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Probabilistic cost-benefit analysis for mitigating hydrogeological risks in underground construction

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A R T I C L E I N F O

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A B S T R A C T

Leakage of groundwater into underground facilities can subsequently cause groundwater drawdown, subsidence and subsidence damages to the built-up environment. In order to reduce the risk of damage, measures to mitigate the risks must often be implemented. The aim of this paper is to describe and demonstrate a probabilistic cost-benefit analysis approach to assess the economic profitability of investing in different risk mitigation alternatives. Since underground construction is always associated with uncertainties, the analysis uses probability distribution functions for uncertain parameters and Monte Carlo simulations to quantify probabilities of damage and implementation costs. The proposed approach is exemplified with a case study, the road tunnel project Bypass (Förbifart) Stockholm in eastern Sweden, for which four risk mitigation alternatives were evaluated. In conclusion, the approach helps to highlight the economic effects of different risk mitigation approaches and constitute a transparent support for decisions on implementation of risk mitigation. For the case study, the analysis indicates that the implementation costs of ∼ 7000 MSEK (700 million EUR) for risk mitigation needed to fulfil the legal requirements, from the Swedish Land- and Environmental court, in the form of ambitious sealing strategies are disproportionate relative to the benefits of ∼ 50 MSEK (5 million EUR) gained in the form of reduced damage risk for the built-up environment. In other words, billions SEK of taxpayers' money are spent on unnecessary expenses to fulfill legal requirements without societal benefits. The novelty of the paper constitutes the coupling of models and combination of established methods for management of hydrogeological risks.

1. Introduction

Dewatering of groundwater resources induced by leakage into constructions is common to many underground projects around the world, see e.g., (Kværner & Snilsberg, 2013; López-Fernández et al., 2012; Yoo, C. et al., 2012). Groundwater drawdown can subsequently result in subsidence in compressible soils and damages to subsidence sensitive buildings and facilities (Boone, 1996; Lindskoug & Nilsson, 1974; Persson, 2007). There are many examples of consequences from groundwater drawdown induced subsidence, e.g. (Burbey, 2002; Karlsrud, 1999; Olofsson, 1994). Since groundwater drawdown induced by leakage can affect large areas surrounding the underground facility (Burbey, 2002; Gustafson, 2012), the number of objects at risk can be extensive. As an example, the cost of subsidence damages (e.g. repairment of foundations and cracks in walls) due to dewatering of groundwater resources in the Netherlands are estimated to around 20 billion EUR from 2021 up until 2050 (Van den Born et al., 2016).

To be able to assess the subsidence risks, the whole cause-effect chain, from leakage to damage must be considered. The nature and severity of the damage and thus the consequences are determined by the dynamic interaction between the amount of the leakage into the underground facility, the conditions of the hydrogeological system, the geotechnical properties of the compressible soils and the sensitivity of the objects at risk (Sundell, 2018). This implies that several processes must interact for leakage to cause damage. Although the different components of the cause-effect chain are known, the magnitude and interactions of these are associated with uncertainties. These uncertainties constitute both context-, model-, inputs-, and parameter uncertainties (Walker et al., 2003).

It is in the project owner's as well as in society's interest to implement measures to reduce the risk of costly damages. Legal requirements and regulations may also force the project owner to invest in risk

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mitigation (Merisalu & Rosén, 2020). In a Swedish context, underground projects are always associated with limitations regarding groundwater impacts specified in a permit from the land- and Environmental court. Measures include e.g. sealing (grouting or watertight concrete lining) of the facility to reduce leakage (Panthi & Nilsen, 2005), artificial recharge to maintain stable groundwater levels (Andersson & Sellner, 2000; Ilsley et al., 1991), or reinforcement of building foundations (Peng & Zhang, 2020). Investing in risk mitigation can be both time consuming and expensive (Strømsvik, 2019) and the costs can constitute a significant part of the overall project budget (Beitnes, 2002; Werner et al., 2012). To make efficient use of society's limited resources in a socio-economic context, both the benefits (such as risk reduction) and the costs of implementing measures must be considered.

There are two types of *error risks* for making erroneous decisions associated with the implementation of risk mitigation:

The risk of *not implementing necessary measures*, resulting in damages and damage costs for the project owner, the society, and the environment; and

The risk of *implementing measures when not needed*, resulting in unnecessary implementation costs.

Due to the existence of both these error risks, decision makers must make decisions under uncertainty on resource allocation and prioritizations of risk-mitigation. To support such decisions, a quantitative risk assessment is highly motivated where the risks for leakage-induced subsidence damages are quantified and the cost and benefits of relevant risk mitigation measure alternatives are identified, quantified in monetary terms, and compared. Since uncertainty is a distinctive characteristic of underground construction it must be considered in the risk assessment and in the decision-making process, motivating a probabilistic approach for handling parameter uncertainty that is continuously updated as new information is available (Aven, 2012; Freeze et al., 1990; Peck, 1969; Sturk, 1998).

The overall aim of this paper is to present methods needed to facilitate a real-world practical application of the risk management framework for decisions on hydrogeological risk mitigation presented in Merisalu et al. (2021). The application is on the road tunnel project Bypass (Förbifart) Stockholm. The paper focuses on the presenting methods for the risk assessment part of the framework: 1) risk identification, 2) risk analysis, 3) risk evaluation and 4) sensitivity analysis. Remaining parts of the framework, including the risk treatment and the monitoring and review are also covered but with less emphasis. The specific objectives of the case study are twofold and can be summarized into two questions: 1) what risk mitigation alternative is most profitable to implement for managing hydrogeological risks regardless the requirement set in the legal permit? and 2) what is the cost of fulfilling the legal terms and conditions formulated in the legal permit from the Land- and Environmental court?

2. Methods

In short, this section covers three approaches and methods used for the assessment of hydrogeological risks and mitigation of these risks. First, the risk management framework is presented. Second, the chain of models used for the risk assessment are described with focus on how the different models connect. Third, the concept of expert elicitation is covered.

2.1. The risk management framework

The risk management framework was first published in Merisalu et al. (2021). The framework (Fig. 1) starts with the establishment of context including defining the aim and purpose of the project and deciding on relevant criteria. The following step is to identify all possible risks that may occur due to the underground construction activity. In order to be able to identify possible risks, the hydrogeological system must be conceptualized and the potential objects at harm within the potential hydrogeological impact area of the underground construction must be described. Once the risks have been identified, the risk analysis is carried out. The risk analysis starts with the identifying and determining reasonable risk mitigation alternatives for managing the identified risks. The next step in the risk analysis is to estimate the risk for the reference alternative as well as the risk mitigation alternatives. Risk is defined as a function of probability and consequence in accordance with Kaplan and Garrick (1981). The risk R_i is expressed in monetary units and can mathematically be calculated using the probability density function of an event, f_i, and a function representing the consequences of that event, C_i, as follows:

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

The risk R_i is calculated for all objects identified to be exposed to risk. The risk is calculated by means of data, models and simulations, and expert elicitation. The risk analysis is followed by the risk evaluation where the positive and negative consequences of the risk mitigation alternatives are evaluated by means of cost-benefit analysis (CBA). CBA is a well-established and structured method to compare the societal costs of a project (e.g., implementation of risk mitigation) with its benefits over a specific time horizon. CBA is widely used to support decisions on e.g., transport infrastructure, health care, flood protection, energy system development, etc. CBA is described in various textbooks (often referenced are e.g. Boardman et al. (2017) and (Johansson & Kriström, 2015)) and a vast scientific literature. The EU Commission recently provided a new guideline document on economic appraisal including CBA (EU-Commission, 2021). Application of CBA in a risk management context concerning hydrogeological risks has previously been described by (Merisalu et al., 2020). The results from the risk analysis are used to determine the benefits (the reduced risk expectancy) for each risk mitigation alternative. CBA is a structured method to compare the societal costs of a project (e.g., implementation of risk mitigation) with its benefits over a specific time horizon. The objective function for risk mitigation alternative i and for a time resolution in years is:

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

where NPV_i = net present value, which constitutes the present value of the net benefit (in other words, benefits minus costs) of implementing the risk mitigation alternative i relative to a reference alternative, T = time horizon including years $t(t = 0 \ldots T)$, $B_{i,t}$ = the benefits relative to a reference alternative of implementing the measure i during year t, $C_{i,t}$ = costs relative to a reference alternative of implementing the measure i during year t, and r = discount rate. The framework recommends usage of several discount rates to analyze how sensitive the *NPV* and the ranking of alternatives is to a changing discount rate. Three discount rates were used, 0 %, 1.4 % and 3.5 %, respectively. The 0 % discount rate was chosen to reflect the ethical principles of not at all favoring present generations over future ones, the 1.4 % reflects the average discount rate used in the Stern Review on Climate Change (Stern, 2007), implying a relatively strong recognition of inter-generational equity, and the 3.5 % rate suggested in the Swedish Transport Administration Guidelines for cost-benefit analysis (STA, 2020), reflects an anticipated productivity in society. After the risk evaluation, a sensitivity analysis is carried out to evaluate the model inference. The sensitivity analysis aims at identifying input variables with the largest impact on the uncertainty of the output results from the models used for the risk analysis and the risk evaluation.

