Methodology for Hydrogeological Risk Management of Drilled Steel Pipe Piles

A Case Study of Packhuskajen, Gothenburg

Master’s Thesis in the Master’s Programme Infrastructure and Environmental Engineering

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Cover:
Aerial photo of Packhuskajen (Gothenburg Municipality, n.d.).

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ABSTRACT

Drilled steel pipe piles is a piling method commonly used in areas where it is desirable to avoid e.g., displacement of masses, impacts on the surrounding environment, and large objects in the soil. However, drilled steel pipe piles are associated with the risk of groundwater leakage which could induce a chain of events leading to severe and costly economic, social, and environmental consequences. Hence, it is of interest for both the project owner and society to implement efficient and profitable risk-reducing measures to avoid possible consequences.

Currently there is limited competence in the construction industry regarding how drilled steel pipe piles affects the mechanisms of the hydrogeological system. Therefore, this thesis proposes a methodology integrating a cost-effectiveness analysis (CEA) and the principles of the observational method to the ISO 31000:2018 framework. The methodology is applied to a case study, Packhuskajen, a quay renovation in central Gothenburg which faced leakages through drilled steel pipe piles during the first construction stage. A background study and interviews with employees working with Packhuskajen provided an understanding of the case study which acted as input for the CEA and the observational method. A probabilistic approach is used to manage the uncertain ground conditions when dealing with sub-surface constructions, where expert elicitation is used to quantify costs and uncertainties of risk-reducing measures for the CEA. There is a focus on economic, social, and environmental consequences to promote a sustainable risk management.

Several relevant risk-reducing measures were identified for Packhuskajen, where the result shows that it is profitable to first observe potential groundwater impacts before implementing further measures. Further, the result shows that the proposed methodology can provide a decision support for managing hydrogeological risks associated with drilled steel pipe piles and due to its flexibility, it is also applicable for all types of projects where the ground conditions are uncertain. It also has the potential to reduce the risk of implementing measures when not needed, resulting in both cost- and resource savings.

This thesis constitutes an important documentation of the knowledge gained at Packhuskajen enabling an increased understanding in the construction industry for future projects facing similar risks of how to manage hydrogeological risks associated with drilled steel pipe piles.

Keywords: risk management, groundwater leakage, drilled steel pipe piles, ISO 31000:2018, cost-effectiveness analysis, the observational method

Metodik för hydrogeologisk riskhantering av borrade stålrörspålar
En fallstudie av Packhuskajen, Göteborg
Examensarbete inom mastersprogrammet: Infrastruktur och miljöteknik

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SAMMANFATTNING

Borrade stålrörspålar är ett pålningsalternativ som ofta används i projekt och områden där massundanträngning, påverkan på omgivande miljö samt större hinder i marken vill undvikas. Trots att borrade stålrörspålar har ovannämnda fördelar, är metoden förknippad med risk för grundvattenläckage som kan framkalla en kedja av händelser vilket kan leda till omfattande och kostsamma ekonomiska, sociala och miljömässiga konsekvenser. Därav är det av intresse för både projektägaren och samhället att införa effektiva och lönsamma riskreducerande åtgärder för att undvika dessa konsekvenser.

För tillfället finns det begränsad kunskap i byggbranschen om hur borrade stålrörspålar påverkar det hydrogeologiska systemets mekanismer. Därav föreslår detta examensarbete en metod som integrerar en kostnadseffektivitetsanalys och principerna för observationsmetoden till ISO 31000:2018 ramverket. Denna metod tillämpas på en fallstudie, Packhuskajen, vilket är en kaj som renoveras i centrala Göteborg där det har uppstått läckage genom borrade stålrörspålar under den första etappen. En bakgrundsstudie och intervjuer med anställda på Packhuskajen gav en förståelse av fallstudien som sedan användes som underlag för att genomföra en kostnadseffektivitetsanalys samt applicera observationsmetoden. Ett probabilistiskt arbetssätt används för att hantera osäkerheter associerade med undermarksbyggande, där expertelicitering användes för att kvantifiera kostnader och osäkerheter för de riskreducerande åtgärderna i kostnadseffektivitetsanalysen. Arbetet har ett fokus på ekonomiska, sociala och miljömässiga konsekvenser för att verka för en hållbar riskhantering.

Flera riskreducerande åtgärder relevanta för Packhuskajen identifierades, där resultatet visar att det är lönsamt att först observera en potentiell grundvattenpåverkan innan ytterligare åtgärder införs. Vidare visar resultatet att den föreslagna metoden kan utgöra ett beslutsstöd för att hantera de hydrogeologiska riskerna som kan associeras med borrade stålrörspålar och på grund av metodens flexibilitet, kan den också appliceras på alla typer av projekt med osäkra markförhållanden. Metoden har även potential för att reducera risken av att implementera åtgärder när de inte behövs vilket kan leda till kostnads- och resursbesparingar.

Detta examensarbete utgör en viktig dokumentation av kunskapen som erhållits vid Packhuskajen, vilket leder till en ökad förståelse inom byggbranschen hur man hanterar hydrogeologiska risker förknippade med borrade stålrörspålar i liknande projekt.

Nyckelord: riskhantering, grundvattenläckage, borrade stålrörspålar, ISO 31000:2018, kostnadseffektivitetsanalys, observationsmetoden

Contents

Preface

All good things must come to an end, and so does our five years at Chalmers. This thesis of 30 credits was written as the final part of our master's degrees at Chalmers University of Technology. The thesis was carried out at the department of Architecture and Civil Engineering in collaboration with Skanska Väg och Anläggning. The work has been interesting and rewarding, where we will bring valuable lessons with us into our professional careers working with deep foundations.

The thesis has been supervised by Johanna Merisalu at the division of Geology and Geotechnics and we would like to express our deepest gratitude for sharing your superb expertise and valuable inputs with us. Your positive mindset and encouragement have been inspiring and increased our interest in the subject.

We also want to thank Skanska for the opportunity to use their project Packhuskajen as a case study for the thesis. A warm thank you goes to our supervisor at Skanska, Jan Leinonen, for always being helpful contributing with valuable information. Last but not least, we want to thank Linn Ödlund Eriksson at Sweco, Henrik Andersson at KEA Bygg and Linus Andersson at Skanska for taking your time participating with your expertise.

Gothenburg, May 2022
Clara Alkemark
Julia Christoffersson

1. Introduction

This chapter introduces the thesis where Section 1.1. presents the background. Further the aim and objectives, and limitations of the study are presented in Sections 1.2.-1.3.

1.1. Background

When constructing larger infrastructure projects and buildings, it is often a necessity with deep foundations and ground reinforcement work that transfers the load of the structure to soil layers or rock with sufficient bearing capacity. Piling is a commonly used method for deep foundations, often used for superstructures and other large structures to stabilize the ground when the soil does not have adequate characteristics for bearing and subsidence. Depending on soil layer characteristics, the type of structure, and consideration for the surrounding environment, different types of piles and piling methods can be used. Three commonly used pile types include cohesion piles, frictional piles, and end-bearing piles. The Gothenburg area is widely known for its great depths of sensitive soft clay, where piling in clay is associated with several risks such as displacement of masses (depending on the pile type) and structural disturbances to the soil such as decreased strength, stability, and bearing capacity (Hintze et al., 1997).

Drilled steel pipe piles is a piling method with advantages that can mitigate the common risks associated with piling in clay as mentioned by Hintze et al. (1997). These advantages include minimal displacement of masses, minimal impact on the surrounding environment, decreased vibrations and noise during the installation, and increased precision at the installation resulting in avoidance of large objects in the soil (Bredenberg et al., 2010). However, this method is also associated with several risks including leakage of groundwater. When drilling, the pile is flushed at a high velocity from the inside to remove the soil material, creating a negative pressure at the bore crown (L. Ödlund Eriksson, personal communication, 8th March 2022). Consequently, groundwater can be sucked into the pile together with the soil material, especially in high permeable soil layers. This leakage cannot be avoided. If a confined aquifer is penetrated by a pile during the installation, further leakage may occur since the pressure head of the groundwater could rise above the upper edge of the pile. A leakage can in turn result in a cascade of events which could lead to economic, social, and environmental consequences which can be described with a chain of events.

Figure 1 illustrates an example of a possible cause-effect chain from a leakage of groundwater to damage costs and costs for delays. If a leakage occurs, a groundwater drawdown could develop and in turn result in a pore pressure reduction in the soil. The pore pressure reduction may lead to loss of strength in the soil and therefore induce vertical settlements. Land subsidence in urban and rural areas could lead to expensive external consequences such as damages to the built-up environment and consequently restoration costs. Settlements and resulting damages are a known problem from around the world (Burbey, 2002; Ortega-Guerrero et al., 1999; Karlsrud, 1999 and Olofsson, 1994 as cited in Sundell, 2018). For example, the city of Hanoi experienced extensive foundation failures to infrastructure, old buildings, and residential houses due to a groundwater drawdown induced land subsidence (Dang et al., 2013). In addition, leakages could result in project internal consequences. If the conditions of the water court ruling are violated, due to a potential drawdown, additional costs such as fines could arise (Czemplik, 2014; Aibinu & Jagboro, 2002). Furthermore, the project may need to stop, leading to costs for construction downtime i.e., fines and cost for standstills of machines and personnel. Even though the events of the possible cause-effect chains are known, there are still uncertainties regarding if the event will happen and if so, to what extent. These uncertainties are a result of nature inherent variability and a lack of knowledge of the hydrogeological system (Burgman, 2005).

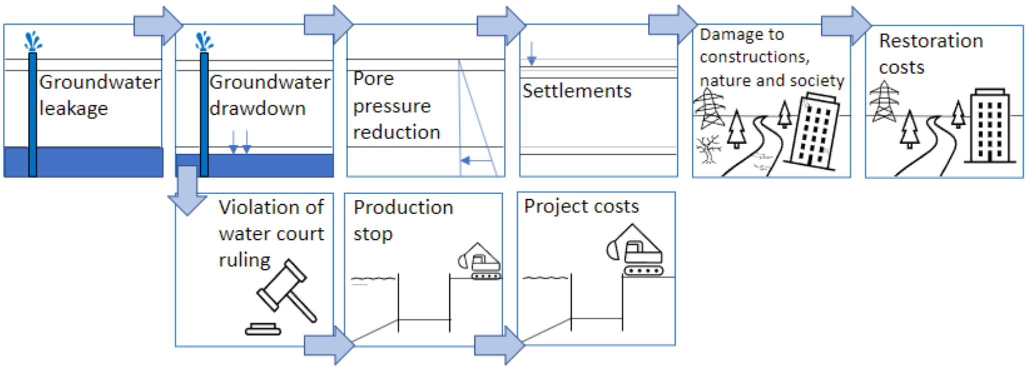


Figure 1: Possible cause-effect chain of a groundwater leakage.

Since the consequences associated with groundwater leakage can be severe and costly, implementing risk management by means of risk-reducing measures is of interest for both the project owner and the society (Merisalu et al., 2021). Generally, risk-reducing measures are implemented to decrease the potential project internal and external consequences. However, implementing these measures can lead to economic, social, and environmental consequences on its own, both internal for the project and external in society. Therefore, the socioeconomic effects of the measures should be assessed to manage society's limited resources in an efficient manner (Merisalu et al., 2021).

Further, two main project risks are associated with implementation of risk-reducing measures, (1) *the risk of not implementing measures when needed* and (2) *the risk of implementing measures when not needed* (Sundell, 2018; Merisalu et al., 2021). The first risk results in damage and costs to the project owner, society, and the environment meanwhile the second risk results in unnecessary costs for implementation and waste of resources. Both these risks need to be accounted for to promote an efficient use of society´s resources.

The ongoing project Packhuskajen in central Gothenburg faced leakage of groundwater through piling when penetrating a confined aquifer with artesian pressure in the first stage. This leakage resulted in a drawdown of the groundwater level in the surrounding aquifers. Measures to reduce the leakage and counteract the groundwater drawdown was implemented with success. However, the upcoming stages of Packhuskajen faces the same risk of leakage. To reduce the risk of damaging impacts on the surrounding environment and the risk of implementing inefficient costly measures, it is necessary to assess the profitability of the chosen risk-reducing measure strategy from stage one at Packhuskajen and investigate other relevant risk-reducing strategies.

The uncertainty and complexity of projects often results in knowledge not being shared or reused due to lack of efficient methods to transfer and acquire it (Cheng, 2009). Consequently, knowledge is often lost and a need to "reinvent the wheel" emerge in new projects (Ren et al., 2018). In addition to project Packhuskajen, several other projects in Gothenburg have experienced groundwater leakages related to drilled steel pipe piles e.g., Hisingsbron and Västlänken (L. Ödlund Eriksson, personal communication, 24th March 2022). Therefore, there is a need for development of a general methodology that demonstrates how to manage hydrogeological risks caused by groundwater leakage through drilled steel pipe piles.

1.2. Aim and Objectives

The overall aim of this thesis is to demonstrate a methodology for management of hydrogeological risks caused by groundwater leakage through drilled steel pipe piles, by integrating a cost-effectiveness analysis (CEA) and the principles of the observational method into the ISO 31000:2018 structure. The thesis applies the methodology on a case study currently under construction in central Gothenburg, Packhuskajen.

To meet the overall aim there are four specific objectives:

- Identify possible economic, social, and environmental risks that can be expected or foreseen when piling with drilled steel pipe piles in urban areas.
- Identify relevant risk-reducing measures to counteract leakages and groundwater impacts from drilled steel pipe piles.
- Conduct a CEA to assess which measures are the most profitable to implement for the case study.
- Demonstrate how the principles of the observational method can be used for management of hydrogeological risks in projects using steel pipe piles.

1.3. Limitations

The limitations of this thesis included difficulties in estimating the costs, consequences and uncertainties caused by a groundwater leakage through the drilled steel pipe piles. Expert elicitation was used to quantify costs and uncertainties; however, it was not possible conduct these in a fully correct manner due to the scope and timeframe of the thesis. Therefore, the results are not completely accurate but rather highlights a methodology for how these problems can be handled. The *Communication and Consultation* part of the ISO framework was not included in the application to the case study since stakeholder engagement is not within the scope of the thesis.

2. Literature Review

Chapter 2. presents the theories and concepts relevant to the thesis. The first Section, 2.1., introduces the concept of risk, consequences, and uncertainties, followed by Section 2.2. where the theory behind expert elicitation is presented. Further, the risk management framework ISO 31000:2018 as well as theory behind knowledge transfer is presented in Sections 2.3. and 2.4.

2.1. Risk Concept

The definition of risk, according to ISO 31000:2018, can be described as the effect of an uncertain deviation from the expected outcome. To simplify, risk is usually assessed as the product of a potential event's probability and its consequence, seen in *Figure 2* (Wladis & Rosén, 2018). The total risk is the sum of several possible events with different probabilities and consequences. Depending on the severity of the consequence and the probability of an event it will pose a certain risk, ranging from those with high probability and low consequence to low probability and high consequence.

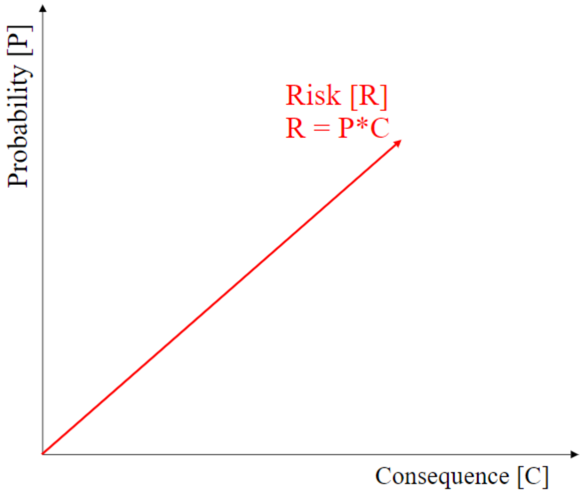


Figure 2: Risk described as a function of consequence and probability.

2.1.1. Consequences

The Cambridge Dictionary (n.d.) defines consequences as “a result of a particular action or situation, often one that is bad or not convenient”. The outcome of the cause-effect chain of an unwanted event determines the nature and severity of the consequence (Merisalu et al., 2021). Consequences can be both negative and positive and evaluating them is important from an organizational and decision support perspective (Merisalu et al., 2020; Wladis & Rosén, 2018). The positive and negative consequences should be weighed against each other to see if the positive consequences are larger than the negative (Merisalu et al., 2020).

Consequences can be economic, social, and environmental and in order to enable a comparison of the positive and negative consequences they should be expressed in monetary terms as far as possible (Merisalu et al., 2021). If the consequence cannot be defined as a cost, it should be described qualitatively to assess its final effects of the resulting outcome (Merisalu et al., 2020). To manage the consequences in a project, safety measures can be implemented to either reduce the probability of a consequence occurring or to reduce its severity.

2.1.2. Uncertainties and Probabilities

Working with sub-surface constructions are associated with a lot of uncertainties regarding the hydrogeological system (Sundell, 2018), e.g.:

- Can a leakage of groundwater due to piling occur in this hydrogeological setting?
- If a leakage occur, will the groundwater levels in surrounding aquifers be impacted and if so, to what extent?
- Can a groundwater drawdown cause any negative consequences such as e.g., subsidence?
- Are there any sensitive objects such as buildings and pipes that can be damaged from subsidence?

Uncertainties are defined as deviations from the expected event or outcome (Sundell, 2018). According to Aven (2012), uncertainties in hydrogeological risk assessments are often categorized as aleatory, epistemic or linguistic.

Inherent or natural variability of e.g., hydrogeological properties, are called aleatory uncertainties (Burgman, 2005). Large data collections can help understand the randomness of samples, but not fully eliminate or reduce the uncertainty. Errors and deviations in this type of data should always be considered when modelling to achieve a realistic result.

Epistemic uncertainty is a so-called non-random uncertainty which is due to lack of knowledge (Burgman, 2005). Unlike the aleatory uncertainty it can be reduced by collecting data with e.g., more soil samples. Epistemic uncertainty can also originate from systematic intentional or unintentional errors when estimating data. Inspections, expert opinions and reproducing data are efficient solutions when dealing with this type of uncertainty.

Linguistic uncertainty is connected to inadequate communication and includes vague language or a lack of context (Burgman, 2005). These uncertainties can be reduced by good project management which presents clear boundaries, aims, terms, and context.

It is necessary to recognize and quantify the uncertainties such that well-informed decisions regarding the management of the risks can be made (Parnell et al., 2013). Quantifying uncertainty is complex and using only one strategy managing all sources of uncertainty could be unfavourable (Sundell, 2018). When quantifying uncertainty by only using available data it can be defined as limiting frequency (Paté-Cornell, 1996; Christensen et al., 2011). This method can be inadequate when dealing with projects where only a small amount of data is known, such as e.g., hydrogeological systems. Another common method is to define uncertainty as a probability distribution which is based on both data and expert opinions, known as the Bayesian method.

Studying the effect quantified uncertainties have on the results can be done in several ways, where Monte Carlo simulation is a commonly used method in risk assessments (Sundell, 2018). This method simulates possible results by iterating random sampling of data within the probability range i.e., probability distributions (Couto et al., 2013). *Figure 3* illustrates how several inputs can be combined into one output uncertainty, making the results easier to interpret and tracking what variables the result depends on.

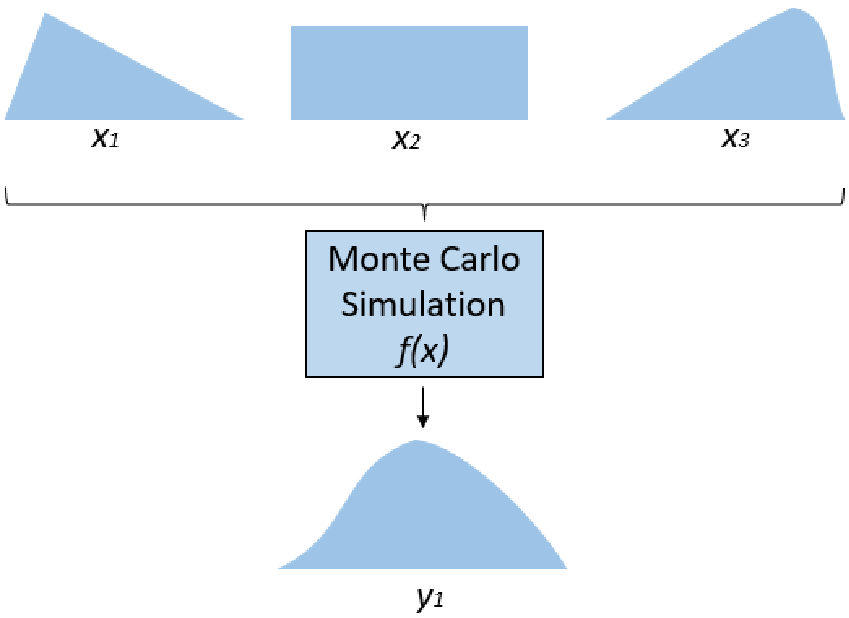


Figure 3: Illustration of Monte Carlo Simulation.

2.2. Expert Elicitation

Expert elicitation is a method which aims to systematically use experts to collect their judgements and opinions when there is a limited amount of data available (Wladis & Rosén, 2018). In complex decision making where the consequences of a certain event are associated with substantial uncertainties difficult to assess, expert elicitation can be used to facilitate the quantity of these uncertainties (O'Hagan et al., 2006). Further, expert elicitation is an excellent tool for complex engineering projects as there tends to be limited experience regarding both individual and combined components meaning it is natural to consult experts.

Often more than one expert is used by the decision maker when quantifying uncertainties with expert elicitation, meaning it is desirable to summarize the judgements into a single distribution (O'Hagan et al., 2006). This can be achieved either with a mathematical or behavioural approach. The mathematical approach first elicits one distribution individually from each expert and then combines them into one single distribution. The behavioural approach instead aims to create a group interaction with all the experts where the single distribution is elicited based on consensus among the experts.

It is important to acknowledge that expert elicitation in practice may lead to issues regarding the quality of the study. Quantified probability distributions are based on judgements and opinions and can therefore vary from the real-world events (O'Hagan et al., 2006). Extracted data can be characterised from bias and non-coherent judgements. Elicited judgements are not pre-formed values or beliefs, but instead constructed as response of the questions asked by the facilitator. O'Hagan et al. (2006) proposes that such statements could be "intrinsically relative" due to our psychological nature. The precision of elicited probability distribution can be compromised by deficient accuracy or a limited number of judgements. Such problems could be solved by for instance impartialness or by combining the elicited data with quantitative data, i.e., using the Bayesian method.

2.3. Risk Management Framework

Risk management aims to establish a comprehensive overview of safety measures and mitigation of potential damages for a project. ISO 31000:2018 is a framework with guidelines and principles for risk management, where the process includes *communication and consultation*, *establishing the context*, *risk identification*, *risk analysis*, *risk evaluation*, *risk treatment*, and *monitoring and review* (*Figure 4*).

