunnels in hard rock: A new concept for the design and evaluation of permeation grouting. *Tunnelling and Underground Space Technology, 25*(2), 114-121.

Cashman, P. M., & Preene, M. (2001). *Groundwater lowering in construction: A practical guide*: CRC Press.

Einstein, H. H., & Baecher, G. B. (1983). Probabilistic and statistical methods in engineering geology. *Rock mechanics and rock engineering, 16*(1), 39-72.

Fischhoff, B. (1995). Risk perception and communication unplugged: twenty years of process 1. *Risk Analysis, 15*(2), 137-145.

Freeman, A. M., Herriges, J. A., & Kling, C. L. (2014). *The measurement of environmental and resource values: theory and methods*: Routledge.

Freeze, R. A., Massmann, J., Smith, L., Sperling, T., & James, B. (1990). Hydrogeological decision analysis: 1. A framework. *Groundwater, 28*(5), 738-766.

Garshol, K. F. (2003). *Pre-excavation grouting in rock tunneling*: MBT, International Underground Construction Group.

Gosling, J. P. (2018). SHELF: the Sheffield elicitation framework. In *Elicitation* (pp. 61-93): Springer.

Graffner, O. (2007). *Miljöuppföljning bergtunnelsprojekt* (2007:2). Retrieved from Borlänge, Sweden:

Griffiths, D., & Fentont, G. A. (2007). The random finite element method (RFEM) in steady seepage analysis. In *Probabilistic Methods in Geotechnical Engineering* (pp. 225-241): Springer.

Grøv, E., & Woldmo, O. (2012). Modern pre-grouting technology in Norway. In *Grouting and Deep Mixing 2012* (pp. 805-815).

Gustafson, G. (2012). *Hydrogeology for rock engineers*: BeFo Stockholm, Sweden.

Hamby, D. M. (1994). A review of techniques for parameter sensitivity analysis of environmental models. *Environmental monitoring and assessment, 32*(2), 135-154.

Hernández-Espriú, A., Reyna-Gutiérrez, J. A., Sánchez-León, E., Cabral-Cano, E., Carrera-Hernández, J., Martínez-Santos, P., . . . Colombo, D. (2014). The DRASTIC-Sg model: an extension to the DRASTIC approach for mapping groundwater vulnerability in aquifers subject to differential land subsidence, with application to Mexico City. *Hydrogeology Journal, 22*(6), 1469-1485.

Huggenberger, P., Epting, J., Affolter, A., Butscher, C., Fäh, D., Gechter, D., . . . Zidane, A. (2011). Urban Geology: Process-Oriented Concepts for Adaptive and Integrated Resource Management. In P. Huggenberger & J. Epting (Eds.), (pp. 95-191). Basel: Springer Basel.

Iman, R. L., & Conover, W. J. (1979). The use of the rank transform in regression. *Technometrics, 21*(4), 499-509.

ISO. (2018). *ISO 31000: Risk Management: Principles and Guidelines*: ISO.

James, B. R., & Freeze, R. A. (1993). The worth of data in predicting aquitard continuity in hydrogeological design. *Water resources research, 29*(7), 2049-2065.

Johansson, P.-O., & Kriström, B. (2015). *Cost-benefit analysis for project appraisal*: Cambridge University Press.

Johnston, R. J., Rolfe, J., Rosenberger, R. S., & Brouwer, R. (2015). *Benefit transfer of environmental and resource values* (Vol. 14): Springer.

Kadefors, A., & Bröchner, J. (2008). Observationsmetoden i bergbyggande: Kontrakt och samverkan. *SveBeFo Rapport K, 28*.

Kaplan, S., & Garrick, B. J. (1981). On the quantitative definition of risk. *Risk Analysis, 1*(1), 11-27.

Kasperson, R. E., Renn, O., Slovic, P., Brown, H. S., Emel, J., Goble, R., . . . Ratick, S. (1988). The social amplification of risk: A conceptual framework. *Risk Analysis, 8*(2), 177-187.

Kitterød, N.-O., Colleuille, H., Wong, W., & Pedersen, T. (2000). Simulation of groundwater drainage into a tunnel in fractured rock and numerical analysis of leakage remediation, Romeriksporten tunnel, Norway. *Hydrogeology Journal, 8*(5), 480-493.

Kværner, J., & Snilsberg, P. (2008). The Romeriksporten railway tunnel—drainage effects on peatlands in the lake Northern Puttjern area. *Engineering geology, 101*(3), 75-88.