The following parts of the framework is not applied in this paper since those parts should be carried out by the decision maker which in this case is the project owner. However, the parts are described in the following text. Based on the CBA analysis and the sensitivity analysis, a

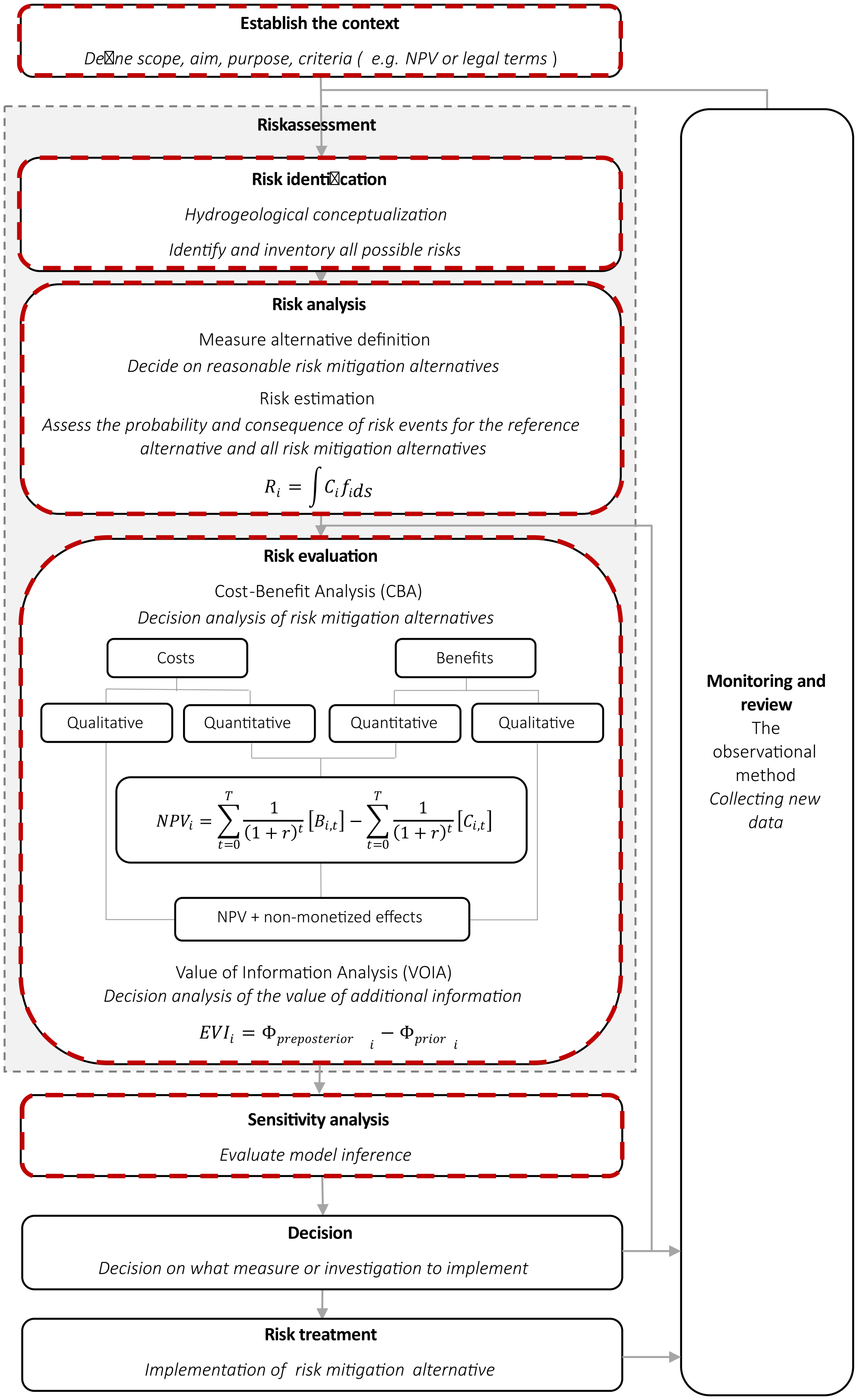

Fig. 1. The hydrogeological risk management framework for decision support on implementation of risk mitigation alternatives, modified from Merisalu et al. (2021). The red dashed boxes indicate the modules within the framework that are covered in the case study presented in this paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

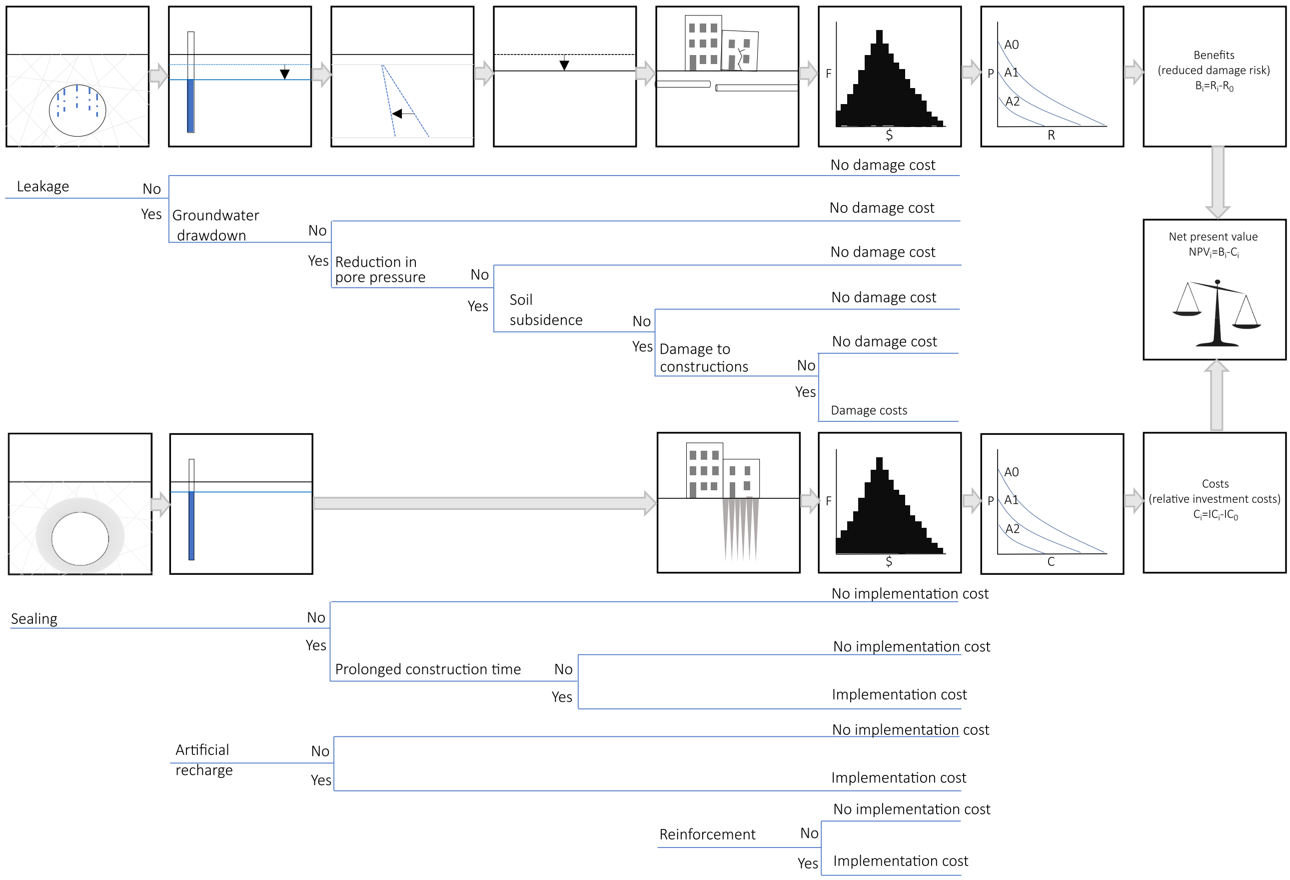

Fig. 2. Schematic illustration of the coupled models for evaluation of cost and benefits of risk mitigation. The upper part of the Fig. illustrates the chain of events (models) used for the simulation of risk expectancy used in the risk analysis. The lower part illustrates the chain of events (models) used for the simulation of implementation cost. The last column of the Fig. illustrates the risk evaluation where the benefits and costs are compared for all defined risk mitigation alternatives.

decision is taken to eighter implement or postpone the implementation of a risk mitigation measure. If a measure is implemented, the effects of the measure is monitored and reviewed. If the implementation is postponed, the CBA should be updated by means of VOIA (value of information analysis). the aim of the VOIA is to evaluate if the cost of collecting more data is smaller than the expected benefits in the terms of reduced risk of making an erroneous decision on implementation of risk mitigation measures. Independent on what decision is made, the effects of measures and the characteristics of the hydrogeological system should be continuously monitored and reviewed following the principles of the observational method meaning that relevant and observable control parameters that are representative for the hydrogeological system and can capture the effects of the measures are set. The continuous collection and processing of data enables a continuous update of the models and are a key part of the framework which enables an iterative process that continues throughout all stages of a project, from the feasibility and design phase to the construction and operation phase.