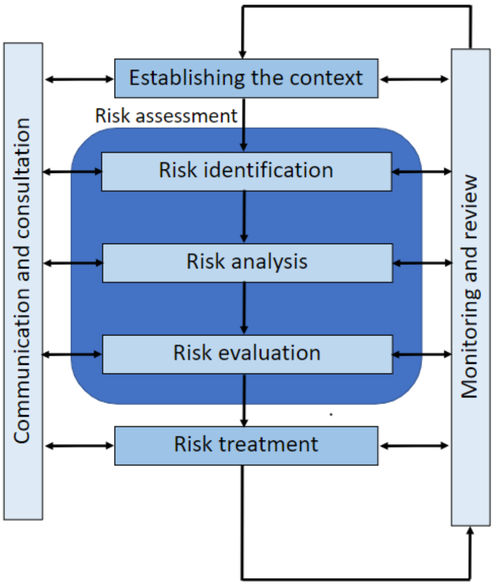


Figure 4: Risk management principles according to ISO 31000:2018.

Risk management practices implemented and maintained according to ISO 31000:2018, may result in e.g., increased probability of achieving project objectives, proactive management, improved governance, a reliable basis for decision making, and minimized losses. For example, projects could benefit from assessing if the risk of acting when not required is more favourable than not acting when it is needed, i.e., if implementing risk-reducing measures or not would be the best alternative. Risk management is complex since the uncertainty of an event makes it difficult to predict the outcome (Parnell et al., 2013). However, by following a risk management framework, it becomes less likely that the outcome will be of a negative nature.

2.3.1. Communication and Consultation

Efficient communication and consultation with stakeholders are important throughout the entire risk management process as it can ensure that all stakeholders understand what basis decisions are made on and why specific actions may be required (ISO, 2018). This communication and consultation should be developed at an early stage of the project.

Further, stakeholders tend to make judgements of risk based on their idea of risk, meaning their perceptions may vary greatly due to different values, assumptions, needs, and concerns (ISO, 2018). The stakeholder’s views should be mapped, recorded, and considered in the decision-making process, where it is important to work in a truthful and transparent manner where confidential and personal integrity aspects are considered as well.

2.3.2. Establish the Context

In this step, the objective and approach of the risk assessment is described (ISO, 2018). Both external and internal contexts should be established as well as the risk criteria to ensure that the affected organization understands the benefit, strategies, and scope of the project. The external context describes the external environment where the objectives is to be achieved. It includes for example political, financial, legal, environmental, and geographic requirements from external stakeholders. Establishing the internal context ensures that the risk assessment is aligned with the requirements from the organization, in this case Skanska. This can for example include governance, organizational structures, policies and the strategies to achieve them, capabilities of the organization, and the form and extent of contractual relationships. Defining the risk criteria should reflect on the recourses, aim, and values of both the organizations and legal requirements by including the following:

- What type of events that can be expected and how its consequences and probabilities will be measured;
- The timeframe of the events;
- How the risk level is to be determined;
- Stakeholder perspectives;
- Acceptable risk levels;
- If combinations of several risk events should be considered.

2.3.3. Risk Identification

Risk identification is the first fundamental step of the risk assessment. This step aims to identify sources of risk, areas of impact and events with both their causes and potential consequences. Identified risks are based on events that might enhance, prevent, accelerate or delay the achievement of project objectives (ISO, 2018). Sources of risk could for example be facilities, operations or events that causes the risk, while the areas of impact are the recipients of the risk, e.g., people, projects, businesses, eco-systems, and facilities affected by the negative outcomes of the risk (Wladis & Rosén, 2018).

2.3.4. Risk Analysis

The risk analysis aims to establish a form of understanding of the risk, where the analysis is usually conducted by means of a qualitative or quantitative estimation of the risk level (Wladis & Rosén, 2018). The risk analysis generates inputs to the risk evaluation and potential decisions regarding risk treatment (ISO, 2018).

Risk events are complex since they can occur during all phases and stages of a project as well as having different origins, e.g., from physical planning, technical solutions or from legal considerations (Wladis & Rosén, 2018). A comprehensive design of the concept of risk is therefore essential to make sure that all occurring events can be handled in a uniform manner.

Usually, it is not possible to determine whether an event will occur or not. However, the probability of an event occurring can be estimated based on knowledge of technical, human and natural factors (Wladis & Rosén, 2018). The probability and consequence of an unwanted event are needed to estimate the risk levels. If available, statistical data with information of the probability, frequency, and the consequences of events can be used. When data is not available, estimations can instead be done by expert judgements, see *Section 2.2.*

In underground construction such as the piling of Packhuskajen, underlying processes which controls the outcome can be regarded as stochastic processes, i.e., random and that there are uncertainties regarding the outcomes (Wladis & Rosén, 2018). Hence, a probabilistic approach to the risk can be justified since it provides opportunities for analysis and evaluation useful in complex projects with many risk events and chains of events which can affect the outcome.

2.3.5. Risk Evaluation

The risk evaluation aims to support the decision-making process by considering if safety measures should be applied (ISO, 2018). The risk levels calculated in the risk analysis are compared with a risk criterion considering a wide context, i.e., legal, organizational, individual, and societal requirements. To evaluate the risk, the ALARP (As Low as Reasonably Practicable) principal is considered (Wladis & Rosén, 2018). In *Figure 5*, three levels are described. The unacceptable risk means that the risk cannot be acceptable under any circumstances. The ALARP region describes a risk that can be accepted if all the risk-reducing measures are too inconvenient or expensive. Finally, there is the acceptable risk, where all risk levels are following stated requirements.

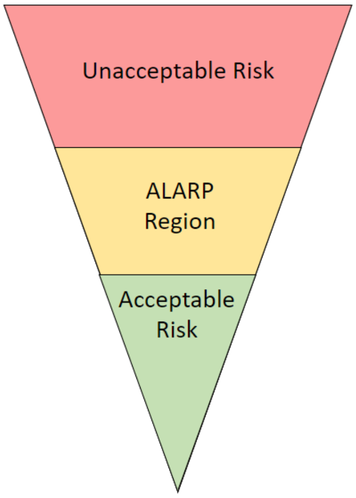


Figure 5: The ALARP method.

Establishing if a risk is acceptable or not can be somewhat difficult, considering that there are no specific guidelines describing acceptable risk levels (Wladis & Rosén, 2018). In Sweden, the decision maker is responsible for the evaluation and a water court ruling can for example serve as the basis for an acceptable risk.

2.3.6. Risk Treatment

The basis for risk treatment is that the risk is either reduced or eliminated (Wladis & Rosén, 2018). A risk reduction can either be achieved by reducing the probability of the event occurring or by reducing the consequences of the event. Therefore, risk-reducing measures can be preventative, limiting or a combination of these.

Risk treatment is a cyclical process of (1) *assessing the risk treatment*, (2) *deciding whether residual risk levels are tolerable*, (3) *if not tolerable, generate a new risk treatment, and* (4) *assessing the effectiveness of the new treatment* (ISO, 2018).

2.3.7. Monitoring and Review

Monitoring and review include surveillance and regular checking during the risk management process (ISO, 2018). This is an iterative way of managing the risk such that the models always can be updated if new information arise (Wladis & Rosén, 2018).

2.4. Knowledge Transfer

Knowledge can be categorized into tacit and explicit knowledge, where tacit knowledge is characterized by that it is “known by heart” and obtained from experience, making it difficult to explain and communicate. Explicit knowledge on the other hand is more concrete and can be communicated and documented to a wider extent (Berg et al., 2012; Cheng, 2009). Examples of explicit knowledge in construction projects include e.g., drawings, tender documents, standard operating documents, and construction rules, which all can be documented and stored in databases (Cheng, 2009). Tacit knowledge on the other hand cannot be stored in documents and databases since it is deeply rooted in the actions and experiences of the employees (Berg et al., 2012). Tacit knowledge is a very valuable way for employees to contribute to organizational performance and there should be a focus on collecting and transferring this knowledge to the entire organization and make it reusable by means of organizational memory using e.g., lessons learned (Berg et al., 2012; Cheng, 2009). However, there is a certain complexity when transferring the knowledge from individuals to the organization since everyone generally interprets and process knowledge differently (Berg et al., 2012).

Cheng (2009) states that “*knowledge is a key resource for construction industry, but it tends to be lost much across different phases or among different projects.*” (pg. 2035). This has to do with the fact that the construction industry consists of project-based organizations, where the construction process tends to be reinvented as a new project is initialized, meaning that valuable knowledge from previous and similar projects is lost (Ren et al., 2018).

Five factors influencing knowledge transfer was identified by Ren et al. (2018), and includes uniqueness, temporality, geographical distance, urgency, and similarity. It is mainly the uniqueness and temporality factors that hinders the process of knowledge transfer. The degree of uniqueness of a project correlates with knowledge transfer, where teams are less likely to share knowledge the more a project is perceived as unique (Ren et al., 2018). However, this uniqueness has been argued to be exaggerated and it has instead been suggested to focus on the similarity between projects and how it can promote knowledge transfer. The temporality and short-term aspect of construction projects results in a lack of organizational memory and routines as they hardly have the time to emerge which hinders continuity and knowledge transfer (Berg et al., 2012).

Knowledge gained is often lost and dispersed at the end of a project when the teams shift to new projects if it is not managed or documented properly (Cheng, 2009). According to Landaeta (2015), knowledge transfer is an efficient way for project-based organizations to deal with issues and problems that arise due to the uncertainty and complex nature of projects. Therefore, the tacit knowledge of engineers and experts is crucial to capture and transfer to facilitate organizational learning for upcoming projects (Cheng, 2009).

3. Case Study Description

Chapter 3. introduces the case study of Packhuskajen. A description of the case study and its prerequisites is presented in Section 3.1. Section 3.2. describes the geology of Packhuskajen, followed by Section 3.3. which describes the hydrogeology. The possible consequences associated with the project are presented in Section 3.4.

3.1. The Project Area

Packhuskajen is a quay situated along the Göta Älv river in central Gothenburg (*Figure 6)* first constructed in the 19th century (Gothenburg Municipality, n.d.a). In the future, Gothenburg is facing extreme weather and increased sea levels due to rising temperatures caused by climate change. The municipality is therefore working on a strategy to secure the city from these weather events, where Packhuskajen is one of the constructions being climate proofed.

Figure 6: The area of Packhuskajen illustrated by the dotted red line (Eniro).

Skanska is currently renovating the quay on request from Gothenburg municipality. The brittle 150-year-old quay is being raised and supplied with a robust steel pile construction as well as provided with a protection for flooding to withstand both higher sea levels and extreme weather to provide safety for surrounding businesses and infrastructure. The project is divided into three stages, see *Figure 7*. Each stage is approximately 100–200 meters of quay, where the first stage is finished, the second stage is under construction and the third stage is planned.

Figure 7: The three building stages of project Packhuskajen (Eniro).

The project includes, among other things; design of the new quay with associated temporary constructions, demolition of the existing quay and construction of the new quay with protection of flooding (Skanska, 2021). Some of the project requirements are that the new quay should have a lifetime of 100 years, that the quay and its surrounding area should fulfil at least safety class 2, and that the quay should withstand a load of 15 kPa (Skanska, 2021). *Figure 8* shows the principal structural drawing of the new quay. The old wooden piles which are piled to a depth of approximately 6-7 meters into the clay will be replaced by steel pipe piles drilled approximately 50 meters down to the bedrock (Gothenburg Municipality, n.d.a).

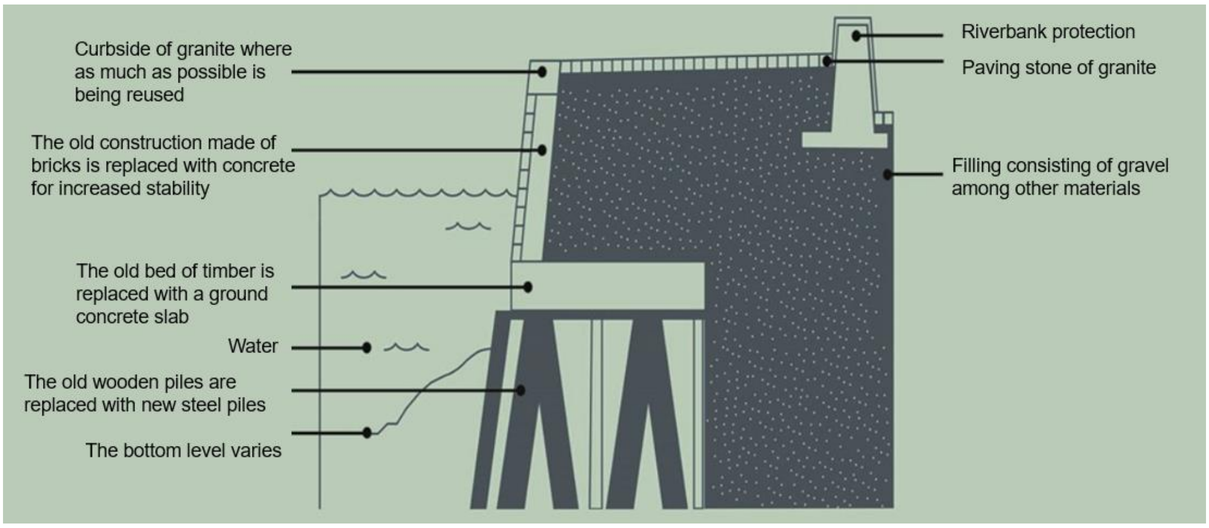


Figure 8: Principal structural drawing of the new quay (Gothenburg Municipality, 2022).

Packhuskajen is located in the central districts of Vallgraven and Nordstaden which are rather urbanized (STA, 2016a). The area borders to Göta Älv in the north and west and to Rosenlundskanalen in the south and east. The area consists of extensive buildings and infrastructure, e.g., Gothenburg's central station. New infrastructure is also under construction in the area, e.g., the Kvarnberget stage of Västlänken where extensive underground work such as grouting, rock- blasting and drilling, and ground reinforcement work is taking place (STA, 2021). In the construction area of Packhuskajen, piping and buildings are found (Skanska, 2021).

The project has no water court ruling, instead it has a permission for water operations (D 531-1524/531-1526 County Administration of Västra Götaland, 2019). Land drainage which is when the hydrogeological properties of the soil permanently change, is forbidden in the county of Västra Götaland (County Administration of Västra Götaland, n.d.). Embankment is classified as one type of land drainage and will be used for constructing the protection of flooding at Packhuskajen. In addition to the permission for water operations, the county administrative board has granted both a permission and exemption for land drainage in the form of embankment for Packhuskajen (D 531-1524/531-1526 County Administration of Västra Götaland, 2019).

3.2. Geology

The Gothenburg area is mostly known for its great depths of sensitive soft clays and several geotechnical studies can declare that Packhuskajen is no exception. Samples from the boreholes carried out during the investigation of Packhuskajen by Skanska, studies made in the area by the Swedish Transport Administration (STA) for the railway tunnel Västlänken and older core samples from The Geological Survey of Sweden (SGU) located close to the area of interest are among the analysed geotechnical investigations (Skanska, 2021a; Skanska, 2021b; STA, 2016a; SGU, n.d.a). The cores showed that the top layer consist of approximately 2 to 5 meters of filling material overlaying a thick layer of clay estimated to be a thickness off 20 to 45 meters. Below the clay layer a coarse-grained soil can be found above the bedrock and has a thickness of 0.5 to 3 meters. The expected stratification can be seen in *Figure 9* below. Looking at core samples from SGU (n.d.a), the lower coarse-grained material can be found in the whole area within the moat and further east to the central station.

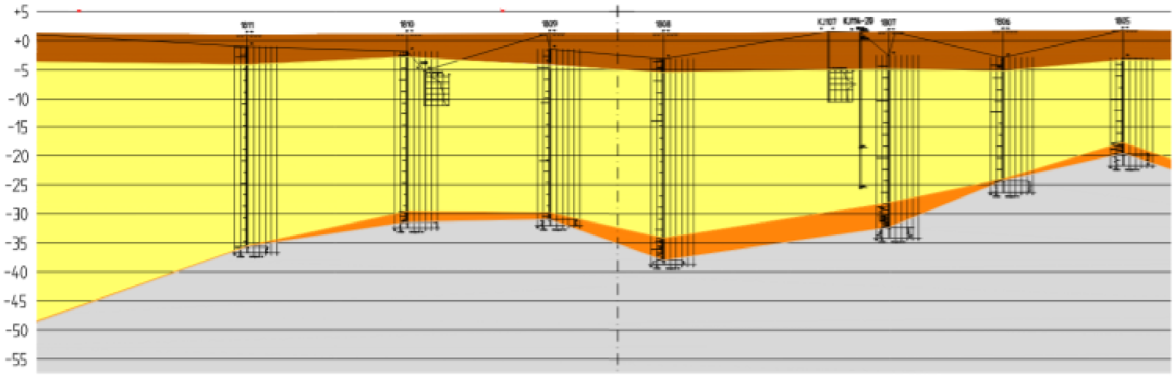


Figure 9: Estimated soil depth for stage two of the quay (Skanska, 2021a).

It is of interest to investigate the local geological history to confirm the information given from the boreholes and to gain further knowledge about the stratigraphy. Starting from the bottom of the stratigraphy, the bedrock is found. Below the case study area, it consists of approximately 1.66-1.59 billion years old tonalite and granodiorite, see *Figure 10.* Tonalite and granodiorite are both magmatic deep-seated, high strength rocks with a coarse-grained structure (SGU, 2021). *Figure 10* shows a local brittle deformation zone that runs across the case study area and thus faults and zones of fracture may occur in the local bedrock.

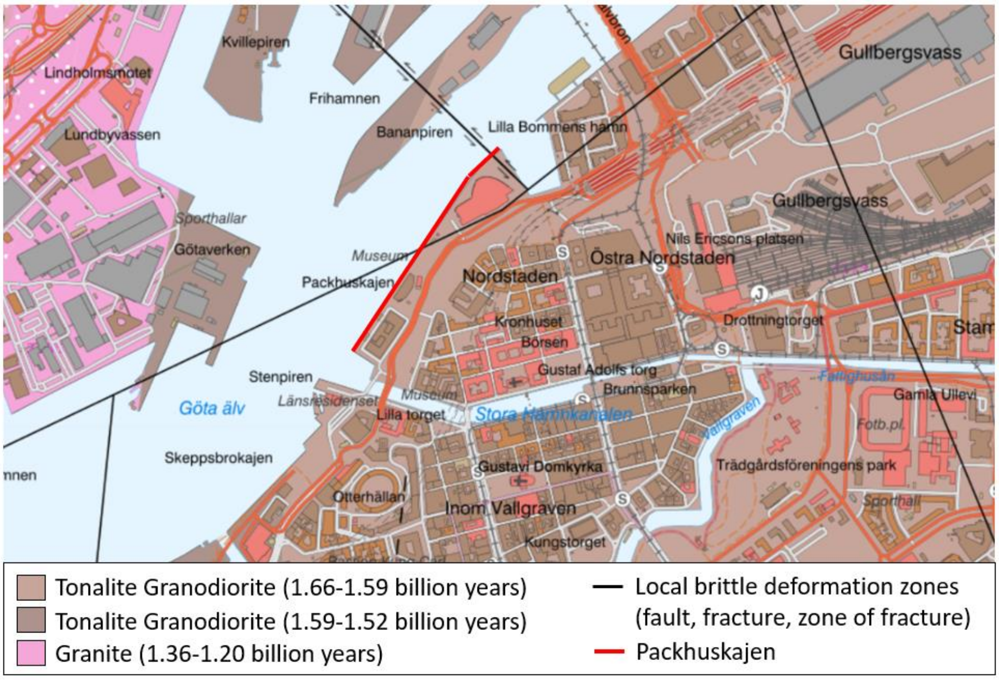


Figure 10: Deformation zones at the Packhuskajen site (modified from SGU, n.d.b).

The soil layer thickness along the Göta Älv river is often significant because of both the topography and the previous ice age (STA, 2016a). The Gothenburg soil was deposited either below the great glaciers (glacial soils) or after when the glacier was retreating (post glacial soils) (SGU, 2020a). The higher grounds, which can be found south to Packhuskajen, have for a long time been exposed to erosion. Due to gravity, surface runoff and the movement of the glaciers the eroded soil has deposited in the river valley (Holland & Turekian, 2014).

The coarse-grained material overlaying the bedrock is probably till, which is a glacial soil with several grain sizes created as the glacier moved over the land surface, taking loose material and pieces of bedrock with it which then deposited in the Göta Älv river valley (SGU, 2020a).

The fine clays were probably deposited both during and after the retreating glacier in calm waters (SGU, 2020b). When the glaciers were melting, the water created tunnels above and below the ground which brought materials with it (SGU, 2020c). The larger grained materials deposited close to the river mouths and the finer materials, glacial clay, and silt, deposited far from the mouth where the water is less turbulent.

The Gothenburg region was situated below the highest shoreline. The land was elastically forced down by the pressure of the glaciers and was therefore below the sea level when the glaciers melted (Stigson, 2016). The ground level has since then been exposed for isostatic uplift due to unloading of the glacier which have led it to rise above the sea level again. Whether an area was below or above the highest shoreline affects the stratigraphy (Andréasson, 2015) and therefore it can be expected that post glacial clays should overlay the glacial clay. This clay deposited in calm sea or lakes which were covering the region for a long time.

The filling material in the area consists of various materials. Studies shows that the top layer consists of asphalt and cobblestone (Skanska ,2021a) and that the filling consists of a mixture of grainsizes such as gravely sand, silty sand, or sand. The excavation pits were probably backfilled with the soil available when the construction of the old quay was done, hence the large variety. Since the area was below the highest shoreline, there could be a chance that the material consists of post-glacial wave-washed materials that often can be found above such clay layers (Andréasson, 2015). This material was deposited by waves along the shoreline of the oceans or lakes.

The stratification found in the borehole samples agrees with the geological history and therefore it can be said with certainty that these layers do underlay Packhuskajen and probably most of the river valley as well.

3.3. Hydrogeology

There are three main soil layers found above the bedrock, the filling layer which overlayers the clay which overlayers the till. There are three aquifers in the area. One unconfined aquifer in the filling material, one confined aquifer in the till below the clay layer and one confined aquifer in the fractured bedrock, see *Figure 11.* It can also be seen that the steel pipe piles are drilled down to the bedrock such that it penetrates the confined aquifer in the till. Furthermore, there is a possibility that the confined aquifer found in the fractured bedrock could be penetrated as well. The area along the river is relatively flat and south from the area three mountain sections can be found, Kvarnberget, Otterhällan, and Kungshöjd. Thus, the groundwater flow is generally toward the river.

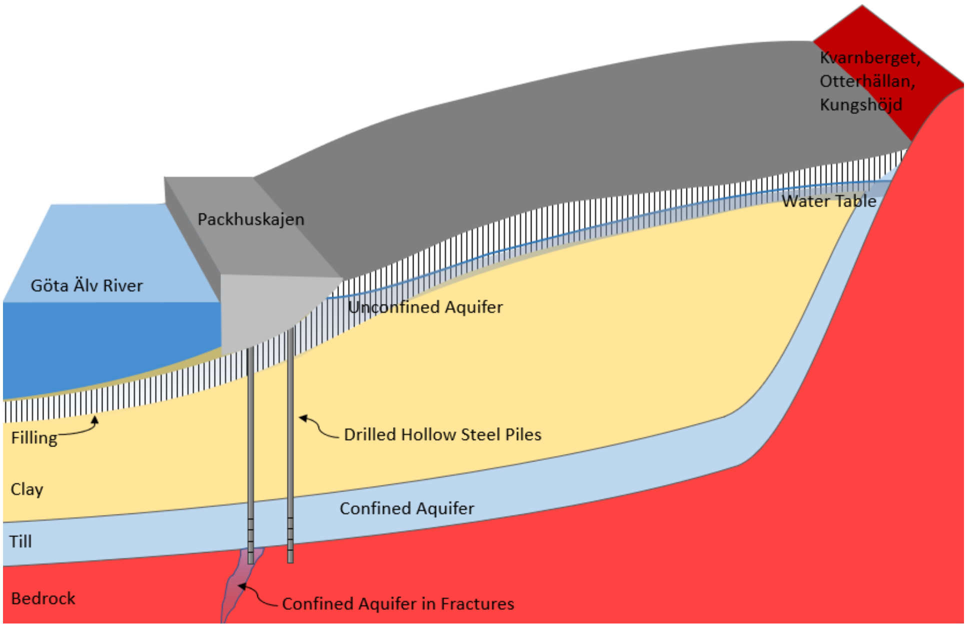


Figure 11: Conceptual model of the hydrogeologic system of the Packhuskajen area from north to south.