Kværner, J., & Snilsberg, P. (2013). Hydrogeological impacts of a railway tunnel in fractured Precambrian gneiss rocks (south-eastern Norway). *Hydrogeology Journal, 21*(7), 1633-1653.

Lewan, E., & Linnér, H. (2008). *Simulering av transpiration från jordbruksgrödor vid grundvattensänkning*.

Lewis, J., Sjöström, J., Höök, M., & Sundström, B. (2013). The Swedish model for groundwater policy: legal foundations, decision-making and practical application. *Hydrogeology Journal, 21*(4), 751-760. doi:10.1007/s10040-013-0966-3

Lindskoug, N.-E., & Nilsson, L.-Y. (1974). *Grundvatten och byggande*. Retrieved from https://core.ac.uk/download/pdf/78626653.pdf

López-Fernández, C., Prieto, D. A., Fernández-Viejo, G., Pando, L., & Fernández, E. C. (2012). Surface subsidence induced by groundwater drainage tunneling in granite residual soils (Burata Railway Tunnel, Spain). *Journal of Geotechnical and Geoenvironmental engineering, 139*(5), 821-824.

Lundman, P. (2011). *Cost management for underground infrastructure projects: A case study on cost increase and its causes.*

McNulty, G., Deshler, B., & Dove, H. (1997). *Value of information analysis-Nevada test site*. Retrieved from

Merisalu, J., & Rosén, L. (2020). *Formulation of terms and condition for groundwater diversion when constructing below the ground surface* (ACE 2020:11). Retrieved from https://research.chalmers.se/publication/516949/file/516949_Fulltext.pdf

Merisalu, J., Sundell, J., & Rosén, L. (2021). A Framework for Risk-Based Cost–Benefit Analysis for Decision Support on Hydrogeological Risks in Underground Construction. *Geosciences, 11*(2), 82. doi:https://doi.org/10.3390/geosciences11020082

Michanek, G., & Zetterberg, C. (2012). *Den svenska miljörätten*: Iustus förlag.

Molinero, J., Samper, J., & Juanes, R. (2002). Numerical modeling of the transient hydrogeological response produced by tunnel construction in fractured bedrocks. *Engineering geology, 64*(4), 369-386.

Mortellaro, S., Krupa, S., Fink, L., & VanArman, J. (1995). Literature Review on the Effects of Groundwater Drawdowns on Isolated Wetlands. In: Technical Publications.

Mossmark, F., Annertz, K. K., Ericsson, L. O., & Norin, M. (2017). Hydrochemical impact of construction of the western section of the Hallandsås rail tunnel in Sweden. *Bulletin of Engineering Geology and the Environment, 76*(2), 751-769.

Mossmark, F., Hultberg, H., & Ericsson, L. O. (2008). Recovery from groundwater extraction in a small catchment area with crystalline bedrock and thin soil cover in Sweden. *Science of the total environment, 404*(2), 253-261.

Naturvårdsverket. (2008). *Vattenverksamhet, Handbok för tillämpning av 11 kapitlet i miljöbalken* (978-91-620-0157-5). Retrieved from https://www.naturvardsverket.se/Documents/publikationer/978-91-620-0157-5.pdf

Nordzell, H., Scharin, H., & Söderqvist, T. (2017). Att göra rimlighetsavvägningen enligt 2 kap. § 7 miljöbalken. In: Rapport.

O'Hagan, A., Buck, C. E., Daneshkhah, A., Eiser, J. R., Garthwaite, P. H., Jenkinson, D. J., . . . Rakow, T. (2006). *Uncertain judgements: eliciting experts' probabilities*: John Wiley & Sons.

Panthi, K. K., & Nilsen, B. (2010). Uncertainty analysis for assessing leakage through water tunnels: a case from Nepal Himalaya. *Rock mechanics and rock engineering, 43*(5), 629-639.

Persson, J. (2007). *Hydrogeological Methods in Geotechnical Engineering: Applied to settlements caused by underground construction.* (Doctoral Thesis), Chalmers University of Technology, Gothenburg, Sweden. (2665)

Saltelli, A., & Funtowicz, S. (2014). When all models are wrong. *Issues in Science and Technology, 30*(2), 79-85.

Saltelli, A., Ratto, M., Tarantola, S., Campolongo, F., & Commission, E. (2006). Sensitivity analysis practices: Strategies for model-based inference. *Reliability Engineering & System Safety, 91*(10-11), 1109-1125.