The risk management framework applies a probabilistic approach to risk analysis and cost-benefit analysis in accordance with e.g. Aven (2012) or Bedford and Cooke (2001). A probabilistic approach where uncertainties are accounted for is necessary since the values for both the costs and benefits rarely are known with certainty (Pearce et al., 2006). This means that input variables to all models included in the quantitative risk analysis and the risk evaluation constituting uncertain quantities are, as far as possible, represented by probability distributions instead of deterministic values. Further, the analysis uses Monte-Carlo simulations to calculate the uncertainties of output variables.

2.2. Chain of models

To evaluate the economic profitability of risk mitigation alternatives, several models describing the separate events of the dynamic cause-effect chain (e.g., leakage, groundwater drawdown, subsidence, and damage) their consequence (damage) costs and the implementation costs must be coupled. The probability of included events can be determined by data-driven or process-based numerical models and simulations, by extrapolating from experimental studies and available data, or by using expert elicitation. What approach to choose depends on several factors such as time and financial limitation, data availability, level of ambition, and the overall circumstances and nature of the project (Merisalu et al., 2021). The chain of models used for the analysis in this paper is illustrated in Fig. 2.

The risk analysis starts with the simulation of groundwater drawdown induced by leakage. The magnitude of groundwater drawdown was determined from groundwater level time series data and expert judgement. The groundwater drawdown may subsequently result in pore pressure decrease which in turn may result in soil subsidence. Simulation of subsidence was made using a simple one-dimensional elasto-plastic compression model. The subsidence can result in damages on buildings, garden areas, pipes and paved surfaces. The damages lead to damage costs, e.g. reimbursement costs for repairment work. The models describing the relationship subsidence-damage and damage-damage cost are developed based on a combination of empirical data which has been evaluated and complemented by means of expert-elicitation. As a final step of the risk analysis, the risk expectancy of leakage is simulated for the reference alternative and all risk mitigation alternatives.

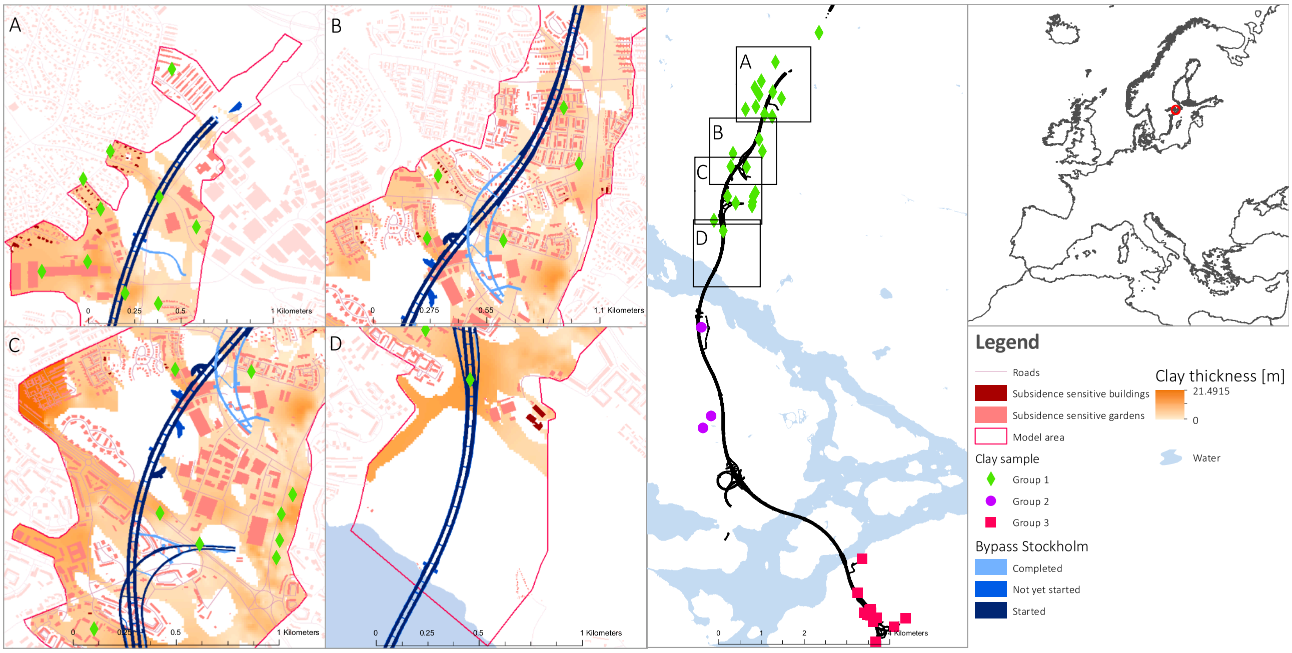

Fig. 3. Map of the model area, including the location of the tunnel in three blue colors representing the status of the project (completed, not yet started, and started) at the time of the study (autumn 2019). The location of subsidence sensitive buildings, buildings with subsidence sensitive garden areas, and roads, are also indicated. The DEM of the clay thickness as well as the location of the oedometer tested clay samples used as input for the subsidence calculations are also displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As a first step in the risk evaluation, the benefits (the reduced risk expectancy) of implementing the risk mitigation alternatives are determined. The benefits are calculated by comparing the difference in risk expectancy of the reference alternative and each risk mitigation alternative. To reduce the risk expectancy from leakage, mitigation measures (sealing of the tunnel, artificial recharge, and reinforcement of constructions) can be implemented. The implementation costs for these measures are simulated from cost models developed based on empirical cost data which has been evaluated and complemented with means of expert elicitation. The cost is determined by comparing the cost for investment, operation, and maintenance of the risk mitigation alternatives with the reference alternative. As a final step, the *NPV* of each alternative is calculated according to Eq. (2). The calculations were performed using two Monte Carlo simulations, each consisting of 3000 iterations. the simulation was repeated twice to investigate how close 3000 iterations was to convergence.

2.3. Expert elicitation

Existing data samples may be too small, too unreliable, too costly to obtain, or unobtainable and thus insufficient to support the risk assessments (Paté-Cornell, 2012; Sjöstrand et al., 2020). If this is the case, the only option for collecting data may be to elicit information from experts (O'Hagan, 2019). The purpose of the expert elicitation is to retrieve knowledge regarding an uncertain variable's quantity. The uncertainty is preferably represented by probability density functions (Jenkinson, 2005). A total of ten people contributed with expert knowledge to the project. Many of these were involved in the project Bypass Stockholm as project leaders, hydrogeologists, geotechnical engineers, and responsible for damage control and reimbursement costs. Consultants without direct connection to the project also contributed knowledge on reinforcement of buildings and damages on pipes.

The expert elicitation was divided into three steps. The first step constituted workshops where the experts involved in the tunnel project presented the difficulties facing the project and during open discussions with questions from the discussion leader (the main author of this paper) established the context and defined relevant risk mitigation alternatives to include in the analysis. The second step constituted collecting and compiling data and information from the tunnel project and other relevant sources by the experts within their respective field of knowledge. The data and information constituted e.g. measured groundwater levels, leakage and subsidence, costs for reimbursement in damage errands, costs for risk mitigation (sealing, artificial recharge), prognoses of needed measures in the unfinished sections of the tunnel and prognoses of delays. Cost data for implementing concrete lining from other projects and costs for reinforcement measures of buildings were also compiled. The third step constituted face-to-face interviews with one or more experts. These interviews aimed at defining damage- and cost models based on the compiled data and the experts experience. If only one expert were elicited, the expert was asked to present the relevant data and assess a best estimate together with a minimum and maximum value for the parameter in question. The expert was also asked to assess their confidence level regarding if the proposed interval contained the true answer. Based on the assessed confidence level, the minimum and maximum value was assessed again. If more than one expert were elicited, the experts were asked to discuss the compiled material and discuss until agreed on a most likely, minimum and maximum value. For some parameters, the experts considered it relevant to only use point data instead of a distribution.

In this case study, we limited the expert elicitation procedure to use only point values or the Beta-PERT model. The Beta-PERT-distribution is an effective and flexible distribution for expert elicitation (Malcolm et al., 1959). The distribution is described by a most likely value together with a minimum and maximum value. The most likely value is weighted four times higher than the minimum and maximum value. A higher weight on the most likely value is motivated in expert elicitation since it is easier to assess the most likely value compared to extreme values (Salling, 2007). In a more detailed analysis, the expert elicitation can preferably be expanded to include elicitation of both parameter values and the distribution model, in accordance with e.g. the SHELF methodology (Gosling, 2018; O'Hagan, 2019).

Table 1
The relationship between subsidence magnitude and damage risk used as input for the risk analysis.