The upper aquifer is found at the same level as the mean water level of Göta Älv river, which is approximately 2 meters down from the ground surface (Skanska, 2021a). This aquifer is expected to be found in the filling material above the clay. The aquifer is recharged with percolation and the pore pressure is hydrostatic from the groundwater surface, meaning that the aquifer is unconfined (Fetter, 2014). These aquifers can also be called "water-table" aquifers since the groundwater surface is at atmospheric pressure.

The lower aquifer can be found in the coarse-grained till layer at the bottom of the soil stratigraphy (Skanska, 2021; STA, 2016a). According to Fetter (2014), an aquifer is defined as confined if it is surrounded by impermeable layers. At the Packhuskajen site, the overlaying clay and the bedrock below acts as a confining layer since it has a low permeability. The groundwater in the confined aquifer is probably infiltrated where the groundwater bearing layer meets the ground surface in conjunctions with the bedrock outcrops, see *Figure 11*. Thus, the till layer could be recharged at higher grounds such as for example Kvarnberget, Otterhällan, and Kungshöjd. The confining layers then allows the water pressures to rise in the aquifer such that the pressure head can be higher than the atmospheric pressure at Packhuskajen, a so-called artesian aquifer.

Groundwater can also appear in deformation zones of crystalline rocks, such as granites or granodiorite (VISS, n.d.). Groundwater found in the fracture zones at the case study site are probably recharged by water coming from the till and from other fractures. The surrounding layers are confining, allowing the pressure to be artesian in the fractures as well.

3.4. Possible Consequences Associated with the Project

There are two types of consequences associated with the risk of leakage and implementing risk-reducing measures: project internal and external consequences. These consequences can be of economic, social, and environmental character.

3.4.1. Project Internal Consequences of Leakage

The possible project internal consequences affecting the organisation, due to a potential leakage, can be both economic and social (Dziadosz et.al., 2015). There is a possibility that a leakage could lead to delays or standstills of the construction activities, meaning that the ongoing production might have to stop to fix the leakage to avoid further leaking (Czemplik, 2014). Operational disruptions often lead to increased construction expenses such as e.g., additional costs of technical equipment, machinery, manhours, and schedule changes (Aibinu & Jagboro, 2002). Further unexpected expenses can include fines for not being able to meet the agreed deadline, e.g., each extra construction week cost a certain amount in fines for the contractor (Swedish Work Environment Authority, 2022).

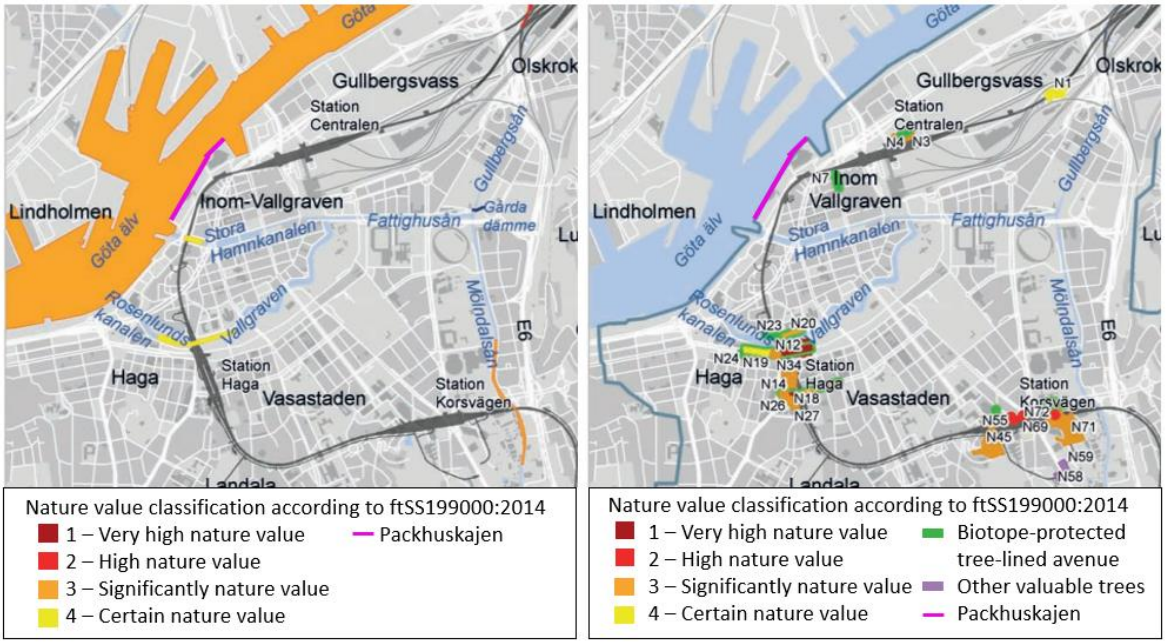
How sub-surface constructions should be managed are regulated by functional, technical, economic, and environmental regulations. The regulations are a framework for how the external environment both can- or should not be, affected by construction activities. Water court ruling is a required permit for water activities, regulating for example groundwater disturbance (SFS 1998:808, 11 ch.). A violation of the permit may lead to expensive fines or production stops for the project owner. The project owner is financially responsible for further consequences due to groundwater impacts (SFS 1998:808, 16 ch.).

Difficult situations could also affect the psychological health of the staff by means of a high workload and increased stress levels (Swedish Work Environment Authority, 2022). According to the regulations on organizational and social work environment (AFS 2015:4), employees should not be in the position to fall ill due to an unhealthy workload. Stress often leads to deteriorated communication between the contracting parties concerning risks and responsibilities which could lead to expensive misunderstandings, damaged relations or reputations (Bartsch & Jergeas, 2008).

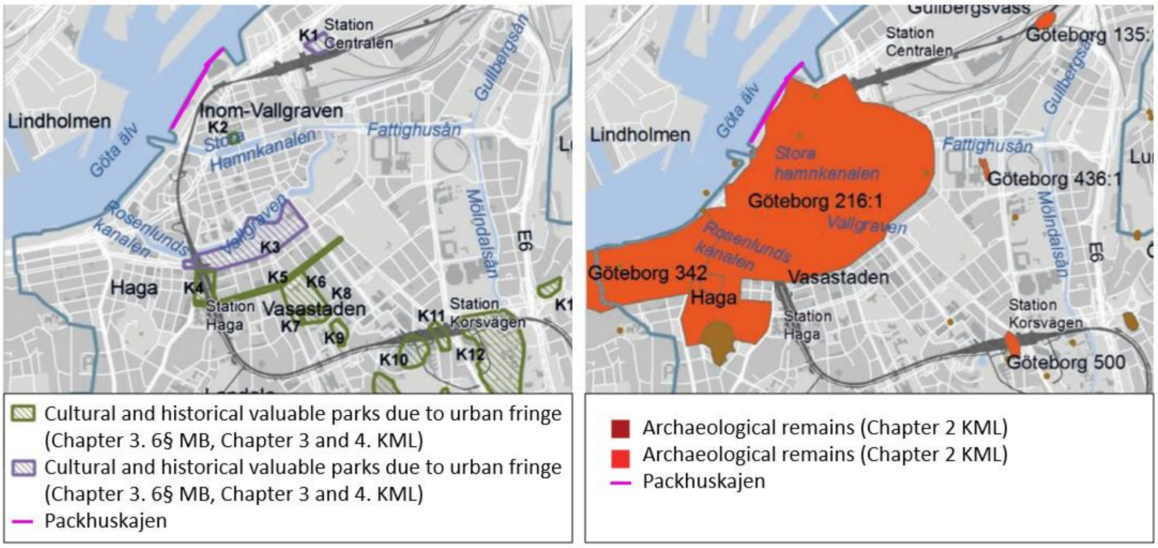
3.4.2. Project External Consequences of Leakage

The possible external consequences due to a leakage are associated with environmental, social, and economic consequences. External consequences associated with a groundwater leakage are mainly linked to drawdowns which could affect ecological systems and natural environments (Wladis & Rosén, 2018). According to Merisalu et al. (2021), a significant drawdown could have an impact on water bodies, change groundwater chemistry, and mobilize contaminants. Furthermore, a drawdown could damage groundwater dependent historical and archaeological important values since it would change the water supply, chemistry or lead to oxidation.

During the investigation of the railway tunnel Västlänken, the STA carried out an environmental impact assessment, including the case study area Packhuskajen (STA, 2016b). Therefore, a significant risk inventory of how a groundwater drawdown would have affected the area already exists. Several water bodies, recreational, cultural, historical, and environmentally important values were found in the area, see *Figure 12a* and *12b*. Furthermore, several cultural and historically important parks as well as archeologically important areas are found (*Figure 12c* and *12d*) together with protected species (ASF 2007:845 8§) such as *potamogeton trichoides* and *flavoparmelia caperata*. The consequences of a drawdown could therefore be social, environmental, and economical affecting possible drinking water supplies, reducing provision of ecosystem services, damaging recreational spaces (Gilchrist & Allouche, 2004) as well as leading to large economic costs of restorations and fines (Wladis & Rosén, 2018).



(a) *(b)*



(c) *(d)*

Figure 12: Important nature values in the central Gothenburg considering a) important water-bodies b) terrestrial environments c) cultural and historical nature values d) archaeological remains (Modified from STA, 2016b).

Sub-surface constructions can compose a considerable risk in subsidence sensitive areas (Sundell, 2018). Compressible soils, such as clays, are significantly vulnerable for drawdowns, since it has a high probability of causing settlements (L'Heureux et.al., 2014). Included in the category sub-surface constructions are deep foundations such as steel pipe piles. Groundwater leakage through sub-surface constructions can cause drawdowns over a large area in central Gothenburg as seen in *Figure 13.* The drawdown may then affect the pore pressures in the clay (Sundell, 2018). Loss of pore pressure affects the stresses in the soil causing a strength reduction which could then cause settlements. This is a well-known problem and has over the decades caused severe damages in Scandinavia as well as all over the world (Sundell, 2018). Depending on the local geotechnical and hydrogeological conditions the extent of drawdown induced settlements will vary. *Figure 13* illustrates the settlement sensitive clay in central Gothenburg (STA, 2016b). Large areas around Packhuskajen are classified in the highest risk group, meaning that it is a high probability of settlements if there would be a groundwater drawdown.

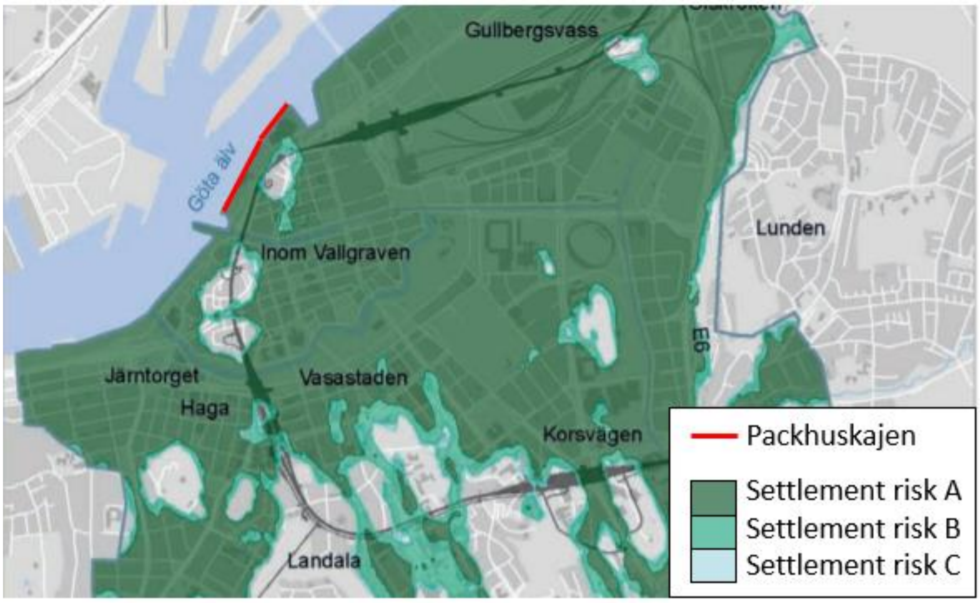
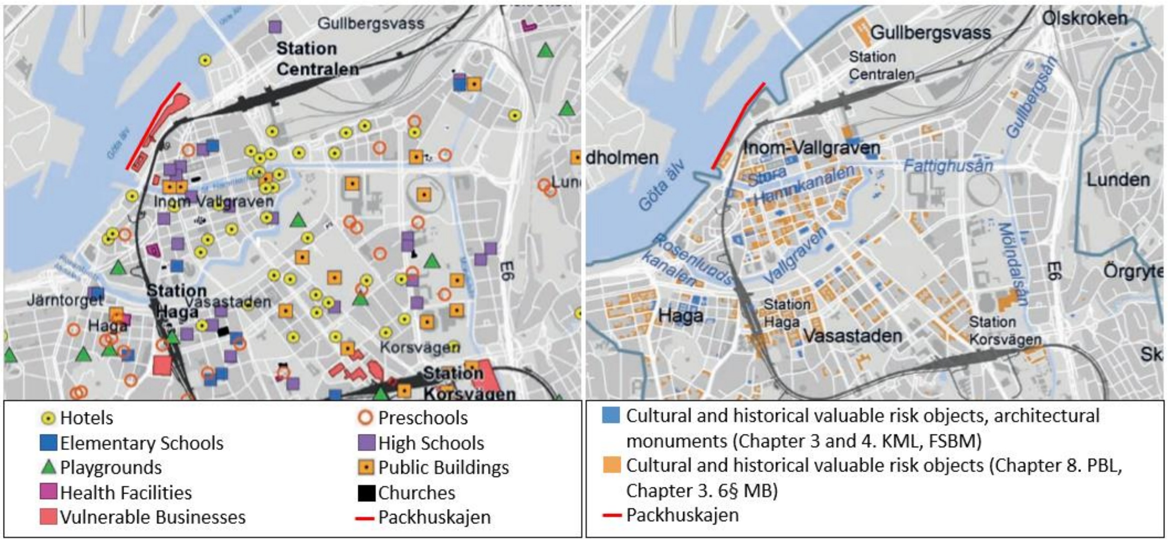


Figure 13: Risk areas for settlement sensitive clay. Settlement risk A represents the area that shows the most probable distribution of > 1 meter settlement sensitive clay. B and C represent areas with relatively high probabilities of settlement sensitive clay > 1 meter. Outside the marked areas, the probability of the presence of settlement sensitive clay > 1 meter is very low (modified from STA, 2016b).

Settlements in the area could damage important buildings in central Gothenburg (STA, 2016b). *Figure 14a* and *14b* shows the potentially affected buildings. Health facilities, schools, businesses, and buildings of cultural and historical value are examples of buildings found in the area with foundations that are dependent on the groundwater level. Several of these buildings are also included in the Gothenburg municipality conservation programme which aims to preserve the cultural heritage, promote local cultural identity, and to raise awareness of aesthetic values and historical contexts (Gothenburg Municipality, n.d.b). Buildings addressed as particularly valuable may not be distorted according to the Swedish planning and building act (SFS 2010:900, 8 ch.). There is also a possibility that settlements could damage important infrastructure such as roads, piping, and energy wells or nature values as well as cultural and historical values (STA, 2016b; STA, 2016a). A potential drawdown could therefore lead to both economic and social consequences, including reparation costs and loss of irreplicable and meaningful buildings.



(a) *(b)*

Figure 14: Important buildings in the central Gothenburg considering a) important businesses and b) cultural and historical values (modified from STA, 2016b).

Damaged infrastructure, buildings, and parks or just a delayed construction time could lead to social consequences connected to the surrounding communities (Gilchrist & Allouche, 2004). Retailers can experience loss of income due to decreased accessibility to stores since e.g., roads can be blocked or annoyances such as noise, dust, or air pollution. Reduction in sales and personal income could thereby also lead to a loss of tax revenues. Communities could suffer property damage because of settlements. Residential areas and businesses can be found in the case study area, such as e.g., the Gothenburg opera house and the casino, meaning there is a potential risk of social impacts (Gothenburg Municipality, n.d.c).

Another social consequence is connected to traffic disruptions. The inhabitants might have to take detours or experience utility cuts as well as reduction of road space (Gilchrist & Allouche, 2004). This can lead to less parking spaces, additional fuel costs, increased travel times, increased number of accidents, wear and tear of roads and vehicles, and road rage. These consequences are strongly connected to increased expenses, decreased productivity as well as environmental and health aspects for both inhabitants and businesses.

Increased delays in traffic along with heavy machinery at the construction site are linked with social and environmental consequences such as noise, dust, vibrations, and pollution to air and water (Babisch, 2014; Mannucci et.al., 2015; Naturvårdsverket, 2021). Communities could therefore experience increased health issues such as respiratory or cardiovascular diseases.

3.4.3. Project Internal Consequences of Implementing Measures

The project internal consequences are essentially linked to economic consequences, i.e., implementation costs. According to Wladis & Rosén (2018), additional costs of further building materials, machines, transports, and manhours could be expensive for the project owner. Depending on the technological difficulty to install the safety measure and how expensive it is, this could be a significant economic consequence. In some sub-surface constructions, measures can constitute as a significant part of the overall project budget (Merisalu et al., 2021).

However, the internal consequences due to implementing certain safety measures can also be associated with social risks related to the working environment, e.g., not keeping a proper safety distance to working machines such as the drilling rig.

3.4.4. Project External Consequences of Implementing Measures

The project external consequences are mainly associated with environmental and social consequences. According to Merisalu et al. (2021) the consequences are due to usage of energy, petroleum products, and natural resources. The installation of a risk-reducing measures could be energy or fuel consuming and other measures may need a large amount of water, e.g., drilling with water or artificially recharging the aquifer with drinking water. Some risk-reducing measures would require usage of extra building materials which could lead to environmental consequences due to the material manufacturing. Producing both plastic and steel which are common materials used in construction, requires large amounts of energy but are also leading to increased emissions and usage of limited resources (Palm et al., 2016; Price et al., 2002).

Further, extra transportation could lead both to increased emissions and several social consequences. As already described in *Section 3.4.2.*, an increased number of transports would lead to traffic disruptions, less road space and parking, additional fuel costs, increased travel times, increased number of accidents, wear and tear of roads and vehicles, road rage, and health effects due to noise, dust, vibrations, and air pollution (Gilchrist & Allouche, 2004; Babisch, 2014; Mannucci et.al., 2015).

4. Methodology

Chapter 4. presents the chosen methodology for the thesis. Section 4.1. presents the research design. The methods for collection and processing of data are presented in Sections 4.2.-4.4. including both the theory behind the methods as well as the application of them. The last sections of the chapter include discussion of the research quality, Section 4.5, and considerations regarding ethics and sustainability, Section 4.6.

4.1. Research Design

This thesis has been divided into five main steps as shown in *Figure 15*. The thesis used a risk-based approach following the principles of the risk management framework ISO 31000:2018. The first step was the background- and literature study which provided a description of the project, Packhuskajen, a conceptualization of the hydrogeological system, the consequences associated with the project as well as an introduction to important concepts for the thesis. The second step which included qualitative interviews with actors involved in Packhuskajen were conducted to identify what happened, why it happened, and what risk-reducing measures were implemented in the first construction stage as well as other potential measures. The identified risk-reducing measures was then evaluated in step three by means of a CEA. The fourth step included applying the observational method to establish an action plan for how hydrogeological risks associated with leakage from drilled steel pipe piles should be handled in the future. The retrieved information from the background study, interviews and the CEA acted as input for the observational method. In the fifth and last step, conclusions of how to handle risks with steel pipe piles were presented.

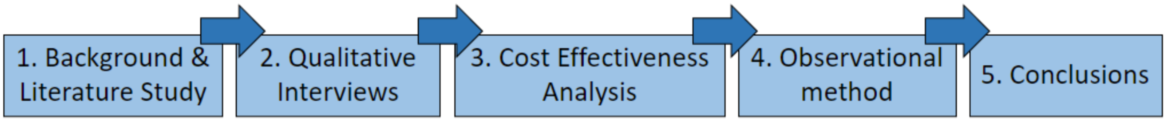


Figure 15: Schematical model showing the methodology process.

Since parts of the thesis were heavily reliant on gathering project specific data by means of interviews, a qualitative approach was deemed to be appropriate. Further, this thesis followed the abductive research approach systematic combining. Dubois & Gadde (2002) describes systematic combining as a process of continuously going “back and forth” between the empirical data and the theoretical framework, allowing for them to evolve simultaneously and inform each other. It is argued that this process is beneficial as the understanding between reality and theory can be expanded since theory cannot be understood without empirical material and vice versa. Systematic combining was considered appropriate for this thesis since iterative matching between theory and empirical material allows for redirections towards relevant findings, i.e., a general methodology for hydrogeological risk management. *Figure 16* illustrates the process of systematic combining.

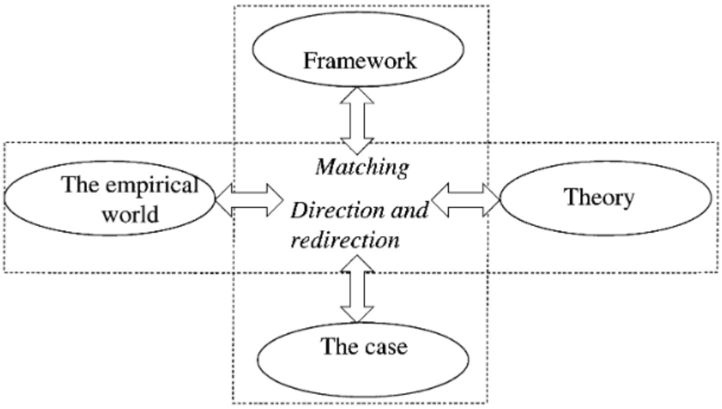


Figure 16: The process of systematic combining (Dubois & Gadde, 2002).

4.2. Qualitative Interviews

This section presents theory regarding qualitative interviews in *Section 4.2.1.* followed by the application of them in *Section 4.2.2.*

4.2.1. Theory

Interviews in qualitative research differentiates from interviews in quantitative research, the main difference is that qualitative interviews tend to be less structured since the emphasis is put on keeping the initial research ideas general and on the interviewee's personal perspectives (Bell et al., 2019). It is not uncommon that the emphases of the research might have to be adjusted because of significant information that arises during the interviews. It is encouraged to go off track and be flexible as it provides insight to factors that are important and relevant for the interviewee and more detailed answers (Bell et al., 2019). Qualitative interviews are less structured and aims to collect rich and detailed answers meanwhile quantitative research are structured and aims to maximize the reliability and validity of the collected data.