Slovic, P. (1987). Perception of risk. *Science, 236*(4799), 280-285.

Slovic, P. (1993). Perceived risk, trust, and democracy. *Risk Analysis, 13*(6), 675-682.

STA. (2020). *Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0*. Retrieved from https://www.trafikverket.se/contentassets/4b1c1005597d47bda386d81dd3444b24/asek-6.1/asek_6_1_hela_rapporten_180412.pdf

Stern, N. (2007). *The economics of climate change: the Stern review*: cambridge University press.

Stille, H. (2015). *Rock grouting: theories and applications*: Befo, Rock Engineering Research Foundation.

Strømsvik, H. (2019). Assessment of High Pressure Pre-Excavation Rock Mass Grouting in Norwegian Tunneling.

Sturk, R. (1998). *Engineering geological information: its value and impact on tunnelling.* (Doctoral Thesis), Royal institute of Technology, Stockholm.

Sundell, J. (2018). *Risk assessment of groundwater drawdown in subsidence sensitive areas.* (Doctoral thesis), Chalmers University of Technology, Gothenburg.

Sundell, J., Haaf, E., Norberg, T., Alén, C., Karlsson, M., & Rosén, L. (2017). Risk Mapping of Groundwater-Drawdown-Induced Land Subsidence in Heterogeneous Soils on Large Areas. *Risk Analysis*.

Sundell, J., Haaf, E., Tornborg, J., & Rosén, L. (2019a). Comprehensive risk assessment of groundwater drawdown induced subsidence. *Stochastic Environmental Research and Risk Assessment, 33*(2), 427-449.

Sundell, J., Norberg, T., Haaf, E., & Rosén, L. (2019b). Economic valuation of hydrogeological information when managing groundwater drawdown. *Hydrogeology Journal, 27*(4), 1111-1130.

Sundell, J., Rosén, L., Norberg, T., Wladis, D., & Alén, C. (2015). *A Framework for Risk Assessment of Groundwater Drawdown Induced Subsidence*. Paper presented at the International Sympisum on Geotechnical Safety and Risk (ISGSR2015), Rotterdam, the Netherlands.

Söderqvist, T. (2006). *Diskontering i samhällsekonomiska analyser av klimatåtgärder* (5618). Retrieved from https://www.naturvardsverket.se/Documents/publikationer/620-5618-2.pdf

Söderqvist, T., Jirvell, G., Malmaeus, M., Roseman, E., Tegeback, A., Gotting, J., . . . Lundmark, L. (2015). Hur tillämpas miljöbalkens rimlighetsavvägning. In: Rapport.

Vatovec, M., & Kelley, P. L. (2007). Biodegradation of Untreated Wood Foundation Piles In Existing Buildings. *STRUCTURE, 54*.

Walker, W. E., Harremoës, P., Rotmans, J., Van Der Sluijs, J. P., Van Asselt, M. B., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated assessment, 4*(1), 5-17.

Werner, K., Onkenhout, J., & Löv, Å. (2012). Effects on hydrogeological and hydrological conditions due to groundwater diversion from rock facilities. Step 1 - Pre study. *SveBeFo Rapport, Swedish Rock Engineering Research*(117).

Wladis, D., & Rosén, L. (2018). *Riskhantering för att undvika driftstörningar i byggskedet i stora infrastrukturprojekt i urban miljö*. Department of Architecture and Civil Engineering, Chalmers University of Technology. Gothenburg, Sweden.

Yoo, C., Lee, Y. J., Kim, S. H., & Kim, H. T. (2012). Tunnelling-induced ground settlements in a groundwater drawdown environment–A case history. *Tunnelling and Underground Space Technology, 29*, 69-77.

Zetterlund, Norberg, T., Ericsson, L. O., & Rosén, L. (2011). Framework for value of information analysis in rock mass characterization for grouting purposes. *Journal of Construction Engineering and Management, 137*(7), 486-497.

Zetterlund, M. S., Norberg, T., Ericsson, L. O., Norrman, J., & Rosén, L. (2015). Value of information analysis in rock engineering: a case study of a tunnel project in Äspö Hard Rock Laboratory. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 9*(1), 9-24.

Zhang, L., & Franklin, J. (1993). *Prediction of water flow into rock tunnels: an analytical solution assuming an hydraulic conductivity gradient.* Paper presented at the International journal of rock mechanics and mining sciences & geomechanics abstracts.