Objects at risk	Damage category	Magnitude subsidence [cm]	Source
Building	No damage	< 1	Driscoll (1995) and Sundell et al. (2019)
	Aesthetic	> 1 & < 3	
	Function	> 3 & < 7.5	
	Stability	> 7.5	
Gardens	No damage	< 10	Ongoing damage cases within the project and expert elicitation
	Damage	> 10	
Pipes	No damage	< 1	STA (2011a) and expert elicitation
	Low probability *(f = 0.05)*	> 1 & < 10	
	Moderate probability *(f = 0.50)*	> 10 & < 15	
	High probability *(f = 0.95)*	> 15	
Paved surfaces	No damage	< 1	Ongoing damage cases within the project and expert elicitation
	New layer of asphalt	> 1 & < 10	
	Road repairment	> 10	

3. Framework application

3.1. Case study location

The framework was applied on a part of the road tunnel Bypass Stockholm (Fig. 3). The tunnel constitutes a new link between the southern and northern regions of Stockholm for reducing the car traffic in central Stockholm. The whole project covers 21 km in which 18 km constitutes tunnels in both bedrock and soil. The construction of the tunnel within the model area started in 2018 and the opening of the tunnel was originally planned to 2026. The original budget for the project was 34 billion SEK in 2018 years price level.

The hydrogeology in the tunnel-area sensitive to ground subsidence constitutes three main aquifers: a lower aquifer in the fractured crystalline gneiss bedrock, a lower confined aquifer in glacial till or glaciofluvial material located on top of the bedrock and below a layer of glaciomarine clay, and an upper unconfined aquifer in course material (beach sand deposits or filling material in the built-up areas). The two lower aquifers have a high connectivity in some areas. The lower aquifer and upper soil aquifers are separated by a layer of impermeable clay but are connected adjacent to bedrock outcrop areas (STA, 2011). The clay within the area of influence of the tunnel is considered to be sensitive for groundwater lowering and subsidence (STA, 2013).

3.2. Establish the context

The framework used propose an evaluation of risk mitigation alternatives based on economic valuation of costs and benefits where the alternative with the highest *NPV* is implemented. However, in the case of this study, the tunnel was also submitted to abide legal terms and conditions formulated in the permit for the tunnel by the Swedish Land- and Environmental court. These terms and conditions constitute a limitation for using a pure utilitarian approach, i.e. only using the *NPV*, when deciding on what measures to implement.

3.3. Risk identification

The first step of the risk identification was to delimit the project and thus the model area. The area of influence described by STA (2011) was used as model area. Objects at risk within the area of influence were identified and described. The objects were categorized into buildings, gardens, pipes, and paved surfaces. Buildings assessed to be sensitive to subsidence has a shallow raft or mat foundation and is thus prone to damage in case of subsidence. Gardens is a broad category that includes the built-up environment surrounding a building. The buildings in this category have a deep foundation that is resistant to subsidence. However, constructions such as porches, paved corridors and driveways, and smaller complement buildings e.g. storehouses, often lack deep foundations and are therefore sensitive to subsidence even if the main building of the property is not. Larger main pipes and sewer systems often have a shallow foundation constituting a gravel bed whereas smaller pipes in and out from buildings often lack foundation. All pipes within the area were therefore considered as subsidence sensitive. Paved surfaces include parking spaces and roads. The damages can e.g. constitute cracks, slope changes and depressions. Paved surfaces often have a shallow foundation constituting gravel beds that is sensitive to subsidence.

3.4. Risk analysis

Risk mitigation alternative definition.

Risk mitigation alternatives were defined by the group of experts involved in the project. The group defined five risk mitigation alternatives, including a reference alternative. The alternatives are based on the legal requirement of maximum allowed leakage of groundwater into the tunnel specified in the legal permit (Case M11838-14, The Swedish Land- and Environmental Court of Appeal 2014) and the project owner's intention to avoid damage due to groundwater drawdown in the lower confined aquifer. The alternatives are all based on different combinations of sealing-, artificial recharge-, and reinforcement strategies. In order to enable the evaluation of societal profitability of risk mitigation regardless of the legal requirements constituting a boundary condition for the project, both alternatives that met the legal requirements and alternatives that did not meet the legal requirements where defined.

Risk estimation.

The risk estimation constitutes a major part of the risk analysis. Each risk estimation was carried on it several steps and a new risk estimation was in turn carried out for each iteration of the Monte Carlo simulation. One risk estimation included a subsidence model, a damage model, and a cost model.

Subsidence calculation.

The subsidence calculations were based on Sundell et al. (2017). The method constituted a probabilistic one-dimensional elasto-plastic compression model for simulation of subsidence which incorporates spatial heterogeneity and uncertainty as well as statistical analysis of dependencies between variables and differences in mean values among groups of data. The spatial heterogeneity and uncertainty among the soil properties used as input for the subsidence calculations was dealt with by making the soil property parameters dependent on the varying stratigraphy and by specifying probability density functions (PDFs) for the dependencies between parameters. The differences in mean values among groups of data were estimated using ANOVA. The method was chosen based on its applicability on the available data in this project. The available data included an existing stratigraphy model and a sparse dataset on soil parameters evaluated from constant rate of strain (CRS) oedometer tested clay samples. a summary of the method used together with details on how it was applied in this project is presented in Appendix A. Simulation of subsidence.

Probability of damage due to subsidence.

The probability of damage due to subsidence ($f(ss)_j$) was determined by several damage models describing the relationship between subsidence magnitude and damage (Table 1). As indicated in the table, subsidence magnitudes < 1 cm was not considered to cause any damage.

Buildings were divided into four damage categories in accordance with Driscoll (1995). The damage categories were: no damage, aesthetic damages are e.g. cracks in wallpapers and painted surfaces, function damages are e.g. difficulties opening doors and windows, and stability damages are damages to the load-bearing structure.

Table 2
The cost (SEK) of damages for all the damage categories for all objects at risk.

Reparation cost	Unit	Abbreviation	Distribution [a]	Parameters	Source
Aesthetic damage buildings	sek	Aesthetic	LN	μ=5.99, σ = 0.557	Sundell et al. (2019)
Function damage buildings	sek	Function	LN	μ=9.55, σ = 0.463	
Stability damage buildings	sek	Stability	LN	μ=10.55, σ = 0.277	
Repairment garden	sek/m^2	$Cost_{gardent}$	BP	Min = 450, Mode = 550, Max = 3000	Ongoing damage cases within the project and expert elicitation
Sewer main pipe	sek	Sew_{MP}	LL	μ=10.8353, σ = 0,5416	Cost data origin from the municipality of Gothenburg's database (20200130)
Sewer building connection	sek	Sew_{BC}	E	μ=67620	
Water main pipe	sek	Wat_{MP}	LL	μ=10.7652, σ = 0.3575,	
Water building connection	sek	Wat_{BC}	LL	μ=10.5654, σ = 0.3928	
New layer of asphalt	sek/m^2	$Cost_{asphalt}$	BP	Min = 175, Mode = 250, Max = 350	Ongoing damage cases within the project and expert elicitation
Repairment road	sek/m^2	$Cost_{road}$	BP	Min = 800, Mode = 1100, Max = 1400	

[a] LN = Lognormal distribution, and Be-pert = Beta PERT, E = Exponential, LL = Loglogistic.

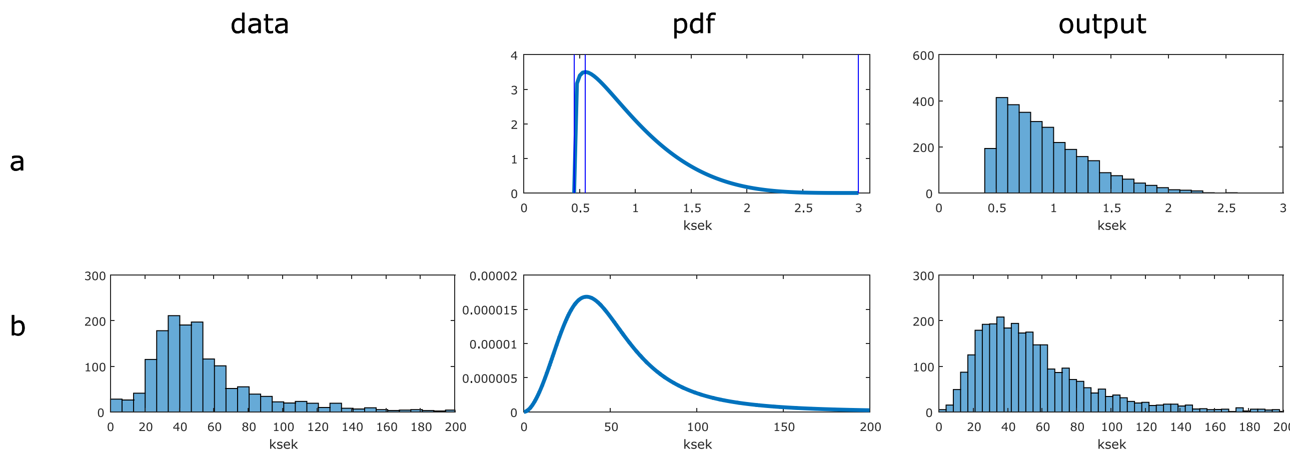

Fig. 4. a) the developed pdf for the parameter repairment garden together with the min, most likely and max value elicitated by the experts indicated with blue lines, and the generated output from the Monte Carlo simulation with 3000 iterations. b) the cost data for repairment of main water pipes together with the developed pdf and the generated output from the Monte Carlo simulation with 3000 iterations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Damages on garden areas were divided into only two categories, no damage, and damage. The subsidence magnitude causing damage was assessed by three experts within the project working with ongoing reimbursement errands regarding damaged garden areas. The magnitude considered to cause damage was thus based on the actual subsidence magnitude in the areas in which damage had occur.