Further, the interviews can be organized in an unstructured or semi-structured manner (Bell et al., 2019). Unstructured interviews have a very brief set of questions, sometimes only one, where the character of the interview tends to be like a conversation. Semi-structured interviews instead have some predetermined open-ended questions where there is a possibility for flexibility by means of allowing new questions to arise and be asked during the interview as a direct result of what the interviewee says, with a focus on exploring certain themes.

4.2.2. Application

The interviews for this study were conducted with a semi-structured manner due to the variation of research objectives where it contributed to collect open-ended data and the participants experiences. Three interviews with participants working with different roles at Packhuskajen were conducted. The participants included the construction manager, the production manager and the hydrogeologist responsible for the monitoring programme. An interview was conducted with each participant which aimed to collect experiences gained during the first construction stage.

An interview guide with questions was sent out by email to the participants a few days prior to the interview (*Appendices A and B*). The construction- and production manager received the same interview guide, meanwhile the interview guide for the hydrogeologist included questions specifically related to hydrogeology. Since the interviews followed a semi-structured approach, supplementary questions arose during the interview which led to further discussions. Additional questions which emerged after the interviews were sent out by email to the participant in question.

All interviews were recorded for transcription with permission from the participants. The participants were also asked if they wanted to remain anonymous to ensure their integrity. Once the interviews had been conducted, they were transcribed and coded. *Table 1* shows the date and lengths of the interviews.

Table 1: Overview of the conducted interviews.

Interview Participant	Date of the Interview	Time of the Interview
Construction Manager	3/3-2022	56:29
Production Manager	4/3-2022	31:32
Hydrogeologist	8/3-2022	53:43

4.3. Cost-Effectiveness Analysis

In this section the theory and application of the CEA analysis method is described in *Section 4.3.1.* and *4.3.2*.

4.3.1. Theory

CEA is a method used to evaluate risk-reducing alternatives with regards both to their costs and their effectiveness to reach a certain outcome (Levin & McEwan, 2000). CEA is commonly used as a decision-making tool to evaluate and choose the most cost-effective alternative to allow for an efficient use of society´s resources. It is important to acknowledge that the most effective alternative could be several times more expensive than the most cost-effective alternative.

Furthermore, the alternatives in a CEA should relate to the same goals and outcome, in this case to investigate risk-reducing measures to counteract groundwater drawdowns as a result of a leakage. The costs represent the economic, environmental, and social costs, in monetary terms, of carrying out the risk-reducing alternative. The effectiveness represents the degree to which each risk-reducing alternative meets the goal of not impacting the groundwater. Thus, this method allows for all risk-reducing alternatives to be evaluated with regards to their costs and how well they meet the same effectiveness goal. The risk-reducing alternative with the lowest calculated cost/effectiveness ratio will be considered the most profitable alternative to invest in (Levin & McEwan, 2000). However, this method does not consider the benefits of each risk-reducing alternative, meaning it cannot be known whether the total benefits exceed the total costs of the risk-reducing alternatives. Therefore, benefits of the risk-reducing alternative must be accounted for in another way, e.g., by describing them qualitatively.

4.3.2. Application

The first step of conducting the CEA was to compile the risk-reducing measures identified in the interviews with the construction manager, production manager, and hydrogeologist. The second step included collecting data about the costs related to the risk-reducing measures with expert elicitation (*Section 2.2.*). The consulted experts can be seen in *Table 2.*

Table 2: Overview of the conducted expert elicitations.

Expert Participant	Date of the Elicitation
Construction Manager	6/4-2022
Production Manager	6/4-2022
Hydrogeologist	8/4-2022

Four types of costs, connected to the risk-reducing alternatives, was of interest when eliciting the data: *implementation costs*, *delay costs*, *environmental costs*, and *social costs*. The implementation cost includes material, manhours, and machinery costs. The delay cost includes the cost of the time of which the project is delayed due to implementing the risk-reducing alternative. The environmental cost includes the costs of carbon-dioxide equivalents (CO_2-eqv.) from transportations and from the machines used on-site. The social costs include air pollution, noise pollution, and accident risk from transportations related to the risk-reducing alternatives. *Appendix C* presents the expert elicitation guide.

Two elicitation sessions were conducted, one with the project manager and one with the construction manager. Both the production- and construction manager worked close to the production at stage one of Packhuskajen and had good knowledge regarding the implementation- and delay costs related to the risk-reducing alternatives. Additional questions which arose after the elicitation sessions were sent out by email. Data that could not be collected from the production- and construction manager was obtained by consulting the hydrogeologist. The amount of CO_2-eqv. from transportations and machines on-site were calculated with an environmental tool developed by Skanska. The transportation routes were retrieved from environmental product declarations (EPD) and from the material suppliers. The analysis method ASEK 7.0 (STA, 2020) was used to retrieve the cost per emitted kilogram CO_2-eqv., *7 kr/kg CO_2-eqv.*, as well as marginal costs for air- and noise pollution, and accident risks.

Some costs were not included in the CEA due to lack of data or because they were not relevant for the specific case study. Environmental costs from production of the materials were not accounted for since there was no available data for some of the risk-reducing measures. The cost of air pollution and noise from construction machines could also not be evaluated due to lack of data. Delay costs related to implementation of the risk-reducing measures were not relevant for the case study, according to the elicited experts since none of the risk-reducing measure alternatives was considered to affect the progression of the project. However, these kinds of costs are valuable to consider if possible since they contribute to a more reliable estimation of the total cost.

To take uncertainties regarding ground conditions, possible disturbances, and expert elicitation into account, a minimum, a most likely, and a maximal value of the costs and the time required to install the measures were elicited. Using the Bayesian method (*Section 2.1.2*) with the built-in excel software @Risk, the Beta-PERT distribution was chosen since it allows for defining a minimum, a most likely, and a maximum value for each cost and time value (Salling, 2007). The Beta-PERT distribution derives a smooth curve, see *Figure 17*, such that the most likely value and the values close to it are weighted higher than the values near the minimum and maximum. According to Salling (2007), this distribution is favourable when eliciting data from experts, however the input quality can limit its ability to construct reliable results. Inevitably, better expert judgements lead to better simulated results. @Risk uses the Monte Carlo method (*Section 2.1.2.*) to simulate possible results by using random data within the chosen probability distribution, 10.000 iterations were used in this analysis. Uncertainties regarding carbon dioxide emissions from transports for alt. 1-6 and from the compressor for alt. 1-8, air- and noise pollution, and accident risk could not be estimated due to data constraints. These were only assigned a point value.

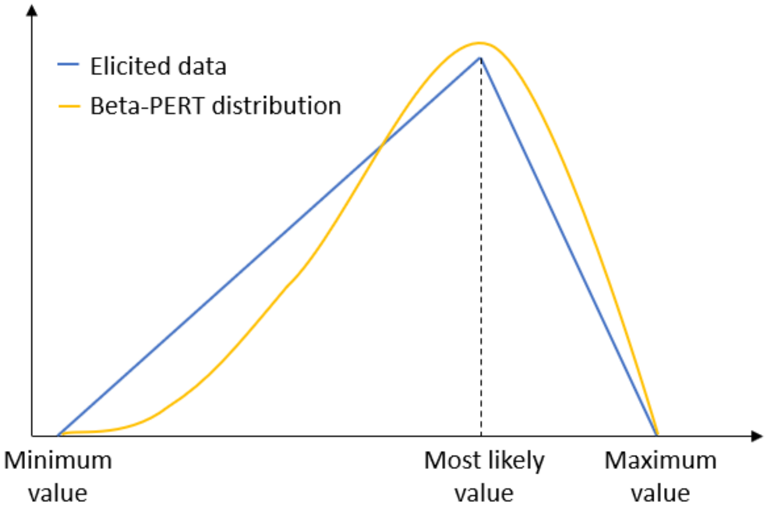


Figure 17: Illustration of an example of a constructed Beta-PERT distribution curve estimated from elicited data (modified from Salling, 2007).

The cost-effectiveness of the risk-reducing measures was calculated with *Equation 1*, suggested by the Prime Minister's Strategy Unit (2004).

$$CE\ ratio = C_X / E_X \qquad (1)$$

Where:

$CE\ ratio =$ the cost effectiveness in [SEK];
$C_x =$ the cost of risk reducing measure x in [SEK];
$E_x =$ the effectivness of risk reducing measure x in [%].

The effectiveness (E_x) in in this analysis was assumed to be 100% for all risk-reducing alternatives since it was derived from the interviews that all measures could be implemented to such an extent that a leakage is expected to not occur. The uncertainty for the different measures is however included in the costs by defining probability functions regarding the cost of implementation and the time needed to implement the measure. The @Risk software was used to perform a sensitivity analysis to determine the contribution of the individual inputs to the uncertainty of the results. For this analysis, the spearman rank correlation coefficient was chosen for the sensitivity analysis. A value close to +1 suggest a strong positive dependency of the specific parameter meanwhile a value close to -1 suggest a strong negative dependency of the specific parameter (Merisalu, 2021). A value close to 0 suggest a weak dependency. To account for the uncertainty of the costs where only point values were available, and to evaluate the impact of these cost parameters on the overall result, a manual sensitivity analysis was performed. The minimum and maximum value for these parameters was set to +/- 5% and +/- 50% to see how they may affect the result. Including these distributions in the sensitivity analysis provides an indication on how an uncertainty of these parameters would affect the overall result making the analysis more robust.

As a final step, the @Risk excel tool was used for calculating the probability of each alternative being the most cost-effective. Using an if-equation, the alternative being the most cost-effective was given the number 1 and the others the number 0. This was done for 10.000 iterations where the probability of being the most cost-effective is given by summarizing the number of times each alternative was given the number 1 divided by the number of iterations.

4.4. The Observational method

In this section the theory (*Section 4.4.1.*) and application (*Section 4.4.2.*) of how the observational method is integrated to this thesis is described.

4.4.1 Theory

The observational method is commonly used for handling changes to the level of uncertainty as a project progress, especially in projects where the ground conditions are uncertain and complex (Peck, 1969). The method is used when designing geotechnical structures and consists of the main objectives to predict, monitor, review, and modify the design as the project gradually progresses (Tidlund et al., 2022). Eurocode 7 (IEG, 2010), the European standard for geotechnical design, recommend using the observational method when the ground conditions and geotechnical behaviour cannot be sufficiently predicted (Spross & Larsson, 2014).

The observational method is implemented in the design phase where a preliminary design is created based on the conditions that can be anticipated or foreseen (Spross & Johansson, 2017). During the construction stage, the structure and conditions are continuously observed with a pre-defined monitoring programme and if the conditions deviate from the anticipated, risk-reducing measures will be implemented in line with an action plan. This means that the final design is not known before the project is completed (Tidlund et al., 2022). The process is iterative and aims to use the information retrieved from observations made during the construction stage to reduce uncertainties due to lack of knowledge and data, i.e., epistemic uncertainty.

When implementing the observational method, the following five requirements stated in Eurocode 7 needs to be fulfilled before the production begins (Spross & Larsson, 2014):

1. Define acceptable limits of behaviour.
2. Determine the range of possible behaviours, which should be within a reasonable probability of meeting acceptable limits of behaviour.
3. Establish a monitoring programme where it can be observed if the behaviour meets the acceptable limits. To ensure that risk-reducing measures can be implemented successfully, the monitoring should begin at an early stage and be performed within reasonable time intervals.
4. Select instruments and procedures which will provide information of deviations from the acceptable limits fast enough, in relation to the hydrogeological characteristics, to ensure that the monitoring programme will be successful.
5. Establish an action plan, including several risk-reducing alternatives, which can be implemented if the monitoring shows behaviours that exceed the acceptable limits.

Generally, the design which offers the lowest possible cost while still meeting set formal requirements such as e.g., structural safety is the most appropriate choice (Tidlund et al., 2022). The observational method offers many possibilities of cost- and time savings while acceptable levels of safety are maintained (Peck, 1969). It has the potential of providing an assurance of a construction where risks are handled in a way that is financially viable.

4.4.2. Application

The principles of the observational method were applied to the *Risk Treatment* and *Monitoring and review* parts of the ISO risk management framework, where the five requirements stated in Eurocode were followed. Minor temporary leakages are set as the acceptable limit since it is inevitable due to the installation process of the piles, however, no permanent groundwater impact is allowed. The minor leakages during the installation process of the piles are within the acceptable range of behaviour, as soon as the leakage shows signs of being more extensive it is out of the acceptable range of behaviour.

Establishing and following a monitoring plan was the main step for monitoring and review to ensure that the actual behaviour was acceptable in real time, allowing for implementation of risk-reducing alternatives in the action plan if signs of groundwater leakage was observed. All risk-reducing measures were combined with a monitoring programme to ensure that the acceptable limit is not exceeded. The monitoring programme used for stage two at Packhuskajen includes information regarding the following:

- Responsibilities and organisation;
- Observation points;
- Measuring of groundwater levels;
- Frequency of the measurements;
- Alert- and alarm levels;
- Functionality check of piles;
- Ocular inspection of piles;
- Potential damages to observation wells and de-establishment;
- Recommendations.

Instruments measuring defined monitoring parameters and analysis of data provides information of deviations from the acceptable limits. An action plan including risk-reducing alternatives arranged as a staircase provided guidelines on what actions to implement depending on the hydrogeological behaviour. The risk-reducing alternatives included in the action plan were chosen based on the results from the interviews and the CEA, where both the profitability and other aspects from the interviews were considered.

4.5. Research Quality

Bell et al. (2019) suggests that qualitative studies should be evaluated according to the criteria *trustworthiness* and *authenticity* to ensure the quality of the study. Trustworthiness consists of four sub-criteria: *credibility, transferability, dependability,* and *confirmability.* The credibility of the study has been ensured partly by verifying that all respondents repeated similar answers which confirmed that the information is accurate, by establishing a prolonged engagement with the respondents which allowed for familiarization of the setting and context to test for potential misinformation and to get to know the retrieved data (Korstjens & Moser, 2018).

As for transferability, qualitative research tends to focus on specific issues with an emphasis on depth rather than breadth (Bell et al., 2019). This study certainly follows the typical narrow path of qualitative research focusing on risk management of a specific piling method. The study is based on an extensive literature review providing a rich number of details as well as one case study also described thoroughly. These extensive, deep descriptions relate to *thick descriptions*, which are rich accounts of details of a specific topic that provides others outside of the specific topic with data to assess the potential transferability of the findings to other contexts (Bell et al., 2019). This is highly relevant for this study as the main aim is to demonstrate a general methodology applicable to not only a specific type of construction project, but all construction projects using drilled steel pipe piles. In addition to thick descriptions, having respondents with different roles and views further increase the transferability of the study.

Regarding dependability, the entire research process has continuously been audited and evaluated by the supervisor. A peer-review performed by an opponent at the end of the study provided valuable input and critique which increased the quality of the study and ensured that the criterion of dependability was fulfilled.

The fourth and last sub-criterion, confirmability, relates to the objectivity ensuring that personal values do not interfere with the results of the study. This criterion was fulfilled by having the two authors involved in all parts of the study as well as having the supervisor involved in the work process and interfere in case there were signs of slipping away from objectivity.

The second criterion, authenticity, puts emphasis on the research to represent different viewpoints. This is mainly ensured by having a focus on three sustainability dimensions: environmental, economic, and social. These sustainability dimensions opened for a broad discussion including additional perspectives beyond the traditionally dominant economic focus in the construction industry.

4.6. Ethical and Sustainability Considerations

It is important to consider ethical aspects when using a qualitative research approach since data is obtained through softer non-numerical methods, for this thesis, interviews. Bell et al., (2019) highlights the following four issues to be considered: *harm to participants, lack of informed consent, invasion of privacy,* and *involvement of deception.*

No participants were harmed (e.g., stress, harm to career prospects or physical harm) during the data collection which consisted of interviews. Regarding informed consent, all the interviewees were informed in advance of the purpose of the interview and how their specific knowledge could contribute making sure they were well informed and could decide to participate or not based on this information. As for privacy, it was asked if the interviewees consented to the interviews being recorded and if they wanted to remain anonymous in the thesis. In addition, it was informed that the recordings would be deleted once the thesis had been accepted. There was no involvement of deception when conducting this thesis, the aim of the research and interviews were clearly stated, transparent and objective. A final ethical consideration regarding the interviews was that the interviewees were chosen based solely on their expertise and how they could contribute to the research, no regards were taken to e.g., gender or personal values.

This thesis took all three sustainability dimensions into consideration since it highlights the economic, social, and environmental consequences of leakages through drilled steel pipe such as e.g., settlement induced damages and costs, stress, and changed ground chemistry due to drawdowns. Furthermore, the three dimensions were considered when analysing the risk-reducing measures by conducting the CEA. A CEA is mainly performed to assess the profitability of risk-reducing measures, i.e., economical sustainability. In a similar way the environmental and social sustainability was addressed by investigating the environmental and social costs of implementing the risk-reducing measures, i.e., cost of CO_2-eqv. emissions, air pollution, noise, and traffic accidents.

5. Results

This chapter presents the results of the study where Section 5.1. presents the empirical data from the interviews. Section 5.2. presents the results from the CEA and from the observational method, i.e., the action plan, in line with the ISO 31000:2018 framework.

5.1. Interviews

The most important data retrieved from the interviews are presented in this section. *Section 5.1.1.* summarizes the answers from the construction manager, *Section 5.1.2.* summarizes the answers from the production manager and *Section 5.1.3.* summarizes the answers from the hydrogeologist.

5.1.1. Construction Manager

Henrik Andersson has worked several years in the civil engineering industry as a construction manager consultant, but also as a project manager and as a contractor (Personal communication, 3rd March 2022). His competencies include, amongst others, construction processes, construction coordination, financial management, time planning, legal risks in construction projects, and environmental issues linked to construction production. At Packhuskajen, Andersson is employed as a construction manager by the client, the parks and recreation department in Gothenburg municipality.

Andersson explains that the groundwater leakage from the drilled steel pipe piles was discovered by the STA at the construction site of the tunnelling project, Västlänken. Västlänken has a water court ruling that prohibits groundwater impacts meaning a complete measurement programme at the area exists. The Västlänken staff noticed a pressure reduction in their observation wells close to Packhuskajen and contacted Andersson. According to Andersson, the management team was first hesitant that the leakage was due to their activities since the groundwater drawdown was not noticed until half of the piles were already drilled. However, a pressure recovery could be seen one hour later after implementing safety measures for the piling indicating that the piles where leaking which subsequently caused an impact on the groundwater levels.

In the early stages of the project, it was intended that the construction would consist of concreate piles but due to the old brittle quay, a concrete pile crane could not be used at the site due to its heavy weight. Even though it was mentioned during the internal discussions of the transition to drilled steel pipe pile that this construction type could lead to a large amount of groundwater leakage, Andersson emphasizes that the groundwater leakage occurred due to lack of knowledge in the project management group. Thus, Andersson thinks that it should have been appropriate to include an action plan from the beginning. Furthermore, Andersson believes that the leakage could occur due to an insufficient water court ruling. The permission for water operations only covered requirements concerning the surface water impact, hence there were no demands regarding groundwater activities.

According to Andersson, no significant project internal consequences was identified during the construction time. The expenses increased marginally since a hydrogeology consultant was hired and since there where extra material, manhours, and machine costs for the implemented safety measures. The identified external consequences concerns stress and extra time for the team working at Västlänken since an investigation of the origin of the pressure drop had to be carried out. Furthermore, the Västlänken team was assisting with data from their observation wells during the production since Packhuskajen did not have this equipment at the time. Andersson mentioned that he did not believe that the impact on the community would be significant due to the geographic location, beside the river, of Packhuskajen. However, nearby businesses can suffer from economic and social consequences such as extended noise, vibrations, dust, and transports, due to implementation of risk-reducing measures, which could affect their business. Furthermore, Andersson explains that the groundwater drawdown induced by leakage would have been greater if no risk-reducing measures had been implemented.

Andersson identified the risk-reducing measures used for stage one in the project at Packhuskajen including an action plan with what risk-reducing measures to implement. The risk-reducing measures included hiring a hydrogeologist with experience in the field, using gentle drilling instead of regular drilling, plugging the piles with fenders and sealing the piles with welded plates. During the installation infiltration was tested, however the test failed due to cold weather conditions freezing the water in the tubes. Andersson also mentions that an increased recovery time for the groundwater between drilling of the piles could be effective, but it would increase the production cost and affect the time plan a lot. Furthermore, Andersson discussed that changing the pile-type would have been an alternative to eliminate the risk of leakage. Due to the geography and brittle quay, this would however have been expensive since the concrete piles needed to be installed from the river. Concreate piles could also lead to other risks such as horizontal displacements which can be avoided with steel piles.

Andersson emphasises that they learnt a lot from stage one and that the gained knowledge is transferred into new routines for stage two. The project is currently applying for a water court ruling for future stages to ensure a better safety. Furthermore, a new extensive monitoring programme including for example several observation wells is going to be implemented for stage two. The leakage is going to be considered in the procurement of subcontractors, in terms of information that leakages may occur, what requirements that are given the subcontractor and how a leakage should be handled. Additionally, it is planned for having a better communication from the beginning with the staff.

5.1.2. Production Manager

The interviewee, Jan Leinonen, is a project manager at Skanska Väg och Anläggning in Gothenburg (Personal communication, 4th March 2022). During the first stage of project Packhuskajen, Leinonen worked as the production manager with responsibility for the production including e.g., following the time-plan and budget while making sure that the project met quality- and safety requirements.

According to Leinonen, the leakage was discovered when the nearby construction of Västlänken noticed changes to the groundwater levels in their observation wells. Since the observation wells which detected changes to the groundwater levels were near the working area of Packhuskajen, and that the personal at site could visually see water leaking from the piles, it was concluded that it might be project Packhuskajen that affected the groundwater levels. This was probably the case since the groundwater levels stabilized quite immediately once Packhuskajen implemented measures to reduce the leakage.

As for reasons why the leakage and drawdowns could occur, Leinonen explains it as a combination of communication failure and a lack of knowledge. In the planning phase of the project, the pile type was changed from concrete piles to steel pipe piles. However, no monitoring programme for managing the potential impacts of groundwater levels due to the change of pile type was implemented or even considered. No one really thought of the risks associated with steel pipes during the planning phase of the project. Instead, it was discovered during the construction phase meaning the project had to try different measures until an adequate method was found. Not identifying the potential problem of groundwater impact was the biggest concern according to Leinonen. Leinonen also emphasizes that it was a construction contract where a consultant firm oversaw the project planning, and that it is not certain that the communication within different disciplines always works as you want it to.

The project did not face extensive internal consequences according to Leinonen. A production standstill was not far away since the groundwater impact became more and more evident. However, they managed to implement measures and restore groundwater levels before the project reached that point. A production standstill could potentially have been a large risk for the project from several points of view. The internal consequences which arose due to the leakage were of marginal nature and included material costs for the measures, extra time and work for skilled workers, time to test different measures and administrative time for the site managers. Regarding the consulting cost for the hydrogeologist and to develop the monitoring programme, Leinonen points out that those costs go directly to the client, but he can imagine that they are not insignificant. As for external consequences, Leinonen cannot identify any external consequences, except for taking up some time from the people working on monitoring the ground water levels at Västlänken.