The probability of damage on pipes was determined based on the subsidence magnitudes presented in the documented preconditions of the project by STA (2011). The Swedish transport administration had assessed the probability of damages on pipes due to subsidence into four qualitative classes: no damage, low probability, moderate probability, and high probability. One expert working with drinking water and sewer systems was elicitated regarding the relevancy of this categorization and relevant quantitative probabilities ($f = 0.05$, $f = 0.50$, and $f = 0.95$ respectively) for these for classes.

Damages on paved surfaces were divided into three categories based on ongoing damage errands within the project. The categories constituted no damage, new layer of asphalt, or larger repairment to road. The magnitude of subsidence separating these categories was assessed by three experts within the project working with ongoing reimbursement errands regarding damages on paved surfaces. The magnitude of damaging subsidence was thus assessed based on the actual subsidence in these areas where damaged had occurred.

Damage costs.

The cost of damages (C_i) was determined by several cost models describing the relationship between damage and costs (Table 2). All defined costs are expressed as reparation costs when a damage has occurred. Two examples of the developed pdfs together with the generated outputs for these distributions from the Monte Carlo simulation with 3000 iterations is shown in Fig. 4.

The cost functions for damages on buildings originate from Sundell et al. (2019) and they are based on a five legal cases on damages on buildings in Sweden as well as expert elicitation.

Cost for damages on garden areas are based on only one errand regarding reimbursement for damages of the area surrounding a building. The part of the garden needed repairment constituted the area surrounding the building, approximately 2 m out from the building. The ongoing errand had a reimbursement cost of 550 SEK/m^2. To account for any deviations in costs for damages on other gardens, two experts working with reimbursement errands assessed a minimum and maximum cost to 450 sek/m^2 and 3000 sek/m^2 respectively.

Cost for damages on pipes was described with a cost model based on registered costs for repair work on pipes within the municipality of Gothenburg, Sweden for five years (2014–2019). Through expert

Table 3
the test statistics for the goodness of fit tests Chi-square, Andersson-Darling and Kolmogorov-Smirnov.

Parameter	Statistic	Fit Value	P-Value
Sewer main pipe	Chi-Sq	7.4142	0.204
	K-S	0.0652	0.806
	A-D	0.2503	0.695
Sewer building	Chi-Sq	1.0269	0.823
	K-S	0.173	0.211
	A-D	0.8051	0.157
Water main pipe	Chi-Sq	120.0726	0
	K-S	0.0396	0
	A-D	5.7206	0
Water buidling	Chi-Sq	16.9027	0.423
	K-S	0.0335	0.195
	A-D	0.3406	0.331

elicitation, one parameter was assessed to influence the costs for damage: transport type. The data was therefore divided into four groups: 1) sewer – main pipe, 2) sewer – building connection, 3) water – main pipe, and 4) water – building connection. The division was based on the assumptions that transport type influences the repair cost since pressured pipes transporting drinking water and non-pressure pipes transporting sewer in general are located at different depths which can influence the amount of time needed for the repair work. In addition, if a damage occur, pressured pipes can be turned off during the repair work while the sewer water from the non-pressured pipes must be collected and handled. The cost for damages on pipes was described with PDFs for the four groups of pipes.

Cost for damages on paved surfaces was based on one errand regarding reimbursement costs for damages on a road. parts of this road needed repairment in the form of a new layer of asphalt, other parts needed larger repairment to the road. The cost for repairment in this errand was 250 sek/m^2 of road for new asphalt and 1100 sek/m^2 for larger repairment of the road. To account for deviations in costs for damages on other roads, the two experts working with reimbursement errands assessed minimum costs to 175 sek/m^2 and 800 sek/m^2 respectively and maximum costs to 350 sek/m^2 and 1400 sek/m^2 respectively.

The goodness of fit for the pdfs developed based on data was evaluated visually and with the tests: Chi-square, Andersson-Darling and Kolmogorov-Smirnov. The results from the tests are shown in Table 3. The goodness of fit for the developed pdfs are overall acceptable. For the parameter *Water main pipe*, the statistics indicate that the data does not follow the defined distribution to a satisfying proportion. A better goodness of fit would have been preferred but given the low impact this parameter has on the overall result, (see result from the sensitivity analysis performed in section 4.4) the selected distribution for this parameter was considered to be acceptable.

Risk estimation.

The aggregated risk expectancy (R_c) for each category (c) of objects at risk was calculated by coupling the calculated subsidence with the models for probability of damage and the models for damage costs. For buildings and gardens, the risk expectancy was simulated for a point located in the center of the building. Pipes and paved surfaces were sequences into 10-meter sections and the risk expectancy was simulated in each of these points. First, the subsidence was simulated in each point. The magnitude of the subsidence determined the damage category. Depending on the damage category, a cost was simulated from the defined cost distributions. The time (t) of damage from the initiated groundwater drawdown was determined from the function *t(s)* described in Appendix A. Simulation of subsidence. The cost of damage was discounted based on the time of damage. The aggregated risk expectancy was calculated according to:

$$R_c = \sum_{j=1}^{n} \frac{f(ss_j) \bullet C_j}{(1+r)^t} \tag{3}$$

Where j is each object at risk within one category c of objects at risk (buildings, gardens, pipes, and paved surfaces), n is the number of objects at risk in category c, f_i is the probability of damage of the magnitude of subsidence ss, C_i is the cost of damage, r is the discount rate and t is the time of damage.

The total risk expectancy (R) is in turn determined by summing the risk expectancy (R_c):

$$R = \sum_{j=1}^{n} R_c \tag{4}$$

Where n is the number of categories of objects at risk.

Table 4
Inputs for the cost calculations.

Cost	Unit	Abbreviation	Distribution[a]	Parameters	Source
Changing of pipes for drainage	msek	C_{cp}	PV	0.1	Expert elicitation
Original contract cost	msek	$CC_{0,2,4}$	BP	Min = 3500, Mode = 3681, Max = 4200	Original contract cost and expert elicitation
Second contract cost	msek	$CC_{1,3}$	BP	Min = 5200, Mode = 5427, Max = 5700	Current contract cost and expert elicitation
Cost design process	msek	C_{DP}	BP	Min = 80, Mode = 120, Max = 200	Cost data from previous projects and expert elicitation
Cost construction concrete lining	msek/100-meter	C_{CL}	PV	105	
Number of 100-meter sections		n_{CL}	BP	Min = 9, Mode = 17, Max = 31	
Reduced cost for post grouting	msek	C_{PG}	BP	Min = 75, Mode = 100, Max = 120	Expert elicitation
Increased construction time	years	T_{delays}	BP	Min = 2.5, Mode = 3, Max = 4	
Cost for delays	msek/year	YC_{delays}	BP	Min = 818, Mode = 850, Max = 892	Cost data from the project and expert elicitation
Volume water artificial recharge 2	l/min	VW_2	BP	Min = 970, Mode = 1350, Max = 2050	Leakage data from the project and expert elicitation
Volume water artificial recharge 3	l/min	VW_3	BP	Min = 460, Mode = 640, Max = 870	
Cost water for artificial recharge	sek/l	C_{water}	PV	0.015	Current cost
Capacity recharge well	l/min	Ca_{RW}	BP	Min = 0, Mode = 27, Max = 100	Data from the project
Cost construction recharge well	msek	CC_{RW}	BP	Min = 0.253, Mode = 0.610, Max = 0.760	
Cost maintenance recharge well	sek/year	YCM_{RW}	BP	Min = 4500, Mode = 18000, Max = 27000	
Cost reinforcement single family home	msek	CR	BP	Min = 1, Mode = 1.5, Max = 2	Expert elicitation

[a] BP = Beta PERT, PV = point value

3.5. Risk evaluation

The risk evaluation constituted the CBA of the risk mitigation alternatives. In this section, the procedure for simulating the cost for implementing the risk mitigation alternatives are described as well as the calculations of costs and benefits.

Implementation cost models.

All the risk mitigation alternatives are associated with implementation costs. The implementation costs were simulated for each iteration of the Monte Carlo simulation. The costs were categorized as: contract costs for building the tunnel (including excavation and grouting measures) and extra sealing measures in the form of concrete lining, costs for delays, costs for artificial recharge (installation, maintenance, and water usage) and costs for building reinforcements. The costs are listed in Table 4.

The amount of leakage into the tunnel has a direct effect on the cost for the project, e.g. due to increased amount of energy used for pumping the water from the tunnel and maintenance of drains. The energy usage was not considered in this study. Increased maintenance costs were assessed to be non-significant by the expert group. However, part of the pipes in one subsection of the tunnel must be replaced for all alternatives with higher leakage than the requirements in the legal permit. The cost for changing these pipes (C_{cp}) was therefore included in the cost calculations for these alternatives.

The implementation costs for all risk mitigation alternatives include contract costs ($C_{contract}$). Two contract costs were considered in this analysis. The first contract cost ($CC_{0,2,4}$) reflects the original procurement and thus the original sealing strategy. The second contract cost ($CC_{1,3}$) represents the modified sealing strategy. The mode value for these costs represents the actual contract costs in the project. Two experts working with the sealing strategy for the tunnel assessed possible deviations for the contract costs by assessing a minimum and maximum cost.

The two experts working with the sealing strategy also assessed that risk mitigation alternative 3 needed extra sealing measures to fulfill the requirements in the legal permit, due to the high inflow of water caused by the high transmissivity in the bedrock in combination with the artificial recharge resulting in high groundwater levels and thus a high gradient into the tunnel. The extra sealing measures constituted concrete lining for parts of the tunnel where the transmissivity of the bedrock is high, and the grouting was assessed to be insufficient. Concrete lining results in direct investment costs for the design process and material and labor but also indirect cost for delays. The direct costs constitute the design process, removal of bedrock to widen the tunnel diameter (necessary since the tunnel was not designed for a concrete lining from the start), leveling of the tunnel walls for a smoother surface, and the reinforcement and casting of the concrete. The cost for the concrete lining was assessed in three steps. First, the cost for the design process (C_{DP}) was assessed. Second, the cost for constructing the lining (CCL) per/100 m was assessed. This cost estimate was based on similar constructions in other tunnel projects. Third, the number of 100-meters sections (n_{CL}) necessary to fulfill the requirements was assessed. The usage of concrete lining in this alternative subsequently resulted in less usage of post-grouting measures (C_{PG}).

The same experts also assessed that the concrete lining would result in an increased construction time. These indirect costs were a result of the spread of delays in the construction chain, e.g. delayed installations. Other costs emerging from delays were the prolonged overhead cost for running the project. The time necessary for the process of widening the tunnel, leveling of the tunnel walls and reinforcement and casting of concrete (T_{delays}) was assessed together with the yearly cost for delays (YC_{delays}).

Risk mitigation alternative 2 and 3 both use artificial recharge to maintain stable groundwater levels. The amount of recharge water (VW_i) was estimated based on the experience of the effects of already existing active artificial recharge facilities used in the project together with the assessed leakage for the risk mitigation alternatives. The cost of water for artificial recharge (C_W) was determined based on the present cost of water for the project. The amount of water needed to be recharged (VW_i) was assessed based on the experience of the effects of 14 wells already installed in the project together with the assessed leakage for the risk mitigation alternatives. The cost of water (CW), the capacity of one new recharge well (Ca_{RWi}), the cost of constructing an artificial recharge facility (CC_{RW}), and the yearly cost for maintenance (YCM_{RW}) were determined based on cost data for these 14 wells. Since the technical life expectancy of the tunnel is 120 years ($T = 120$), the artificial recharge must continue for the same period.

Risk mitigation alternative 4 included reinforcement measures of the most subsidence sensitive buildings. The identification of these buildings was made by simulating the subsidence in the location of all subsidence sensitive buildings with 3000 iterations. The assessed groundwater levels for scenario 1 were used as input data for the subsidence calculations. If the subsidence was>1 cm in minimum 5 % of the simulations, the building fulfilled the criterion for being a target of the reinforcement measure. The reinforcement was considered to be performed before the start of construction and the reinforced buildings was therefore not included in the economic damage risk calculations for buildings for this alternative. The cost of reinforce a single-family home (CR) was assessed by experts specialized in reinforcement of building foundations.

Implementation cost.

The aggregated implementation cost (IC_k) cost for each category of implementation costs k was calculated according to following generic equation:

$$IC_k = \sum_{j=1}^{n} \frac{IC_j}{(1+r)^t} \tag{5}$$

Where j is each cost object, e.g. each artificial recharge well, within one category k of implementation costs (contract costs for building the tunnel, extra sealing measured in the form of concrete lining, costs for delays, costs for artificial recharge, and costs for building reinforcements), n is the number of cost objects, C_i is the implementation cost, r is the discount rate and t is the time of the implementation from the initiated groundwater drawdown.

The total implementation cost (IC) is determined by summing the implementation costs (IC_k):

$$IC = \sum_{j=1}^{n} IC_k \tag{6}$$

where n is the number of categories of implementation costs.

Costs and benefits.

The benefits (B_i) of implementing a risk mitigation alternative i were calculated as:

$$B_i = R_0 - R_i \tag{7}$$

Where R_0 is the total risk of the reference alternative and R_i is the total risk expectancy for the risk mitigation alternative i.

The Costs (C_i) of implementing a risk mitigation alternative i were calculated according as:

$$C_i = IC_0 - IC_i \tag{8}$$

Where IC_0 is the total implementation cost of the reference alternative and IC_i is the total implementation cost for the risk mitigation alternative i.

3.6. Sensitivity analysis

To identify what input parameters that had the largest impact on the output results, a sensitivity analysis was performed. The sensitivity analysis was divided into two parts, one for the subsidence calculations

Table 5
Parameters included in the two sensitivity analysis.

Sensitivity analysis	Risk expectancy	NPV
Parameter	GWD	Risk expectancy buildings
	M_0	Risk expectancy gardens
	M_L	Risk expectancy paved surfaces
	M'	Risk expectancy pipes
	σ'	Costs contracts
	σ'_c	Costs design process lining
	σ'_L	Costs reduced post-grouting
		n 100-meter sections lining
		Time delays
		Yearly cost delays
		Volume water for artificial recharge
		n recharge wells
		Total cost for construction of recharge wells
		Total cost for maintenance of recharge wells
		Cost reinforcement measures

and the risk expectancy, and one for remaining input parameters to the cost-benefit analysis. The argument for dividing the sensitivity analysis is the varying number of dimensions used in the two models where the subsidence is simulated spatially in two dimensions while the cost-benefit analysis only uses one dimension. Both sensitivity analyses were performed by calculating the Spearman rank correlation coefficients for all input parameters and the output parameters: risk expectancy and *NPV*. For the subsidence calculations and thus the risk expectancy calculations, an arithmetic mean for the vertical vector is calculated for each point and used as input to the sensitivity analysis. The input variables included in the two sensitivity analysis is listed in Table 5.

4. Results

This section presents the result for the simulated subsidence for the model area, the cost-benefit analysis (CBA), and the sensitive analysis for the CBA. The sensitivity analysis for the subsidence calculations and the risk expectancy is presented in Appendix D Sensitivity analysis – Subsidence calculations.

The model was simulated two times with 3000 iterations each to compare the absolute coefficient of variance with the purpose to investigate how close the model was to convergence. There were no or very small difference for the coefficient of variance for the two simulations indicating that 3000 iterations are enough for the model to convergence.

4.1. Risk mitigation alternatives

Five relevant risk mitigation alternatives were defined for this study (Table 6). Two sealing strategies were considered relevant to investigate. The first sealing strategy (original sealing strategy) is based on the original sealing strategy specified by the project owner in the planning phase of the project. The second sealing strategy (modified sealing strategy) constitutes a sealing design assessed necessary to implement to fulfill the leakage criterion in the legal permit. The first sealing strategy was based on the accumulated knowledge of the hydrogeological conditions in the bedrock from the planning phase of the project, before excavation started in 2018. The second strategy was based on knowledge regarding the conditions that was revealed during excavation and thus constituted the accumulated knowledge from the planning phase and the excavation phase until autumn 2019 when this CBA was conducted.

Table 6
Risk mitigation alternatives.

Mitigation alternative	**Sealing strategy**	**Recharge strategy**	**Fulfills leakage requirements**	**Cause damage**
0	Original	No recharge	No	Yes
1	Modified	No recharge	Yes	Yes
2	Original	Recharge	No	No
3	Modified	Recharge	Yes	No
4	Original	No recharge	No	Yes*

* No damages on subsidence sensitive buildings

The artificial recharge is divided into no recharge or recharge. No recharge constitutes no recharge at all. Recharge constitute the amount of water assessed needed to recharge in order to maintain stable groundwater within the model area.

One alternative did also include reinforcement measures on subsidence sensitive buildings.

4.2. Simulation of subsidence

The result from the simulation of subsidence is shown in Fig. 5. As indicated by the figure, the magnitude of subsidence varies with low subsidence (<1cm) magnitude for the 5th percentile and large subsidence (>20 cm) for the 95th percentile. The magnitude of subsidence does also vary between the two scenarios with larger subsidence for risk-reducing measure alternative 0 and 4 compared to risk-reducing measure alternative 1. Notice that there is subsidence of a magnitude that may cause damage for both scenarios.

4.3. Cost-benefit analysis

The risk expectancy, benefits, costs and *NPV* for the discount rate 0, 1.4 and 3.5 % are presented for the 5th, 50th and 95th percentile in Fig. 6. More detailed graphs of the risk expectancy for the various categories of objects at risk are shown in Appendix B. Risk expectancy and detailed graphs of the implementation costs are shown in Appendix C. Implementation costs.