When it comes to safety measures, the project had to try different alternatives until a sufficient method was found. Leinonen explains that the piles were plugged with fenders, however, they flew away as soon as there was a change to the pressure in the ground due to surrounding drilling. They also experimented with the cut-off length of the piles to balance the pressure. The most efficient method turned out to be a combination of using fenders to plug the pile and welding a plate on top of the pile to seal it. A measure when a leakage and change to the groundwater levels already had occurred was artificial infiltration of the aquifers. Leinonen emphasizes the importance of managing the risks of the leaking piles, however, it is not always obvious what measures to implement.

For the upcoming stages of construction, Leinonen explains that they have learnt from the first stage. A monitoring programme and a plan for what measures to use is in place. The project has installed their own observation wells to monitor the groundwater. As for knowledge transfer, job plannings including information regarding work stages, measures etc. have been done and will be communicated throughout the upcoming stages of the project. Skanska has a system for descriptions of work stages occurring at a regular basis. However, no large-scale handling of the information has been done since the project is rather unique according to Leinonen. For this project, informal communication between one and another has been common in addition to regular documentation.

5.1.3. Hydrogeologist

Linn Ödlund Eriksson works as a hydrogeologist at Sweco in Gothenburg (Personal communication, 8th March 2022). Ödlund Eriksson has several years of experience of groundwater impact from installation of steel pipe piles where she has developed many monitoring programmes and follow-ups to manage the impacts. For project Packhuskajen, Ödlund Eriksson helped with questions related to the hydrogeology and to develop a monitoring programme.

According to Ödlund Eriksson, project Packhuskajen was contacted by Västlänken who claimed that Packhuskajen had lowered the ground water levels and asked what the solution would be. Västlänken based this on a measuring point in direct proximity to the area where the piles were installed at Packhuskajen which showed that the groundwater level had been lowered. Ödlund Eriksson explains that the lowering of the groundwater level decreased significantly once measures were implemented.

As for reasons why the leakage and drawdown could occur, Ödlund Eriksson emphasizes that a lack of knowledge regarding how the steel pipe piles affects the mechanisms of the hydrogeological system probably was one contributing factor. Generally, there is a very poor understanding of how hydrogeology can affect projects and Ödlund Eriksson highlights that it is difficult to make project organizations realize that consulting a hydrogeologist is a great start for managing these risks. In addition, Ödlund Eriksson mentions that a hydrogeologist and skilled workers and others working in the project probably have very different views of what a leakage is, especially when it comes to confided aquifers. An example is that skilled workers might only believe that the pile is leaking if water is visually seen coming out from the pile, meanwhile a hydrogeologist knows that the pile is leaking if it is just damp on the outside since this implies that water is slowly sipping out of the pile.

Internal consequences according to Ödlund Eriksson included increased stress for the responsible personnel, additional time spent, material costs for measures and costs for hiring a hydrogeologist. Ödlund Eriksson does not believe any substantial costs arose. However, a new project risk with a lot of uncertainties arose which could lead to increased stress levels for the personnel at Packhuskajen. Impacts on Västlänken’s groundwater levels and possibly their ability to meet their requirements constitutes the external consequences according to Ödlund Eriksson.

Ödlund Eriksson explains a few safety measures that can and was used in the first stage of Packhuskajen. Gentle drilling by means of using a water-driven hammer instead of an air-driven one could be a preventative measure. However, it is uncertain to what degree this method is effective. Extending the piles to make them as long as possible could also be a preventative measure as this reduces the risk of the water sipping out of the pile. Ödlund Eriksson emphasizes that plugging and sealing the piles immediately when the impact on groundwater was detected was the first and most effective measure taken at Packhuskajen. Two methods can be used when plugging and sealing the piles, either to implement a routine to seal the piles within x hours from drilling them or waiting and observing if the groundwater levels change and then seal them. Plates were welded to the top of the piles to prevent the fenders from flying away. Artificial infiltration was also used as a measure. In addition, Ödlund Eriksson highlights that providing the project with adequate competence also could be a safety measure.

For the upcoming stages, the project has taken advantage of the lessons learned from stage one according to Ödlund Eriksson. Hydrogeological competence is part of the project organisation, a monitoring programme is in place, observation wells are installed, cooperation with Västlänken and coordination regarding the hydrogeology among the parties involved in the project are all working methods which have been implemented.

5.2. Risk Management of Drilled Steel Pipe Piles at Packhuskajen

This section presents the results of applying the ISO 31000:2018 framework to the case study of Packhuskajen. *Section 5.2.1.* introduces the context of the Packhuskajen risk assessment, followed by *Section 5.2.2.* which qualitatively demonstrates the identified risks connected to Packhuskajen and how to conduct a risk analysis. The identified risk-reducing measures as well as which risk-reducing alternatives are further analysed is also described. *Section 5.2.3.* presents the risk evaluation including results from the CEA and sensitivity analysis. Risk treatment and monitoring and review is presented in *Section 5.2.4.* including the established action plan.

5.2.1. Establishing the Context

The purpose of the general methodology proposed in this study is to provide a strategy for risk management when using drilled steel pipe piles. The risk management aims to result in a reduction of potential risks and provide decision support for implementation of risk-reducing measures based on both project internal profitability and socio-economic values.

A CEA was deemed to be best suited for this case study, since it could be determined, based on the interviews, that all risk-reducing alternatives were 100% effective by means of preventing a groundwater leakage and subsequently damaging impacts from groundwater drawdown. Thus, it was assumed that none of the alternatives contributed to damaging external impacts and therefore no external benefits in the form of risk reduction on potential objects at harm needed to be evaluated.

The risk-reducing alternative with the lowest calculated cost/effectiveness ratio is the alternative implemented as the preliminary design. In line with the observational method, other alternatives are also prepared if any deviation from the preliminary understanding of the technical-hydrogeological system is detected. A risk management strategy for drilled steel pipe piles is of importance for the project at Packhuskajen to manage the risk of groundwater leakage. However, a risk management strategy is also an important asset for future projects implementing steel pipes as their design choice, and that is facing legal requirements in the form of limitations regarding groundwater impact, issued by the Land- and Environmental court and/or from the County Administration.

The timeframe of the event extends though the time during the piling, considering that there is no risk of a leakage through the piles when the installation is complete since the piles are then filled with concrete. However, with regards to a possible detention time before registering leakages, observations of the groundwater pressure head should be done after the piling in completed as well.

5.2.2. Risk Identification and Analysis

The relevant risks connected to this specific case study, identified from the interviews (*Section 5.1.*) and the background study (*Section 3.4.*), are presented in *Table 3.*

Table 3: Identified risks at Packhuskajen.

Risk	Description
Long-term impact on the groundwater.	If no risk-reducing alternatives are implemented, the groundwater may be significantly affected and lead to several risk events. Groundwater drawdowns can lead to settlements which can damage the built-up environment. Natural and archaeological values can be damaged as well, due to changed groundwater level and changes in the groundwater chemistry. A long-term impact could also lead to fines if the permission for water-operations or the water court ruling is violated.
Affecting surrounding construction projects.	Other projects working in the near surroundings of Packhuskajen can be affected by a leakage at the Packhuskajen project. If a drawdown is observed by another project, e.g., Västlänken, an investigation probably needs to be performed. This consequence constitutes stress and extra time for the affected personnel at the other projects. If the leakage is extensive and not handled properly, it could affect the progression of Västlänken negatively which could lead to increased expenses for the project and delayed benefits from the rail tunnel for the society, e.g., reduced carbon dioxide emissions and reduced travel times
Increased stress level for personnel.	A leakage during the production could lead to increased stress for the personnel due to the extra time and effort spent. Lack of knowledge about what a leakage could lead to, both environmentally and economically, may also increase the stress level and therefore loss of competence if personnel choose to resign.
Operational disruptions and downtime in production.	A leakage could lead to operational disruptions and delays of the construction activities. These disruptions and delays often lead to increased project internal expenses such as e.g., additional costs for equipment, material, machinery, manhours, and changes to the schedule. If the construction time is prolonged, surrounding communities could be affected by extra noise and air pollution as well as delayed benefits from the construction.

Assessment of the probabilities and consequences from the identified risk events were not conducted for this study since the risk-reducing alternatives implemented were assumed to always be 100% effective which means that there is no need of monetarizing the risks. This is due to the results of the interviews and implementation of a robust monitoring programme for all risk-reducing alternatives, which makes it possible to detect groundwater impacts before significant risks can occur. Therefore, a CEA could be performed only evaluating the economic, environmental, and social costs for implementing the risk-reducing alternatives. However, the assessment of probabilities and consequences could had been structured by using e.g., an event- or fault tree which are logical models showing all possible outcomes because of an initiating risk event occurring. The probabilities and consequences of the risk events could in turn have been retrieved from e.g., settlement- and traffic-disruption calculations.

For the risk analysis, eight risk-reducing measures were identified as relevant to manage the risk of leakage based on the interviews. The measures expected to be reasonable for further study included:

Plugging and sealing the piles immediately which means that within *x* hours from being installed, the piles are plugged with a fender and a plate is welded on top of it to prevent the fender from flying away in case of large pressure heads in the penetrated confined aquifer. *Plugging and sealing the piles after an observed impact on the groundwater including an automatic system for groundwater measurements* means that the piles are plugged and sealed with fenders and plates first when an impact on the groundwater through observation has been stated, i.e., through the observation wells or with ocular inspection. This measure will require an automatic system for groundwater measurements to ensure that leakages are detected.

Extending the piles to correspond with the groundwater pressure head which means that the pile is extended with the purpose to have the upper edge of the pile higher than the pressure head. If the length of the pile is beneath the groundwater pressure head, water will rise above the edge and leak through it.

Infiltration of groundwater which means that drinking water is infiltrated into the lower aquifer through the drilled steel pipe piles. This method can be used to faster regain the original groundwater level in case of an extensive leakage.

Regular or gentle drilling, constitute a method where the pile is flushed either with air, *regular drilling,* or water, *gentle drilling.* Gentle drilling can reduce the unavoidable groundwater disturbance during the installation since a lower pressure of the flushing water is required to remove material and hence less groundwater would be removed. In addition, gentle drilling also has the advantage of being able to drill through certain objects in the soil.

The risk-reducing alternatives were set to be combinations of the measures described, see *Table 4*. All risk-reducing alternatives were considered to satisfy the acceptable limit, i.e., leakages which cause permanent groundwater impacts does not occur. However, all alternatives were required to be combined with a monitoring programme to ensure that the acceptable limit was not exceeded. For Packhuskajen, the method of measurements depends on which risk-reducing measure is chosen. If safer risk-reducing measures are implemented i.e., sealing and plugging the piles immediately and extending the piles to correspond with the groundwater pressure head, it means that the groundwater level can be measured manually. The other risk-reducing measures, i.e., when plugging and sealing after an observed impact on the groundwater, requires an automatic system for groundwater measurements to detect deviations to the acceptable limits rather immediately.

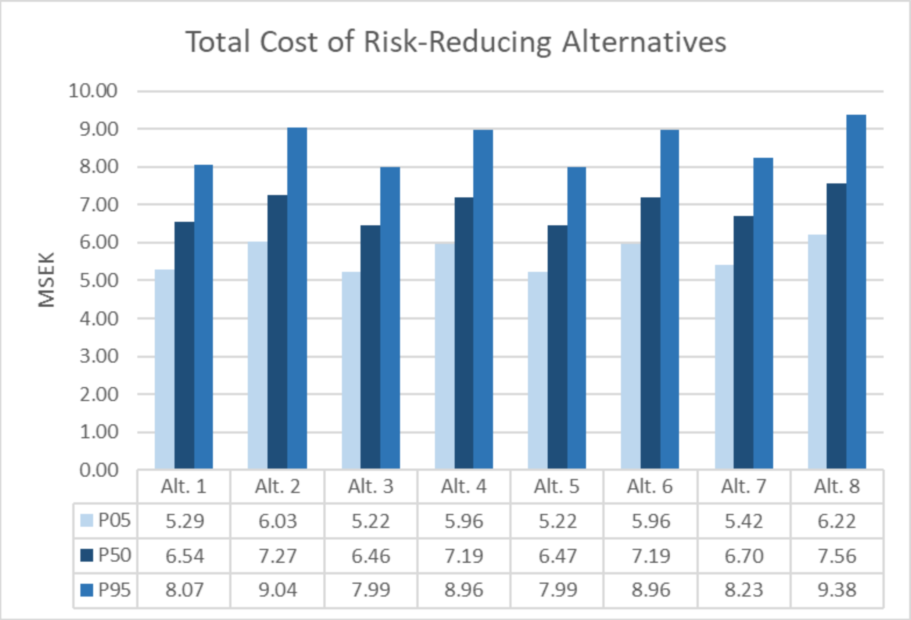
Table 4: Risk-reducing alternatives.

Risk-Reducing Measures	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**	**Alt 6**	**Alt 7**	**Alt 8**
Plugging and sealing the piles immediately	x	x						
Plugging and sealing the piles after an observed impact on the groundwater including an automatic system for groundwater measurements			x	x	x	x		
Extending the piles to correspond with the groundwater pressure head							x	x
Artificial infiltration of groundwater					x	x		
Regular drilling	x		x		x		x	
Gentle drilling		x		x		x		x

5.2.3. Risk Evaluation

The CEA is based on empirical data from the interviews and data retrieved from expert elicitation sessions as described in previous sections. The results are presented with four histograms which shows the total cost for each risk-reducing alternative as well as the costs divided into environmental costs, social costs, and implementation costs, see *Figure 18-21*. The histograms include an uncertainty interval which shows the most probable cost, the 50th percentile from the Monte Carlo simulations, as well as the 5th percentile and the 95th percentile. An exception is the histogram showing the social costs since these were only calculated with an absolute value, the most probable cost due to lack of data and the possibility to elicit experts. A sensitivity analysis for alternative 2 is also presented (see *Appendix D-F* for the sensitivity analyses of the other alternatives).

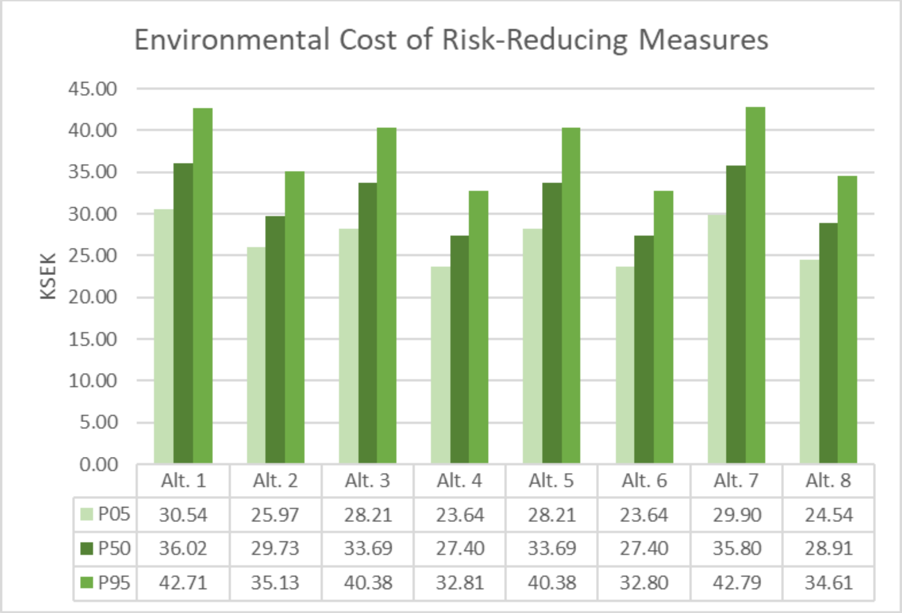
The histogram in *Figure 18* shows the total costs of each risk-reducing alternative from the CEA. Alternatives 1, 3, 5, and 7 include regular drilling meanwhile alternatives 2, 4, 6, and 8 include gentle drilling, where the total costs for respective drilling method are rather similar. All alternatives including gentle drilling have higher total costs compared to those with regular drilling. Alternative 3 has the lowest total cost for the alternatives with regular drilling meanwhile alternative 4 and 6 have the lowest total cost for the alternatives with gentle drilling. Alternative 7 and 8 has the highest total costs for each of the drilling methods.



	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8
P05	5.29	6.03	5.22	5.96	5.22	5.96	5.42	6.22
P50	6.54	7.27	6.46	7.19	6.47	7.19	6.70	7.56
P95	8.07	9.04	7.99	8.96	7.99	8.96	8.23	9.38

Figure 18: Total cost of implementing the risk-reducing alternatives in MSEK.

Figure 19 shows the environmental cost of each risk-reducing alternative. The environmental cost for the alternatives with gentle drilling is lower than the alternatives using regular drilling. The least expensive alternatives are 3 and 5 for regular drilling and 4 and 6 for gentle drilling. Alternative 1 and 2 are the most expensive ones for regular drilling respectively gentle drilling.



	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6	Alt. 7	Alt. 8
P05	30.54	25.97	28.21	23.64	28.21	23.64	29.90	24.54
P50	36.02	29.73	33.69	27.40	33.69	27.40	35.80	28.91
P95	42.71	35.13	40.38	32.81	40.38	32.80	42.79	34.61

Figure 19: Environmental cost of implementing the risk-reducing alternatives in KSEK.

The social costs (air- and noise pollution and accident risks from transportations) of each alternative are presented in the histogram in *Figure 20* and shows that alternatives 7 and 8 by far has the lowest social costs out of all alternatives. Alternative 1-6 all have the same social costs since the transportation distance and vehicle type is the same for all these alternatives. The same goes for alternative 7 and 8 as they also have the same transportation distance and type of vehicle.

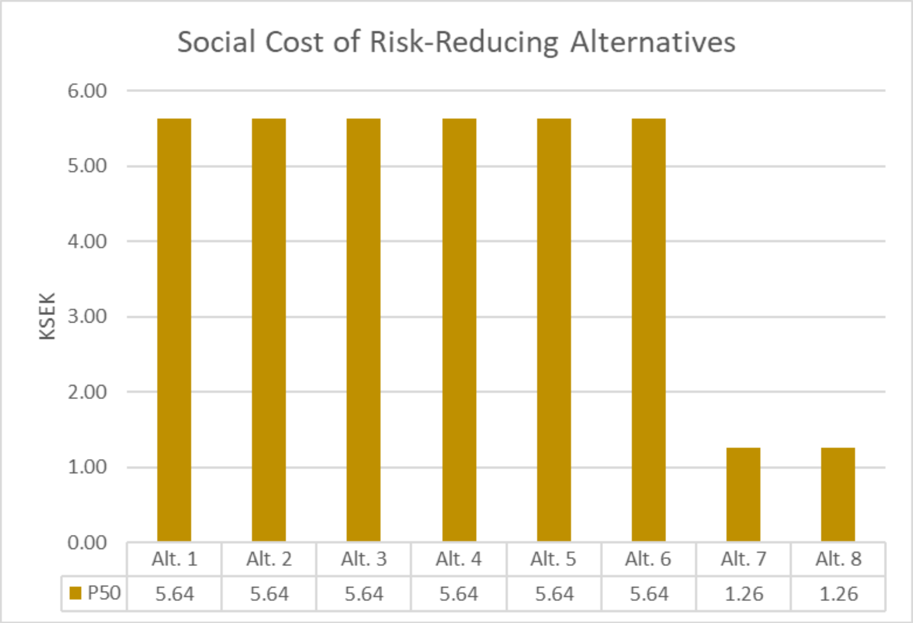


Figure 20: Social cost of implementing the risk-reducing alternatives in KSEK.

The implementation cost (*Figure 21*) is significantly higher than both the environmental and the social costs. Alternative 3 and 5 have the lowest cost for regular drilling meanwhile alternative 4 and 6 have the lowest cost for gentle drilling. The implementation cost for alternative 7 and 8 are the most expensive ones for regular- and gentle drilling.

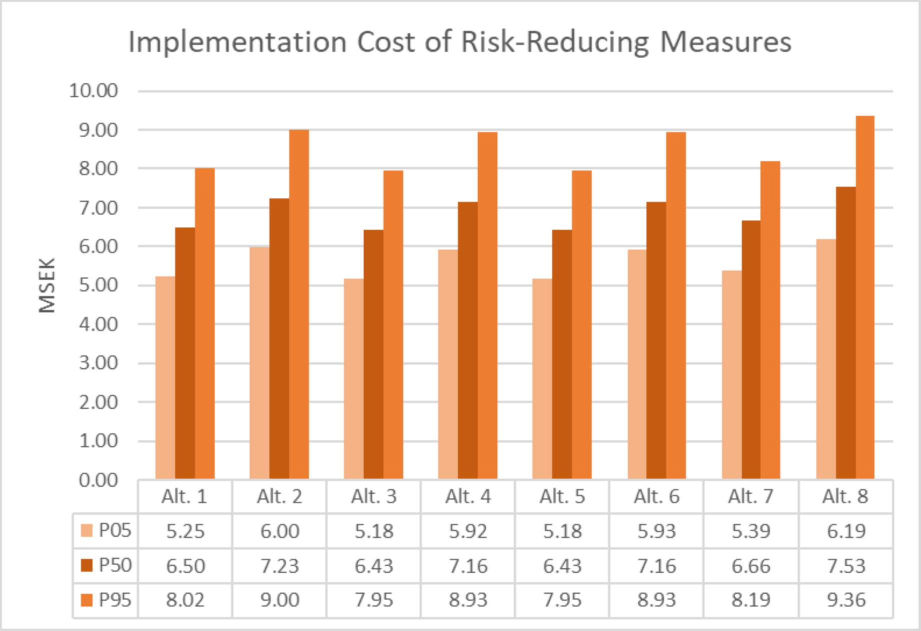


Figure 21: Implementation cost of implementing the risk-reducing alternatives in MSEK.

Figure 22 shows which parameters the total cost is the most dependent of and consequently how they contribute to the uncertainty of the total costs for alternative 2. The total cost is heavily dependent on the implementation cost as this value is 1. The cost of CO2-eqv. from the drilling rig shows a value close to 0, which indicates that it has a weak dependency to the total cost. The result for the other alternatives can be seen in *Appendix D*. As the social costs constitute of absolute values of the most probable cost, no distribution (P05, P50, and P95) was set to these costs meaning they are not included in the spearman rank correlation coefficient analysis.

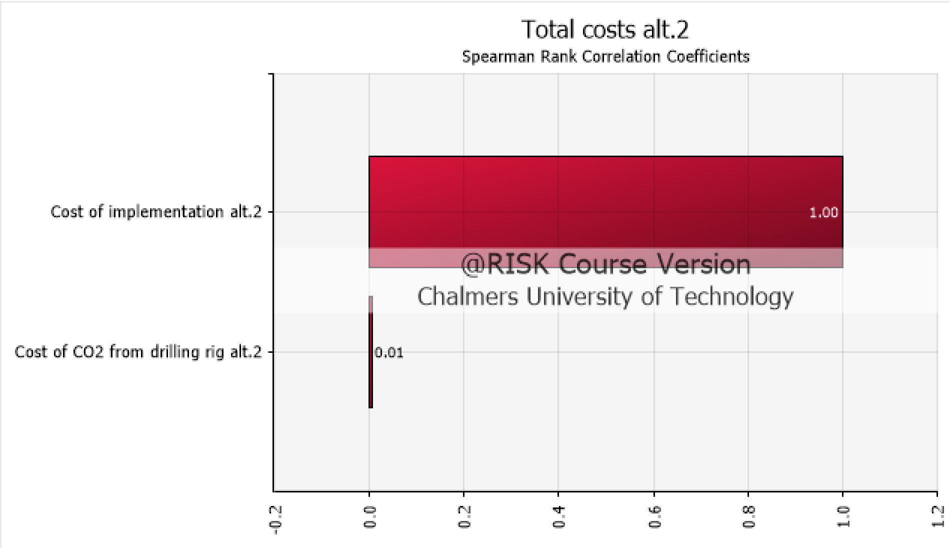


Figure 22: Spearman rank correlations coefficients for alternative 2.