The risk expectancy is highest for the reference alternative (median value around 50 MSEK) followed by risk mitigation alternative 4 (median around 40 MSEK) and alternative 1 (median round 35 MSEK). Risk mitigation alternative 2 and 3 has a risk expectancy of 0 MSEK due to the artificial recharge in both these alternatives that maintain stable groundwater levels subsequently resulting in no subsidence damages. The benefits are highest for alternative 2 and 3 (median value around 50 MSEK). The choice of discount rate is not of importance for the benefits since the subsidence occurs shortly (within a few years) after the initiated groundwater drawdown. This corresponds well with the measurements of subsidence performed continuously as a part of the environmental monitoring program in the project. The implementation cost is highest for risk mitigation alternative 3 (median value around 7000 MSEK). Followed by alternative 1 (median value around 1700 MSEK) and 2 (median value around 660 MSEK) and 4 (median value around 4 MSEK). Both alternative 2 and 3 have recurring costs for the artificial recharge for the life expectancy of 120 years for the tunnel and the choice of discount rate therefore impacts the costs for these alternatives. The *NPV* is highest (median value around 0 MSEK) for alternative 4 followed by alternative 2 (median value around −630 MSEK), 1 (median value around −1692 MSEK) and last 3 (median value around 7140 MSEK).

4.4. Sensitivity analysis

The result from the sensitivity analysis for the cost-benefit analysis for risk mitigation alternative 1–4 for the discount rate 0 % is shown in Fig. 7. The sensitivity analysis for the other discount rates are not presented since the result is very similar regardless of the discount rate. The figure shows the degree to which costs and benefits covariate with the *NPV* outcomes, expressed in the form of correlation coefficients

Fig. 5. Result from the subsidence simulations for the 5th, 50th and 95th percentile. The upper row shows the result for risk mitigation alternative 0 and 4 and the lower row shows the result for risk mitigation alternative 1. Alternative 2 and 3 is not included in the Fig. since they both includes artificial recharge that counteracts any groundwater lowering which eliminates the risk of subsidence.

between − 1 and 1. For risk mitigation alternative 1, the contract costs have the highest impact on the *NPV*. For alternative 2, the volume of water necessary to infiltrate is the single most important parameter. Here, a large volume result in a low *NPV*. For alternative 3, the length of the concrete lining has the highest impact where a high number gives a low *NPV*. For alternative 4, the reinforcement cost for subsidence sensitive buildings has the highest impact. Knowledge that could reduce the uncertainty of these parameters could decrease the overall uncertainty of the result from the CBA. Further investigations and collection of data should thus be appointed towards these parameters.

5. Discussion

The aim of this paper was to present methods needed to facilitate a real-world practical application of the risk management framework for decisions on hydrogeological risk mitigation. The methods presented for calculating the damage risk together with the CBA approach can support decision makers in making informed choices on what risk mitigations to implement. If the framework is applied in an early stage of a project, the result can also be used as support in identifying economically reasonable legal requirements. If the framework is used properly, the models can be used during all phases (planning, construction, and operating) of a project. Once new information is retrieved, the models must be updated to make sure that the decision makers can always base their decisions on the latest knowledge from the project. The main methods used in this paper are well established and commonly used for risk management and decision support for investment in projects in society. However, to the authors' knowledge, combining a risk-based cost-benefit analysis as decision support for management of hydrogeological risks in underground constructions has not previously been done. The novelty of this paper thus constitutes the combining of established methods for application in underground construction with focus on hydrogeological risks.

The study also aimed at evaluating the socio-economic profitability and to assess the effects of measures for risk mitigation for groundwater control in a case study. Four risk-mitigation alternatives were evaluated for the tunnel Bypass Stockholm. It is important to emphasize that the result from the analysis does not constitute a decision but should be regarded as a support in the decision-making process. The result is also only representative for this case study. In another context with e.g., more objects at risk such as a city center with a high density of subsidence sensitive buildings with high cultural value, the result could be the different. Every area of influence of an underground construction is unique and has different types of objects at risk. The risk-analysis for this case study only focused mitigation measures for leakage control for reducing the risk of subsidence damages. However, in other projects the objects at risk can instead constitute groundwater dependent ecosystems, such as peatlands, streams, springs and lakes (Attanayake & Waterman, 2006), groundwater dependent building foundations sensitive to groundwater lowering (Elam & Björdal, 2020), aquifers sensitive to changed gradients, e.g. aquifers in coastal areas that risk saltwater intrusion (Mas-Pla et al., 2013), or forest trees (Behzad et al., 2022). Other hydrogeological risks associated with underground constructions may also be necessary to consider, e.g. the risk of turbidity from constructing the tunnel (Burris et al., 2021), the risk of shield tunnel failure

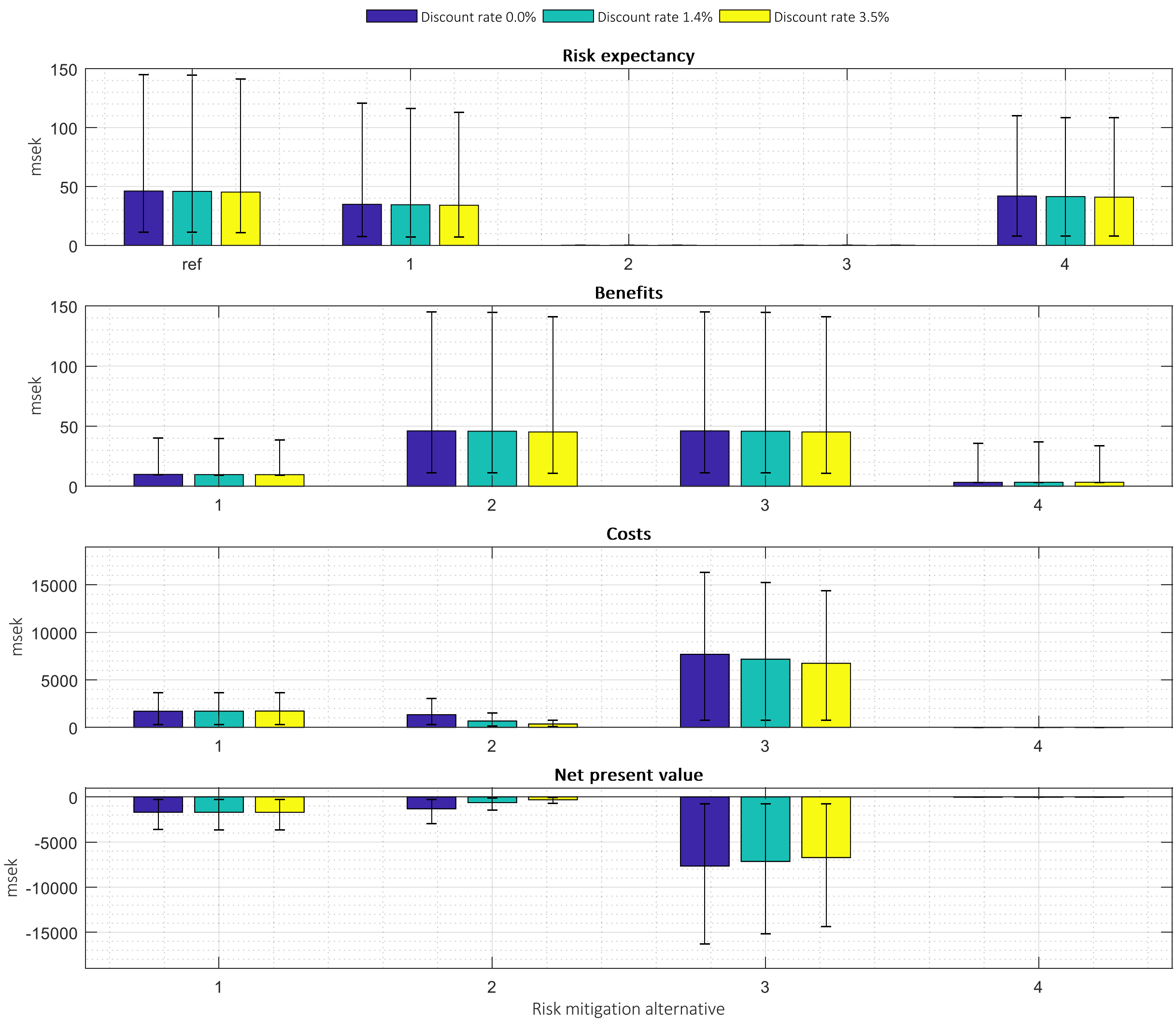

Fig. 6. The risk expectancy for the reference alternative and the risk mitigation alternative 1–4, and benefits, costs, and NPV for the risk mitigation alternatives 1–4 in million SEK and for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile. The value given in text represents the 50th percentile. Note the different scales on the y-axis between the graphs.

due to leakage (Lee & Ishihara, 2010) or the increased risk of leakage due to seismic activity in seismic active regions (Andreotti & Lai, 2019).

In this case study, the reduced risk expectancy constituting benefits from sealing measures are small in relation to the implementation cost. It is also clear that although the sealing measures reduce the risk expectancy, artificial recharge is also required to completely avoid damage. The relatively small benefits are a consequence of the low number of objects at risk within the area of influence of the tunnel. As an example, most buildings with subsidence sensitive foundations are single family houses located close to the bedrock outcrops where the clay thickness is small.