The spearman rank coefficient for alternative 2 for the manual sensitivity analysis when setting the minimum and maximum value of the social costs to +/-5%, is shown in *Figure 23*. The result for the other alternatives can be seen in *Appendix E*. The implementation cost still contributes by far the most to the uncertainty of the total cost while the other costs have a weak dependency on the result.

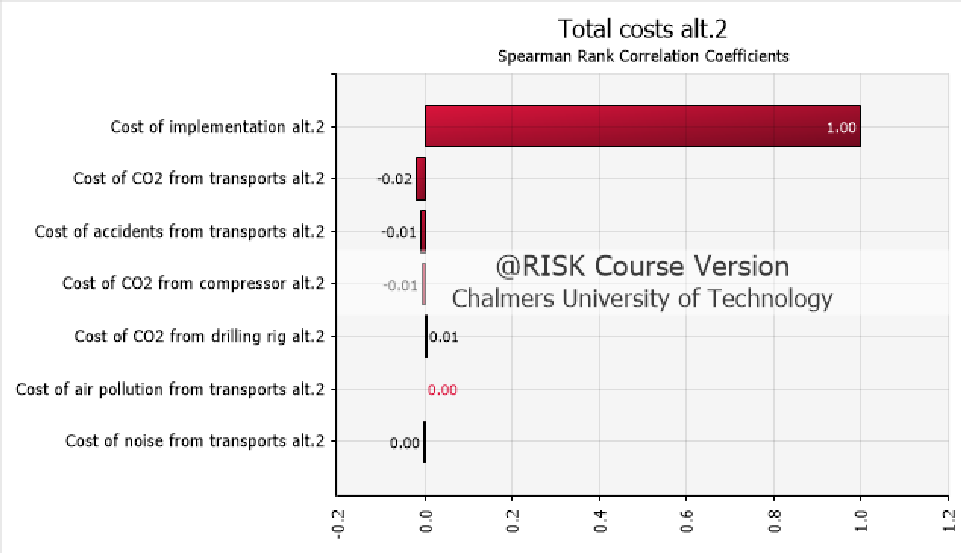


Figure 23: Manual sensitivity analysis of a 5% uncertainty for the social costs for alternative 2.

Figure 24 shows the manual sensitivity analysis for alternative 2, when setting the minimum and maximum values of the social costs to +/-50%. Results from the other alternatives is shown in *Appendix F*. A 50% addition of uncertainty did not change the result much, the implementation cost still has the strongest spearman rank correlation coefficient. The other parameters have a weak dependency on the result.

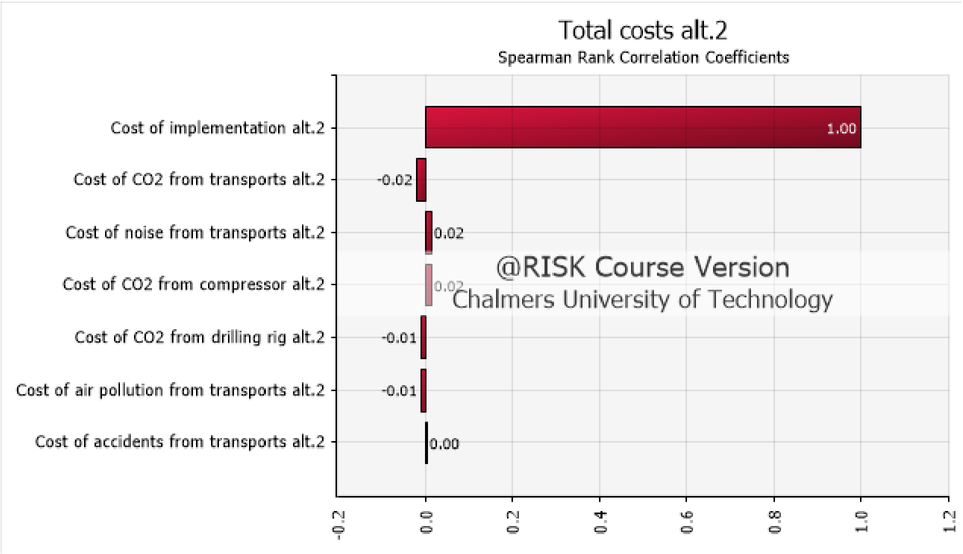


Figure 24: Manual sensitivity analysis of a 50% uncertainty for the social costs for alternative 2.

Table 5 shows the calculated probability for all alternatives being the most cost-effective. As can be seen, the alternatives using regular drilling have a much higher probability of being the most cost-effective alternatives, where alternative 3 has the highest probability.

Table 5: Calculated probability for the most cost-effective alternative.

	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**	**Alt 6**	**Alt 7**	**Alt 8**
Probability of being the most cost-effective alternative	0.2192	0.0301	0.2521	0.0393	0.2471	0.0420	0.1570	0.0132

Gentle drilling is the only drilling method considered as reasonable for Packhuskajen due to unsuitable ground conditions for regular drilling, see further explanation in *Section 5.2.4*. The probabilities of the alternatives using gentle drilling, i.e., alternatives 2, 4, 6 and 8, being the most cost-effective are shown in *Table 6*. Alternative 6 has the highest probability of being the most cost-effective one, closely followed by alternative 4.

Table 6: Calculated probability for the most cost-effective alternative for gentle drilling.

	Alt 2	**Alt 4**	**Alt 6**	**Alt 8**
Probability of being the most cost-effective alternative	0.2553	0.2971	0.2988	0.1488

5.2.4. Risk Treatment and Monitoring and Review

Based on the results from the CEA, alternative 6 is the most profitable one followed by alternative 2. Alternatives 1, 3, 5, and 7 are not relevant for Packhuskajen as there are old wooden piles, the bed of timber, and other potential objects in the soil that regular drilling cannot drill through.

The action plan (*Figure 25*) starts with a*cquiring hydrogeological competence* meaning that the project should advise a hydrogeologist about the hydrogeological conditions and the possible difficulties and risks before the piling starts. The next step is to implement the m*onitoring programme* which includes monitoring and collection of data regarding the natural and undisturbed groundwater levels in the area. Once sufficient data has been collected and analysed in such way that an impact on the groundwater levels can be detected, the piling can begin. Risk-reducing measure alternative 6 is set as the preliminary design for the start of the piling, meaning that this alternative is expected as most suitable for the conditions that could be anticipated and foreseen. Alternative 6 begins with piling and continually *observing* potential leakages and impacts on the groundwater levels. If a leakage or impact occur, *the leaking piles are plugged and sealed*. The monitoring of groundwater levels continuous to evaluate if the sealing measure where effective, thus if the hydrogeological system is recovering. If the hydrogeological system cannot recover within a reasonable timeframe, *infiltration to the adjacent open piles* is implemented to avoid that the production pace for upcoming piles is affected.

As the project progress, data regarding the performance of the implemented alternative is continuously collected to assess whether the next risk-reducing alternative in the action plan needs to be implemented. If the preliminary design shows unacceptable signs of performance i.e., if leakages keep occurring as the piling progresses, alternative 2 is implemented where *all upcoming piles are plugged and sealed immediately* after installation to reduce the risk of damaging groundwater impact. The monitoring and reviewing follows the progress of the construction where observations made reduces the uncertainties as the ground conditions become more and more known. It is important that the monitoring continues once the piling is finished, as it could be the last piles that cause a groundwater leakage and that it potentially could take some time to register a drawdown. To achieve a knowledge transfer, it is essential to document working methods throughout the project, and once the piling is finished, *transfer the gained knowledge to the organisation* so it does not get lost.

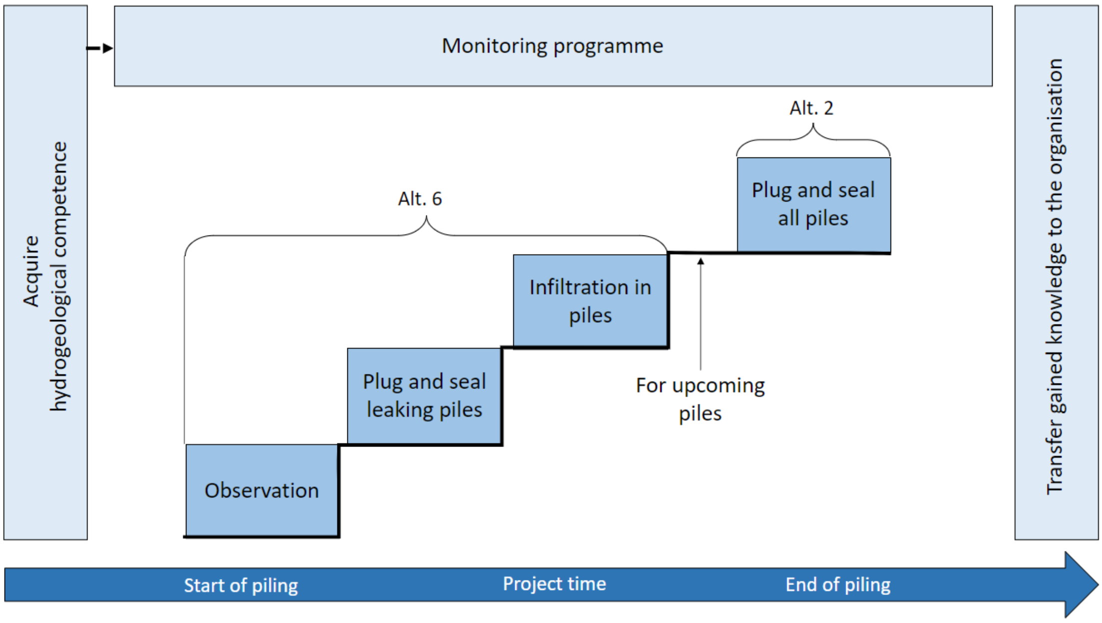


Figure 25: Action plan for risk-reducing alternatives at Packhuskajen.

Note that this action plan was established as a preliminary design for all stages at Packhuskajen to illustrate how it would look like if it was planned in the design phase. For Packhuskajen, continuous observations of leakages have already been observed in stage one. All piles should therefore be plugged and sealed in the upcoming stages.

6. Discussion

Chapter 6. discusses the results from the interviews, CEA, and observational method. The choice of methodology, data used, and how the thesis contributes to the industry is discussed.

The aim of this thesis was to demonstrate a methodology for management of hydrogeological risks caused by groundwater leakages through drilled steel pipe piles following the ISO 31000:2018 structure and to investigate how a CEA analysis and the principles of the observational method can be integrated to the structure. The outcome from the risk analysis should result in increased knowledge for the decision makers to partake in. This thesis applied the methodology on a real-world case study, Packhuskajen.

The result from the CEA shows that the risk-reducing alternatives including regular drilling was less expensive compared to the ones using gentle drilling. It can also be seen from the probability calculations of the cost-effectiveness that these alternatives by far are the most cost-effective ones. Regular drilling is not a reasonable alternative to use for this case study due to the site-specific ground conditions. However, for projects with more suitable ground conditions, i.e., no objects in the soil which regular drilling cannot drill through, it could be beneficial to investigate the benefits of using regular drilling since it had a lower total cost in the CEA. Regular drilling showed a slightly higher environmental cost which could turn out to be more extensive for large and complex projects. Furthermore, gentle drilling is the only drilling method of the two which can be seen as a risk-reducing measure since it is believed to be less intrusive. Consequently, gentle drilling could be beneficial to consider as the primary choice when drilling in environments with objects sensitive to groundwater impacts.

Alternatives 6 and 4 has the lowest total costs, i.e., that they are the most cost-effective, followed by alternative 2. The probability calculations of each alternatives cost-effectiveness are in line with the results of the total costs, where alternatives 6 and 4 has the highest probabilities of being the most cost-effective ones closely followed by alternative 2. Alternative 4 was ruled out since it has almost identical costs to alternative 6 but does not include infiltration as alternative 6 does. It is beneficial to include infiltration in the primary design since it is effective if a more extensive leakage with longer recovery time would occur. Therefore, alternatives 6 and 2 are chosen as the two risk-reducing alternatives of relevance for the action plan for hydrogeological risk management at Packhuskajen. Alternative 6 has a slightly lower cost compared to alternative 2. However, in the interviews, increased stress levels for the personnel were identified as a risk for this alternative. Stress for the personnel can result in both social costs for the society in the form of sick leave and illness, as well as in project internal costs since the project team may be reduced and perform less effectively if several project members suffer from illness or resigns. The social cost of stress has not been accounted for in the CEA. Considering that the difference between alternative 6 and 2 is rather small, approximately 80 000 kr, it could be motivated to only go with alternative 2 to avoid increased stress levels that the uncertainty related to hydrogeological risks may entail. Both alternatives have advantages where a trade-off must be made between cost savings and decreased stress levels for the personnel.

Further, both alternatives relate to the two risks associated with implementation of risk-reducing measures mentioned in *Section 1.1*; (1) *the risk of not implementing measures when needed resulting in costly damages* and (2) *the risk of implementing measures when not needed resulting in unnecessary costs and waste of resources.* While alternative 6 faces the risk of not implementing measures when needed (1), it still has the potential for cost- and time savings while meeting formal requirements which captures the essence of the observational method rather than designing with extensive safety margins. Alternative 2 on the other hand, faces the risk of implementing measures when not needed (2), but goes in line with the more traditional way of designing with extensive safety margins. Following the design principles of the observational method i.e., more extensive design work and continuous monitoring, will likely result in increased costs. However, since the design following the observational method will be in line with the actual hydrogeological conditions, the extra costs associated with the observational method may be outweighed by savings of resources and costs from not designing with extensive safety margins. For Packhuskajen, it could be difficult to motivate the client to follow the principles of the observational method, i.e., to follow the action plan, since an extra 80 000 kr would instil a sense of safety considering that all piles would be sealed and plugged immediately. However, in other projects the difference in total cost between risk-reducing alternatives may be more extensive, which motivates the use of the observational method. In addition, it is recommended by Eurocode to implement the observational method in projects with uncertain ground conditions.

The size and circumstances of a project, such as economic limitation, resources, and ambition level, determines which method to use for analysing the profitability of risk-reducing measures. For projects with minor to moderate risks and consequences, such as Packhuskajen, a CEA would be reasonable to conduct. It is important to design the CEA such that it is applicable to use in the design stage. For a project with circumstances prone to increased risks of damaging impacts because of piling and where the conditions of the hydrogeological system are more challenging with regards to expected success rate of risk-reducing measures, a method that better captures both the costs and benefits of different measures, e.g., a cost-benefit analysis (CBA), would be preferred to use. For Packhuskajen, it was reasonable to disregard the consequences of impacts on the surrounding environment since it was known that the risk-reducing measures implemented in stage one had proven to be successful. Conducting a CBA is rather time consuming and requires a substantial amount of data meaning it is not a method suitable for smaller projects with minor risks and consequences. However, for projects with complex hydrogeological conditions and sensitive objects at risk, a CBA will provide a more trustworthy and robust result.

The sensitivity analysis was performed to examine which parameters had the largest impact on the total cost of implementing each risk-reducing alternative. For Packhuskajen the implementation cost affects the total cost to a significantly larger degree compared to the other parameters. Therefore, it would be reasonable for the decision-makers to gather more comprehensive data about the implementation cost to reduce the uncertainty of the analysis and increase the reliability of the result. From a project economic point of view, it could be reasonable to only analyse the implementation cost in future projects which are facing similar risk. This would make the CEA easier to conduct and save time. However, to make decisions regarding risk-reducing measures in a sustainable manner following the principles of UNs sustainability goals, and often the project owner's own sustainability declaration, it is a necessity to consider social and environmental costs as well.

There were difficulties finding the right experts for the elicitation, mainly because there is limited competence in the industry regarding the risk of groundwater leakages from drilled steel pipe piles. This resulted both in a lack of data simply because some estimations could not be made, but also increased uncertainties of elicited values where the experts had limited expertise. During one of the elicitation sessions, it was suggested that it would probably be best to elicit personnel in charge of the foundational work for more accurate estimates of e.g., times and costs. For future projects using expert elicitations to gather data it is therefore recommended to include several experts within different disciplines to achieve more accurate estimations which the literature suggests generates better results.

Furthermore, there were parameters not included due to lack of data which could have affected the results, e.g., environmental cost of producing the materials for the risk-reducing measures and increased noise- and air pollutions from the machines on-site. All measures are associated with the use of materials and the production of materials are in turn associated with emissions. These emissions could potentially have a large impact on the total cost for a measure, especially the measures using materials that are known to have a large emission footprint such as steel. Drilling the extra pile lengths also leads to increased noise and air-pollutions. Therefore, it would be of interest to analyse if alternative 7 and 8 (extending the pile lengths) still would result in the lowest social and environmental costs compared to the other alternatives if the environmental cost of producing the material was included in the analysis.

No delay costs were identified for Packhuskajen, however, this may not be the case for other projects. For example, other hydrogeological conditions and increased pile dimensions may lead to more extensive leakages, slower recovery of the aquifers, and reduced success rate of the risk-reducing measures. The groundwater could therefore be affected to a larger extent and may lead to e.g., production stops and delays which could generate increased costs and fines. Consequently, it may not be reasonable to only study the implementation cost for other projects since the potential delay cost could differ between the alternatives and affect the total cost.

Currently there is limited competence in the construction industry regarding how drilled steel pipe piles affects the mechanisms of the hydrogeological system. Valuable lessons gained from the case study could be lost since transferring knowledge from individuals to the industry can be complex. This thesis is collecting data from the first stage of Packhuskajen making connections between hydrogeological characteristics, possible piling induced risks, and the cost for managing these risks by implementing risk-reducing measures. The thesis is therefore an important documentation of the knowledge gained from this project which in turn enables that this knowledge is used in future projects facing similar problems. This thesis could therefore contribute to an increased productivity in the construction industry by establishing an increased understanding of how to manage hydrogeological risks associated with drilled steel pipe piles.

The Eurocode 7 presents limited recommendations of how to implement the observational method which can make it difficult to apply in real world cases (Spross & Larsson, 2014). The presented methodology in this thesis demonstrates an iterative way, using the observational method, to handle new information and knowledge regarding e.g., ground conditions by being able to update the choice of risk-reducing measures during the construction time. By implementing the proposed methodology in future projects, it is possible for the organization to reduce costs for the project, the society, and the environment.

The main purpose of the work included carrying out a CEA of several risk-reducing alternatives to identify which alternative would be the most economically, socially, and environmentally favourable. The CEA is therefore providing a well-informed and transparent decision support regarding which risk-reducing alternatives to implement to a potential action plan. It is important to keep in mind that the provided results from this analysis have limitations and should not constitute as a decision itself. It should rather be used as a support for decisions for managing hydrogeological risks when using drilled steel pipe piles. The method proposed in this thesis is also flexible and the use is not limited to decisions on how to manage hydrogeological risks associated with drilled steel pipe piling. The usage of a profitability analysis in the form of either CEA or CBA together with using the principles of the observational method for designing an action plan can be used for handling all sorts of risks related to underground projects where the conditions of the geo-system are uncertain.

7. Conclusions

Chapter 7. presents the main findings from this thesis regarding the main conclusions (Section 7.1.) and suggestions for future research (Section 7.2.).

7.1. Main Conclusions

The main conclusions of this thesis are:

- Several internal and external consequences can be linked to a possible groundwater leakage through drilled steel pipe piles in urban areas. For Packhuskajen the consequences were identified to be of economic, social, and environmental character. Which consequences that will arise depends on the project specific conditions including the hydrogeological setting, the extent and magnitude of the leakage, and the possibility to effectively implement measures. It is therefore a necessity to conceptualize the hydrogeological setting, the potential risks, and possible risk-reducing measures to manage these risks for the specific project.
- Based on the interviews, several risk-reducing measures were identified including Plugging and sealing the piles; Extending the piles to correspond with the groundwater pressure level; Artificial infiltration of groundwater; and Gentle drilling.
- In this case study, the CEA showed that risk-reducing alternatives 6 and 2 were the most profitable to use. By using alternative 6 as the preliminary design the project enables the possibility to reduce costs by not implementing an unnecessary measure. By being prepared to implement alternative 2 if leakages and/or groundwater drawdowns keep occurring, the project owner can efficiently manage the leakage and reduce costly risks for the surrounding environment. The CEA also showed that regular drilling should be considered as the primary method of choice when possible to use. However, for Packhuskajen, using this method was not an option due to the heterogenous ground conditions.
- The principles of the observational method were applied by developing an action plan including both a preliminary design of measures for the conditions that could be anticipated and foreseen and other measures for implementation if any deviation was detected. The action plan also includes relevant descriptions and guidance on how a monitoring program should be used for enabling quick and well-informed decisions on what measure to implement.
- Integrating a CEA and the principles of the observational method to the ISO framework provides a support for decisions on hydrogeological risk management. It can potentially save resources by reducing the risk of implementing unnecessary measures when not needed. In addition, the framework and method used are flexible and can be applied to other types of projects facing risks due to uncertain ground conditions.

7.2. Future Research

The suggestions for future research are:

- To follow up the implementation of the action plan in the case study project, Packhuskajen. The follow up should focus on how efficiently the measures suggested in the action plan reduced the risks of costly groundwater leakages and how the action plan was communicated between the different actors within the project.
- To test the methodology in an early stage of a project, e.g., the design phase. Based on the findings, develop the methodology further with e.g., clarification of Eurocode 7 and development of an excel tool to avoid spending time building a new CEA structure for each new project.
- To further investigate how the delay cost, environmental cost of producing materials and, social costs of noise and air pollution from construction machines would affect the results from the CEA for another project.

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Appendix A – Interview Guide for Construction- and Production Manager

1. *What happened? What were the course of events during the first stage?*
   1. *How was the leakage discovered?*
   2. *Did the measures taken give a desired result?*
   3. *How long did it take to stop the leakage?*

2. *Were there any factors, in the project organization, that contributed to a leakage occurring?*

3. *Was there a water court ruling for stage one?*
   1. *If there was, what conditions were included?*
   2. *Were the conditions complied with, if not, what were the consequences?*
   3. *Do the same conditions apply for stage two?*

4. *What project internal consequences did the leakage cause during stage one?*
   1. *Are there any other potential internal consequences that may occur in addition to those in stage one?*

5. *What external consequences did the leakage have during stage one?*
   1. *Are there any other potential external consequences that may occur in addition to those in stage one?*

6. *This question regard risk-reducing measures:*
   1. *What preventative measures could be implemented to reduce the probability of a leakage or a groundwater drawdown?*
   2. *What preventative measures could be implemented to reduce the consequences of a leakage or a groundwater drawdown?*
   3. *What reactive measures could be implemented to stop a leakage?*
   4. *What reactive measures could be implemented to stop a ground water drawdown?*
   5. *Could the design of the construction had been changed to avoid a leakage?*

7. *Are you doing something different in the second stage with regards to the risk of leakage? And if so, what?*

8. *Have you documented or taken advantage of what you learned in stage one for both future stages but also other future projects?*

9. *Is there anything else you want to mention that connects to what was discussed during this interview?*

Appendix B – Interview Guide for Hydrogeologist

1. *What happened? What were the course of events during the first stage?*
    1. *How was the leakage discovered?*
    2. *Did the measures taken give a desired result?*
    3. *How long did it take to stop the leakage?*

2. *Was there a water court ruling for stage one?*
    1. *If there was, what conditions were included?*
    2. *Were the conditions complied with, if not, what were the consequences?*
    3. *Do the same conditions apply for stage two?*

3. *What project internal consequences did the leakage have during stage one?*
    1. *Are there any other potential internal consequences that may occur in addition to those in stage one?*

4. *What external consequences did the leakage have during stage one?*
    1. *Are there any other potential external consequences that may occur in addition to those in stage one?*

5. *This question regard risk-reducing measures:*
    1. *What preventative measures could be implemented to reduce the probability of a leakage or a groundwater drawdown?*
    2. *What preventative measures could be implemented to reduce the consequences of a leakage or a groundwater drawdown?*
    3. *What reactive measures could be implemented to stop a leakage?*
    4. *What reactive measures could be implemented to stop a ground water drawdown?*
    5. *Could the design of the construction had been changed to avoid a leakage?*

6. *Are you doing something different in the second stage with regards to the risk of leakage? And if so, what?*

7. *What are your thoughts on entering a project early respectively late as a hydrogeologist?*
    1. *What are the risks of not involving a hydrogeologist early in the project?*
    2. *What does a hydrogeologist contribute to this type of project?*
    3. *And what does a hydrogeologist contribute to this specific project?*

8. *Is there anything else you want to bring up that connects to what was discussed during the interview?*

Appendix C – Expert Elicitation Guide

1. *General questions:*
    a. *Do you think that the presented risk-reducing alternatives are reasonable?*
    b. *How much does it cost to operate the construction site per day and how much does a standstill of the construction cost?*
    c. *How many piles are included in stage two?*
    d. *From what percentage of piles could a leakage be observed during stage one?*
    e. *Do you have data and/or calculations of the environmental impact (e.g., air pollution and CO2-equivalents) from construction machines on site?*
2. *Regular Drilling:*
    a. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to drill a pile with "regular drilling"?*
    b. *What are the most likely, minimum and maximum delay cost due to "regular drilling"?*
    c. *What are the most likely, minimum and maximum cost of the environmental impact due to "regular drilling"?*
3. *Gentle Drilling:*
    d. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to drill a pile with "gentle drilling"?*
    e. *What are the most likely, minimum and maximum delay cost due to "gentle drilling"?*
    f. *What are the most likely, minimum and maximum cost of the environmental impact due to "gentle drilling"?*
4. *Risk-reducing Alternative 1 and 2:*
    a. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to plug and seal the pile immediately?*
    b. *What are the most likely, minimum and maximum delay cost to plug and seal the pile immediately?*
    c. *What are the most likely, minimum and maximum cost of the environmental impact for plugging and sealing the pile immediately?*
5. *Risk-reducing Alternative 3 and 4:*
    a. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to plug and seal the pile after observed groundwater impact?*
    b. *What are the most likely, minimum and maximum delay cost to plug and seal the pile after an observed groundwater impact?*
    c. *What are the most likely, minimum and maximum cost of the environmental impact for plugging and sealing the pile after observed groundwater impact?*
    d. *Is it reasonable to assume that the same number of piles would leak in stage two of the project?*
6. *Risk-reducing Alternative 5 and 6:*
    a. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to infiltrate water to the confined aquifer?*
    b. *What are the most likely, minimum and maximum delay cost related to infiltrating water to the confined aquifer?*

    c. *What are the most likely, minimum and maximum cost of the environmental impact to infiltrate water to the confined aquifer?*

7. *Risk-reducing Alternative 7 and 8:*
    a. *What is the most likely, minimum and maximum implementation cost (material + machine hours) to extend the pile to correspond with the groundwater pressure head?*
    b. *What are the most likely, minimum and maximum delay cost to extend the pile to correspond with the groundwater pressure head?*
    c. *What are the most likely, minimum and maximum cost of the environmental impact to extend the pile to correspond with the groundwater pressure head?*

Appendix D – Sensitivity Analysis

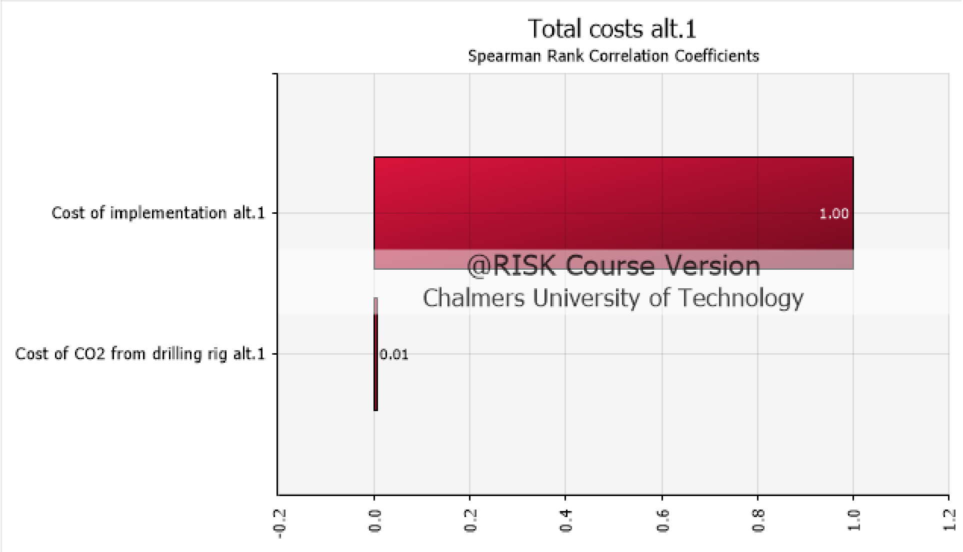

Figure 26: Spearman rank sensitivity analysis for alternative 1.

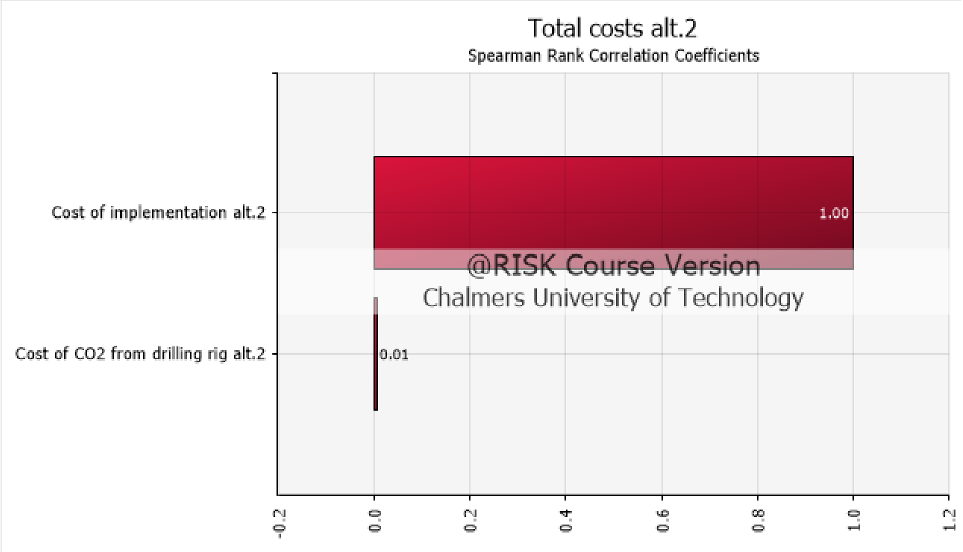

Figure 27: Spearman rank sensitivity analysis for alternative 2.

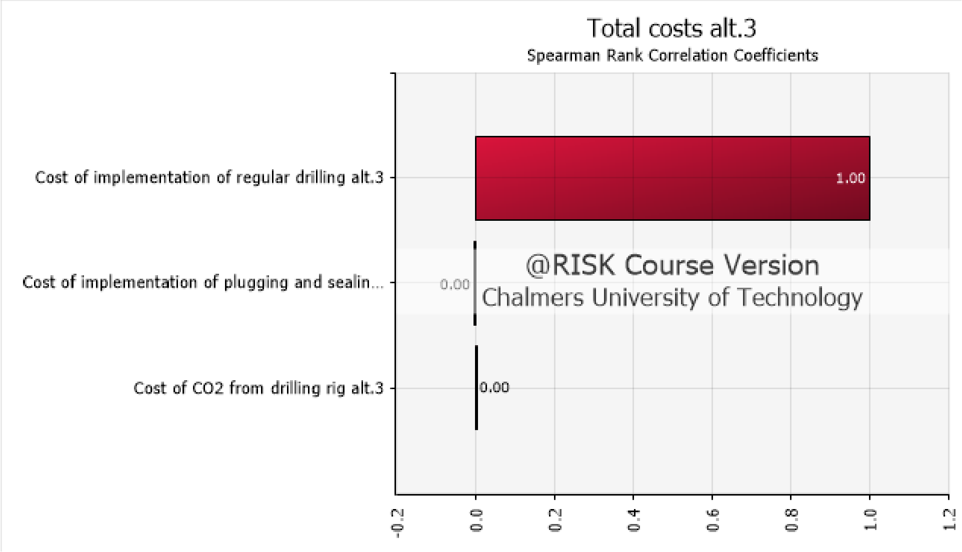

Figure 28: Spearman rank sensitivity analysis for alternative 3.

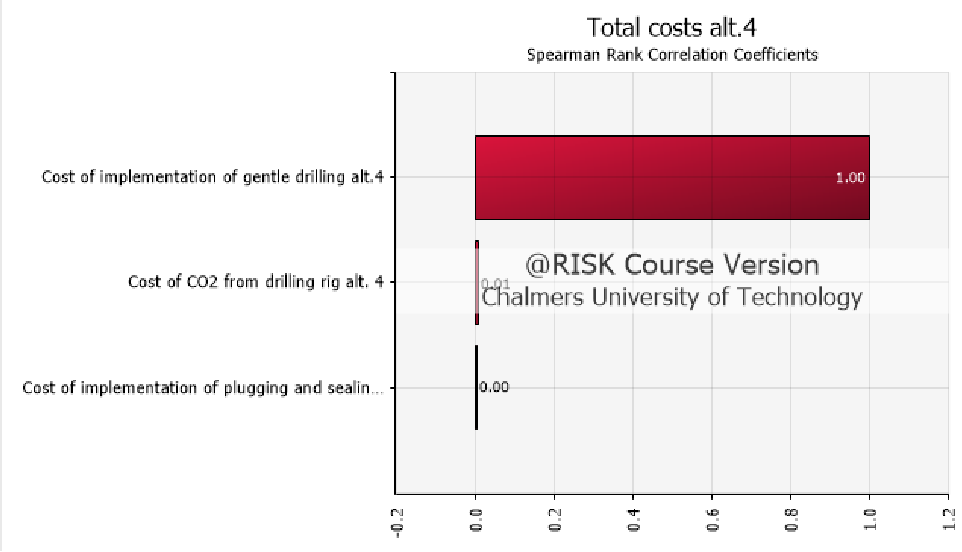

Figure 29: Spearman rank sensitivity analysis for alternative 4.

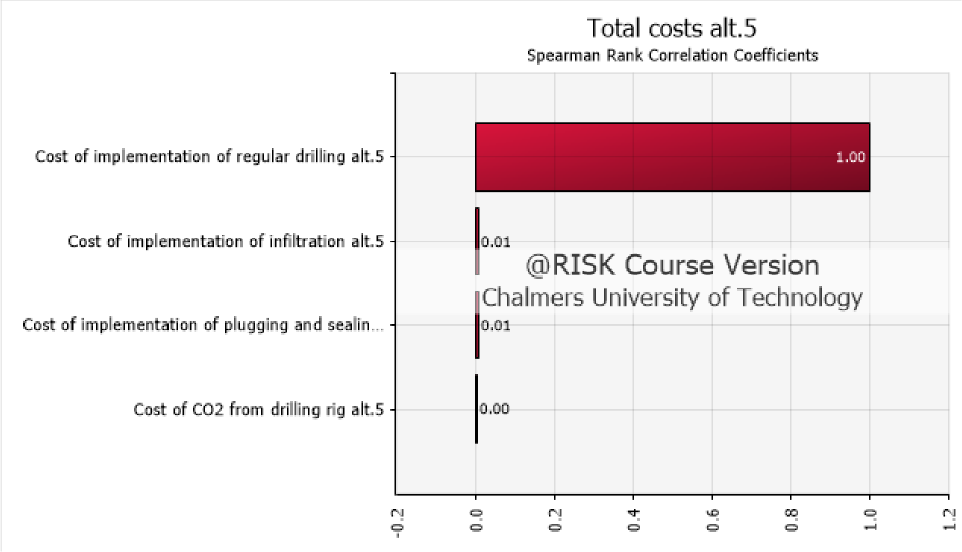

Figure 30: Spearman rank sensitivity analysis for alternative 5.

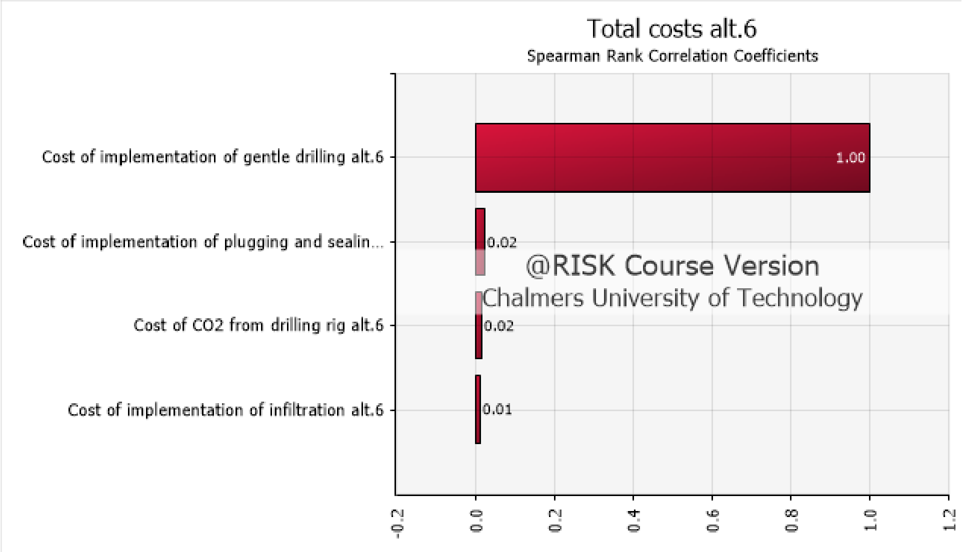

Figure 31: Spearman rank sensitivity analysis for alternative 6.

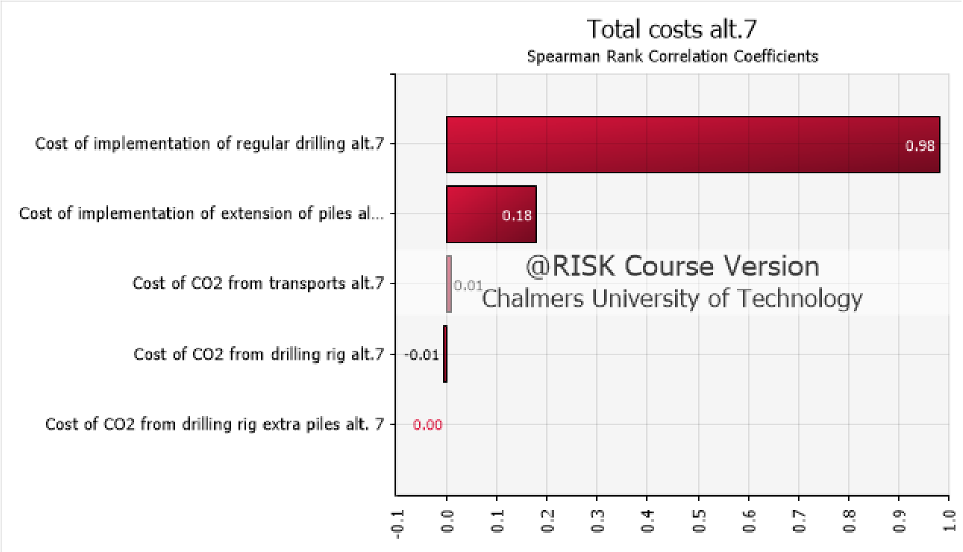

Figure 32: Spearman rank sensitivity analysis for alternative 7.

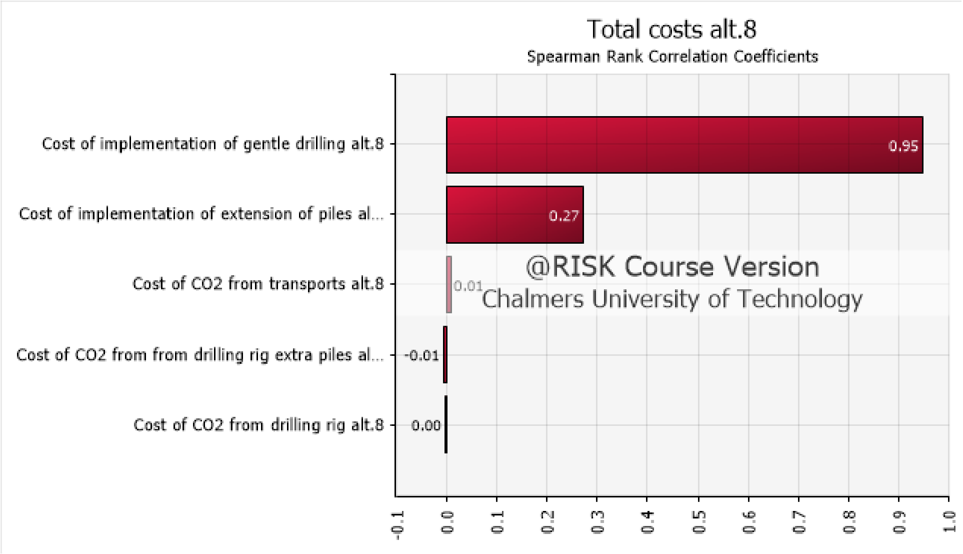

Figure 33: Spearman rank sensitivity analysis for alternative 8.

Appendix E – Manual Sensitivity Analysis, +/- 5%

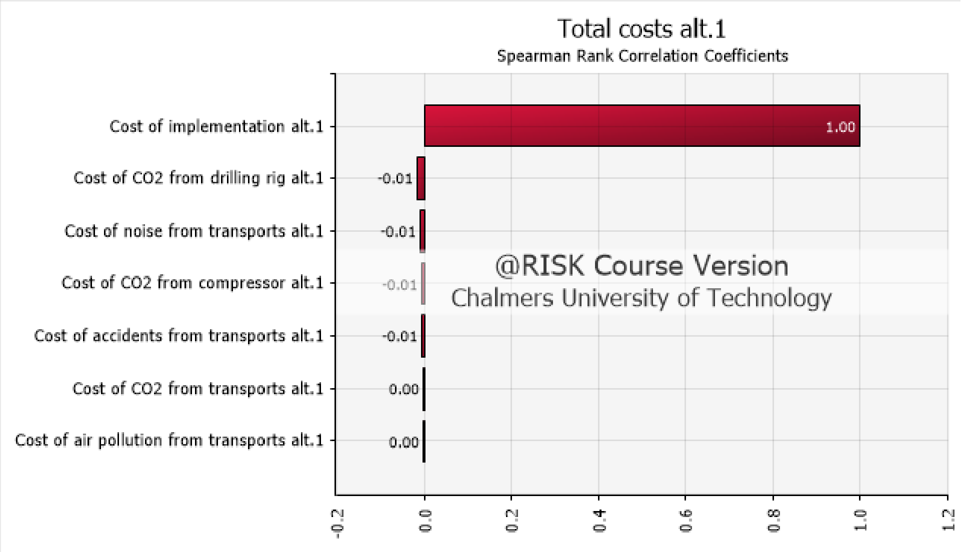

Figure 34: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 1.

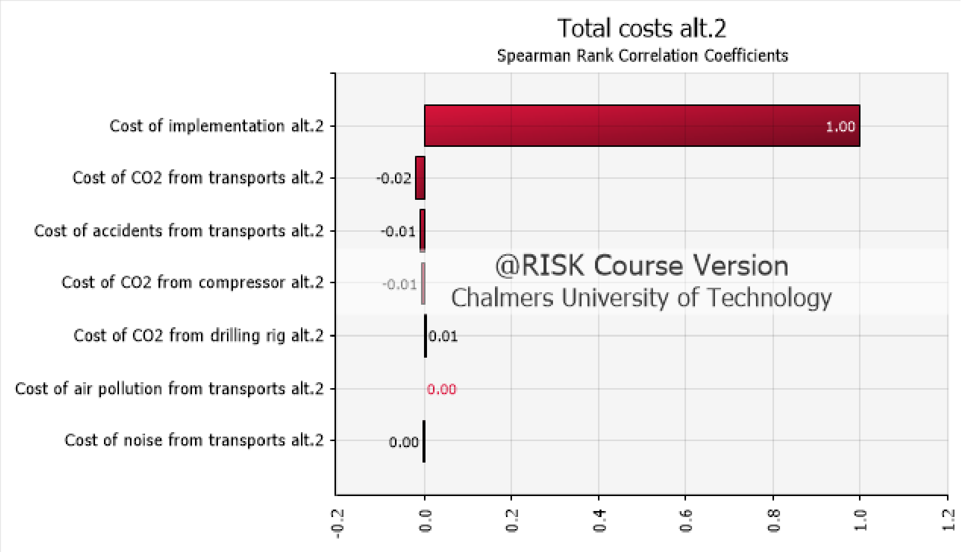

Figure 35: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 2.

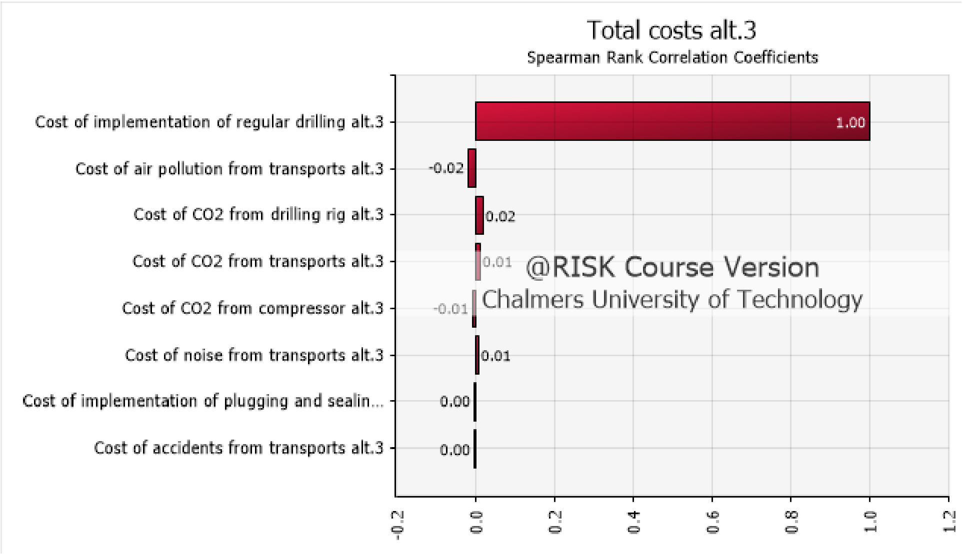

Figure 36: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 3.

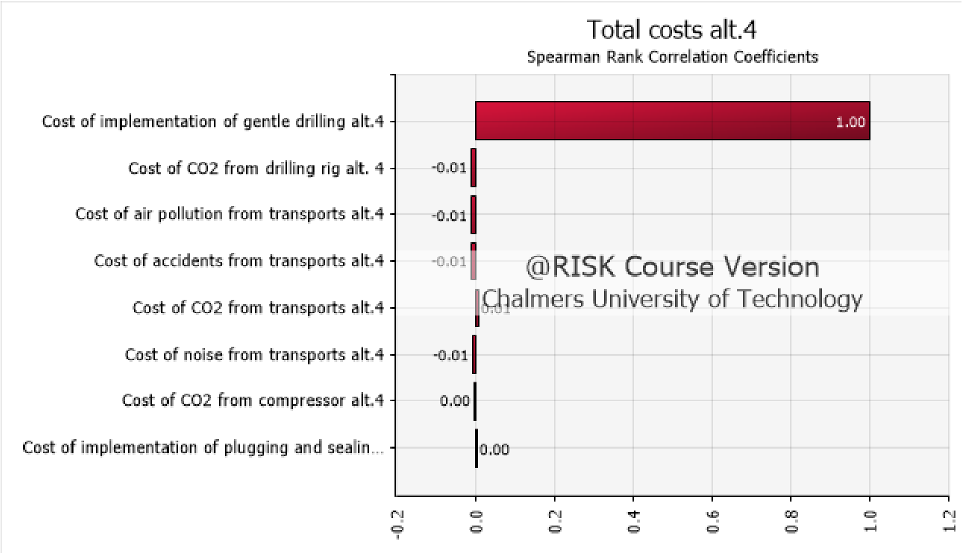

Figure 37: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 4.

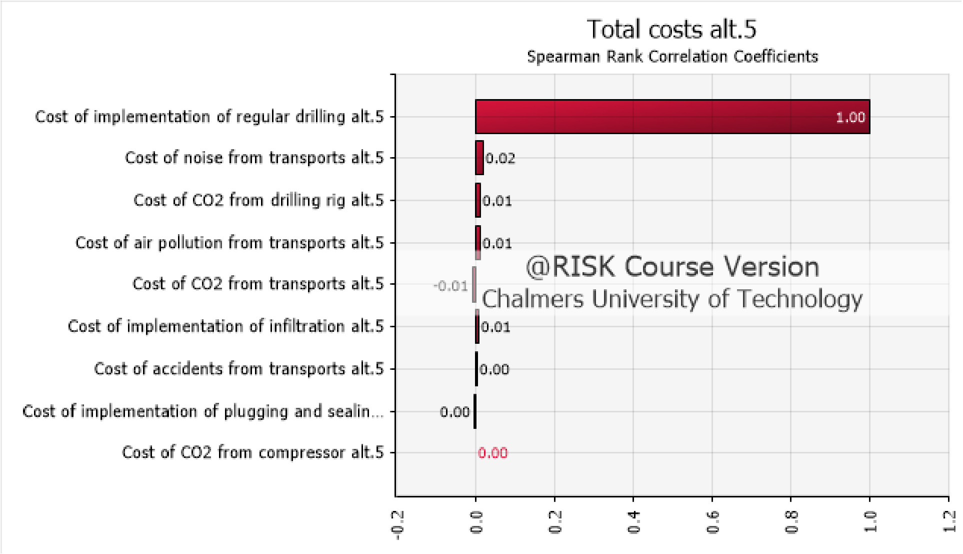

Figure 38: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 5.

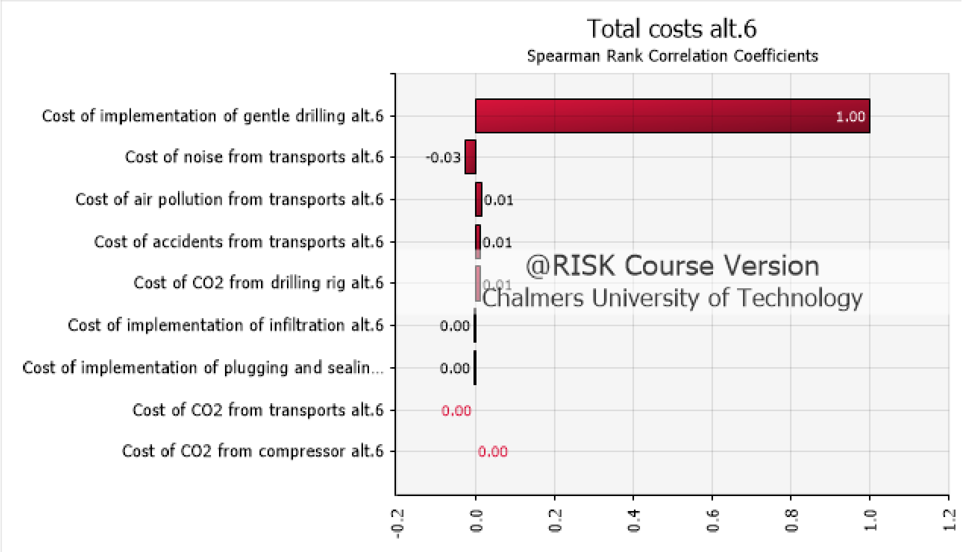

Figure 39: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 6.

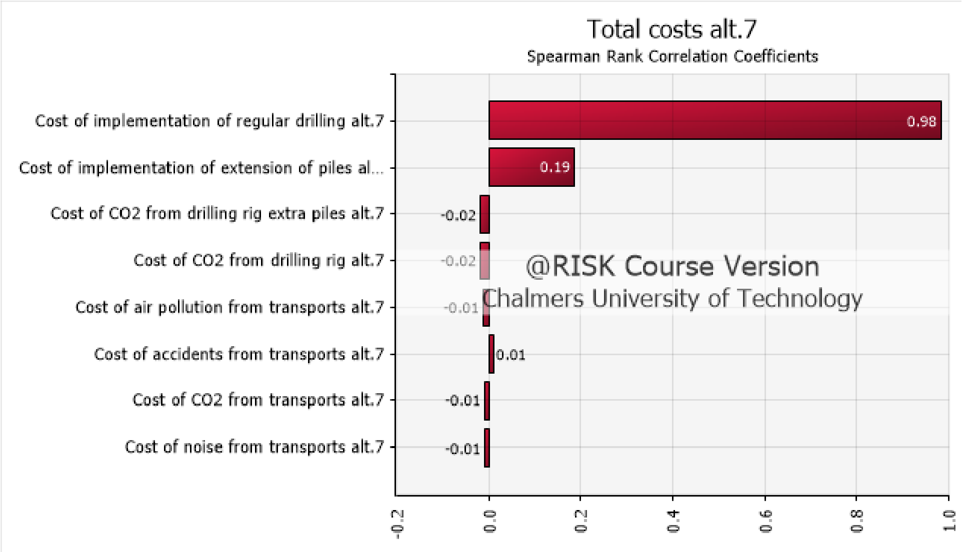

Figure 40: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 7.

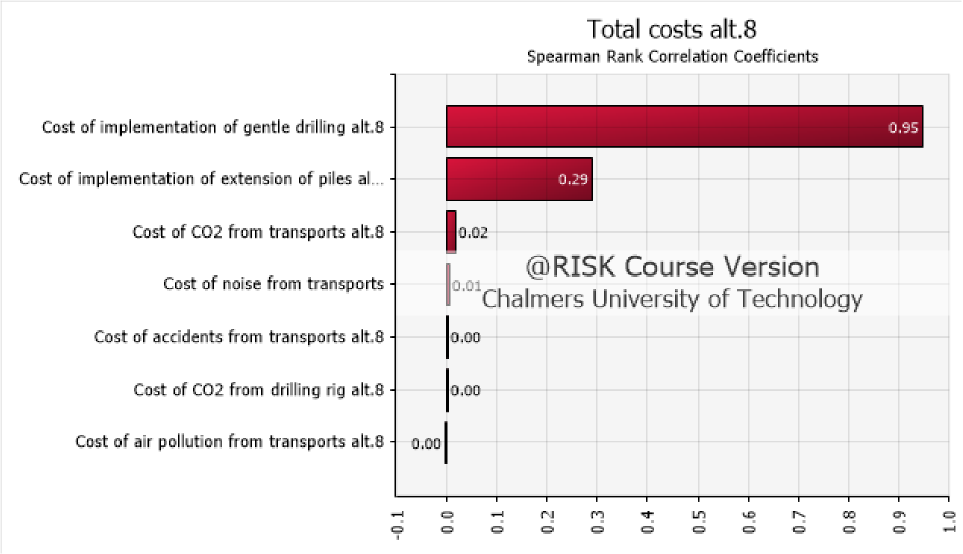

Figure 41: Manual sensitivity analysis showing a 5% uncertainty for the social costs for alternative 8.

Appendix F – Manual Sensitivity Analysis, +/- 50%

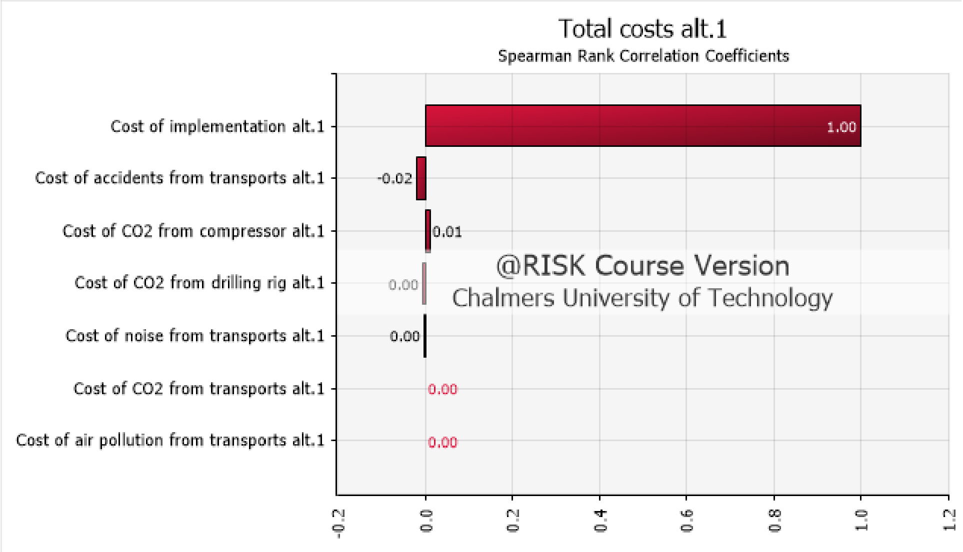

Figure 42: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 1.

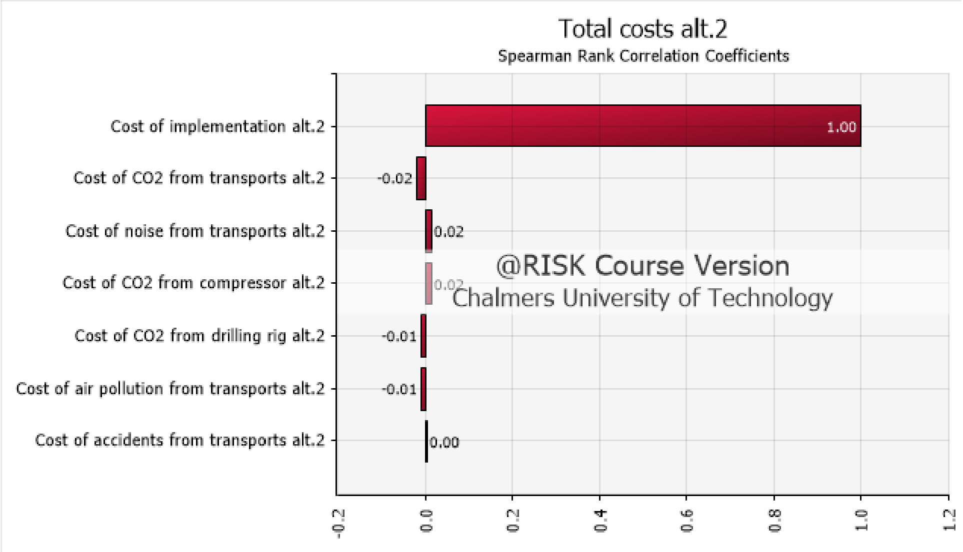

Figure 43: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 2.

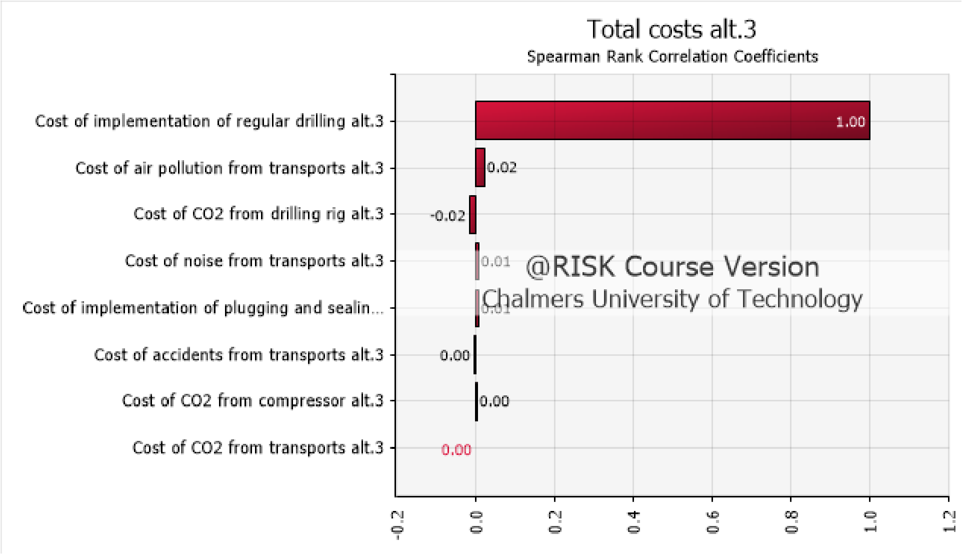

Figure 44: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 3.

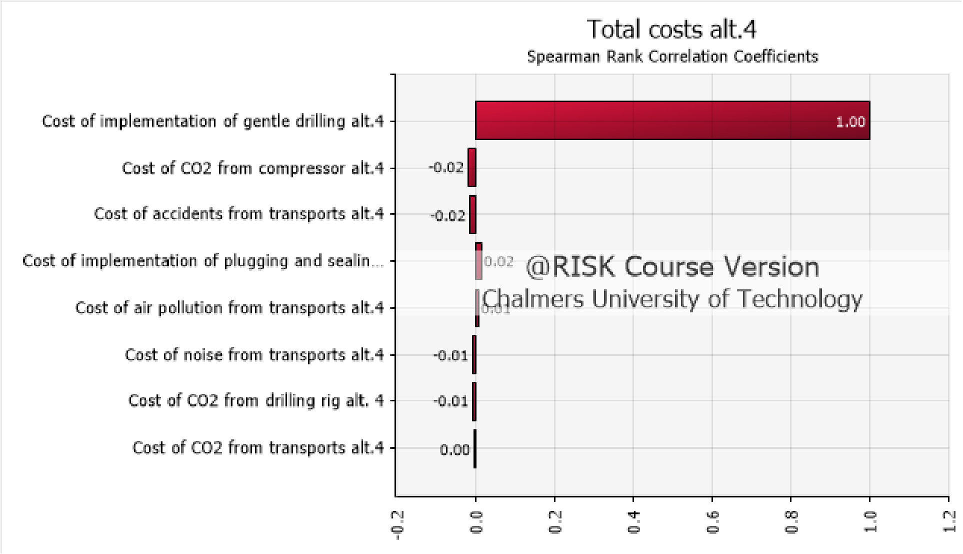

Figure 45: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 4.

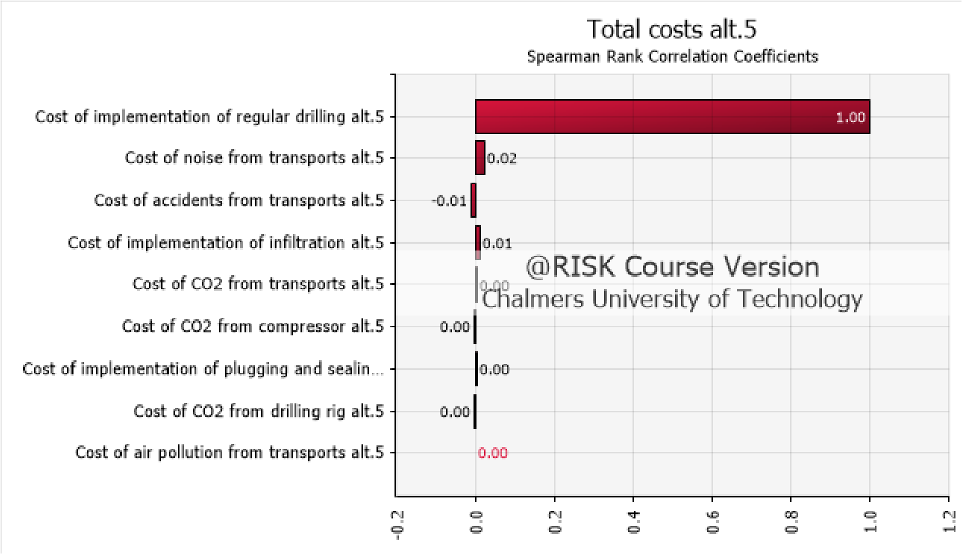

Figure 46: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 5.

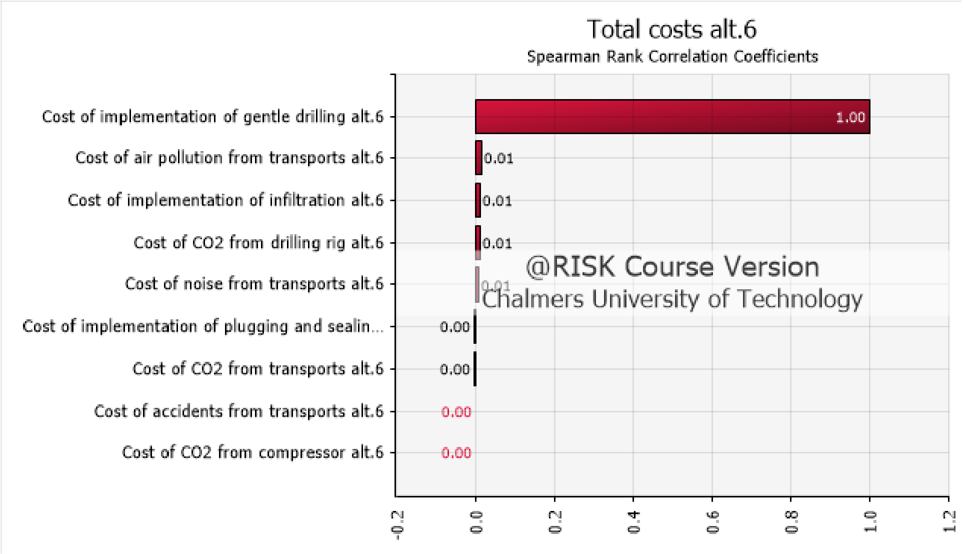

Figure 47: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 6.

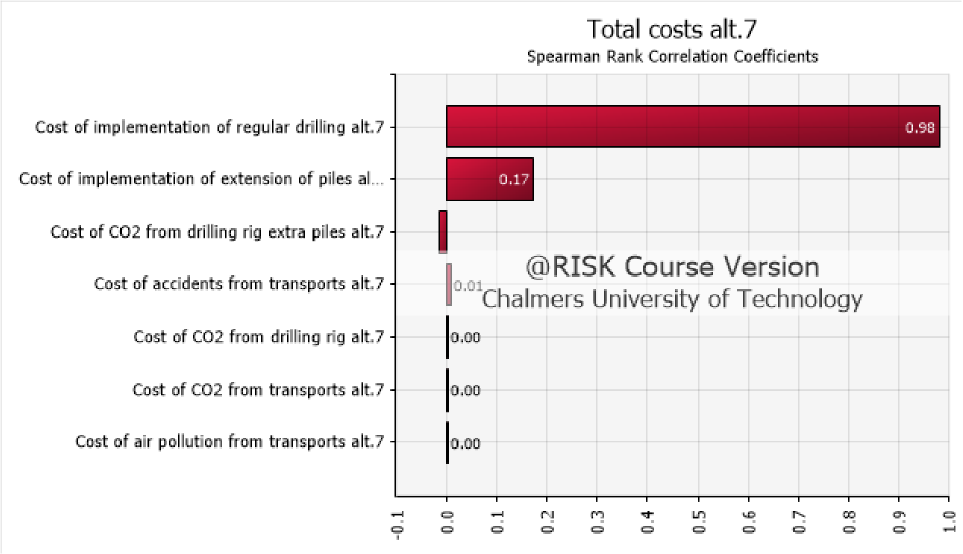

Figure 48: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 7.

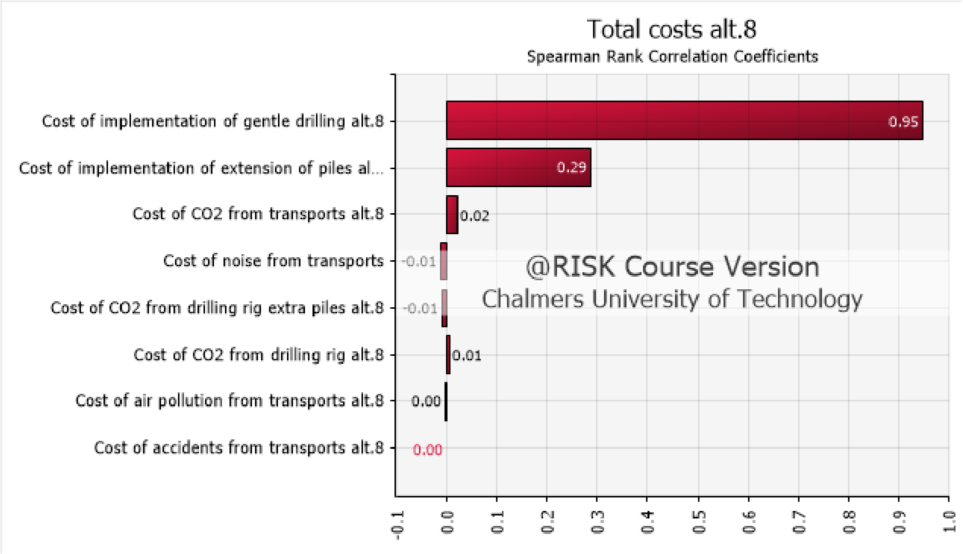

Figure 49: Manual sensitivity analysis showing a 50% uncertainty for the social costs for alternative 8.

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