It is important to point out that there are several limitations associated with this study. First, an important part of modelling is to validate the simulation models to evaluate the reliability of the results. In this study, no simulation models could be validated since the alternatives evaluated represents future scenarios for which no validation data yet exists. For decisions based on the result of non-validated models, it is important to instead evaluate if the process representation is sufficiently detailed and accurate for predicting the system response of stresses such as leakage (Beven, 2007).

Second, there are costs and benefits not included in the analysis. As an example, pipes for district heating were not included in the risk analysis due to unavailable data regarding locations of pipes. However, it is not likely that the result from the analysis would change dramatically if these were to be included since the risk expectancy on the other objects at risk was relatively low compared to the implementation costs for the evaluated risk mitigation alternatives. Other economic, environmental, and social external effects should also be considered in a CBA. An example of an economic external effect is the risk of impacts on real estate values in subsidence sensitive areas (Willemsen et al., 2020; Yoo, J. & Perrings, 2017). As an example of an environmental effect, a more robust sealing strategy results in large costs for emissions of carbon dioxide since both grouting and a concrete lining have a large CO_2-footprint (Strømsvik, 2019). Another example of both societal and environmental costs are delays and subsequently prolonged project delivery time which is associated with traffic congestion, economic activities being interrupted, increased pollution, damage to ecosystems, and impacts on existing infrastructure systems (Adam et al., 2015; Gilchrist & Allouche, 2005). In the case of Bypass Stockholm, a delayed opening of the tunnel directly results in prolonged period with long travel times for the road traffic in the region. If these effects were to be considered in the analysis, it is likely that the NPV for the alternatives including extra sealing measures and thus a delayed project delivery would be even lower. Another limitation of the analysis is that it constitutes the collected knowledge at one point in time. Once the project progresses and new information is retrieved, the models should be

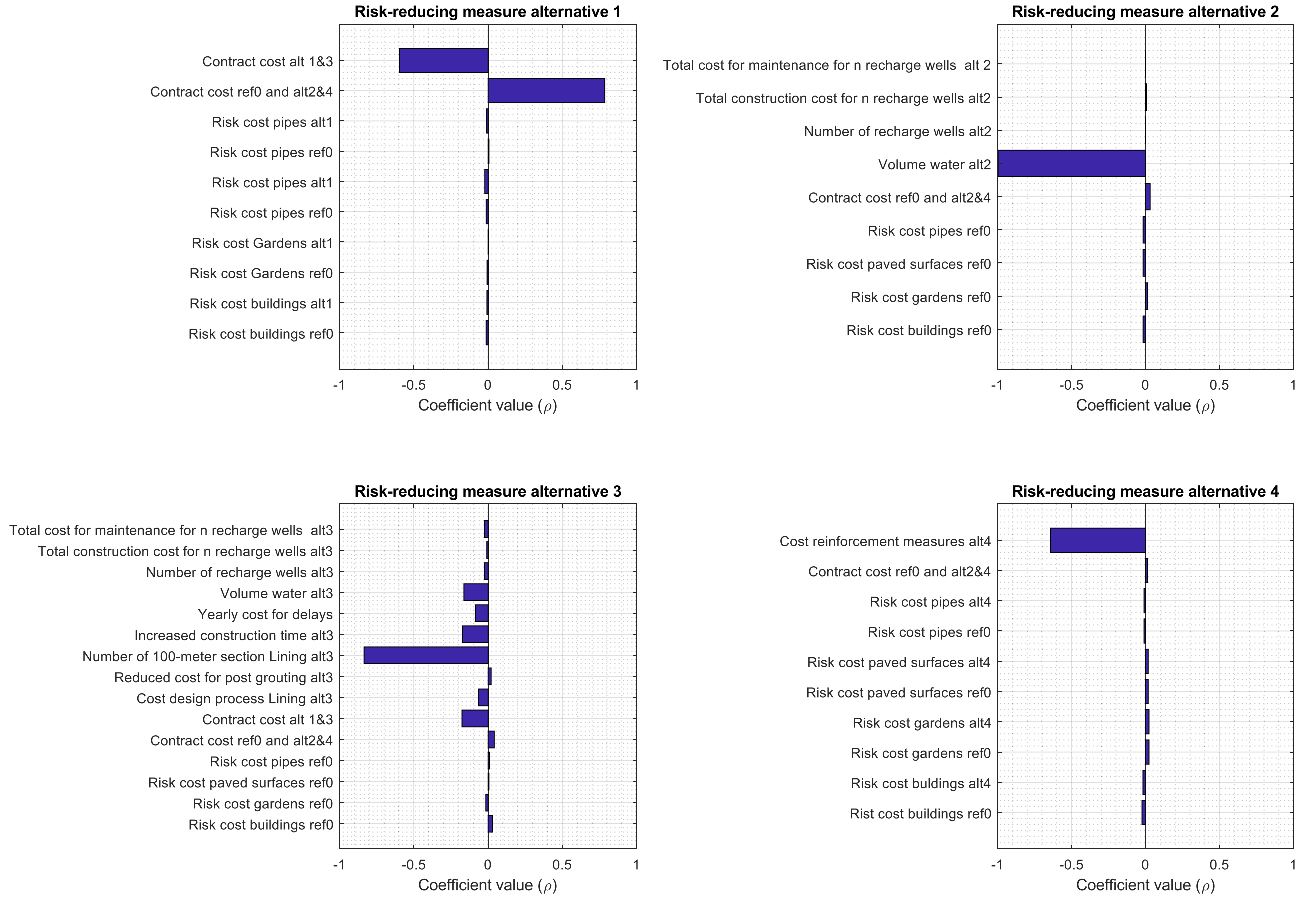

Fig. 7. Sensitivity analysis performed for the cost-benefit analysis with Spearman's rank correlation coefficients for risk mitigation alternative 1–4 for the discount rate of 0%.

updated and the result from the analysis may change.

The probabilistic approach applied in this case study enables quantification of uncertainties and probabilities. However, uncertainties associated with the models themselves are not considered in this study. These uncertainties can be reduced by an improved understanding of the hydrogeological and geotechnical system and thus an update of the conceptual and mathematical model. However, models must be a simplification of reality in order to make the model usable with regards to e.g. computation time (Burgman, 2005; Sturk, 1998).

The study also aimed at evaluating the effects of the legal requirement formulated in the legal permit that the project retrieved from the Land- and Environmental court. There are two types of risks for making erroneous decisions associated with the implementation of risk mitigation:

The risk of *not implementing necessary measures*, resulting in damages and subsequently costs for the project owner, the society and the environment, and

The risk of *implementing measures when not needed*, resulting in unnecessary implementation costs.

The legal requirements aim at protecting against risk 1. In the case of this tunnel project, risk mitigation alternative 3 with the lowest *NPV* is the only alternative that fulfills the leakage requirements in the legal permit and that does not cause any damage, i.e. has a risk expectancy of 0. The requirements are in this case causing large implementation costs in sealing measures although the benefits of these measures are relatively small. The legal requirements thus result in a high type 2 risk and are not considered to follow the proportionality principles of Swedish environmental code.

6. Conclusions

The main conclusions of this paper are:

- Combining expert elicitation with data and empirical models for the cost-benefit analysis constitutes a structured approach for evaluation of the economic profitability of different mitigation alternatives. The probabilistic model also constitutes a transparent approach of managing parameter uncertainties which allows for calculations of probabilities.
- The usage of expert elicitation for development of damage- and cost models are a necessary approach when data is limited, unreliable, too costly to obtain, or unobtainable.
- The identified costs and benefits facilitate the identification of potential consequences of implementing risk mitigation so that effects that otherwise might be overlooked in the evaluation process can be considered and openly addressed.
- External costs and benefits of risk mitigation must also be identified, described, and included in the analysis for a robust evaluation of risk mitigation for management of hydrogeological risks.
- In this case study the CBA showed that the low-cost object-specific measure of extra reinforcements to subsidence sensitive buildings is the only profitable alternative.
- In this case study the net benefit in the form of reduced economic risk expectancy is small relative to the costs for implementation of sealing and infiltration due to the few objects at risk and the large implementation costs that sealing measures entails.
- In this case study the cost of implementing the risk mitigation alternative 3 that fulfills the legal requirements and prevent damages, ~7000 MSEK (704 EUR), are not proportional to the benefits

obtained, ~50 MSEK (5 EUR). The requirements in the legal permit are thus disproportionate.

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CRediT authorship contribution statement

Johanna Merisalu: Conceptualization, Funding acquisition, Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Jonas Sundell:** Conceptualization, Supervision, Methodology, Investigation, Writing – review & editing. **Lars Rosén:** Conceptualization, Funding acquisition, Supervision, Methodology, Writing – review & editing, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. . Simulation of subsidence

This section provides on overview of the methods used for data processing and simulation of subsidence used for the risk analysis.

Changes in effective stress

The subsidence is a function of the changes in effective stress which subsequently is a result of the changing groundwater level induced by leakage into the tunnel. The vertical stress (σ_v) is calculated from the thickness and density of the clay and the overlaying filling material. Surface loads from e.g., buildings or other facilities are not included in the calculations. Information regarding the thickness of the stratigraphic units was derived from a stratigraphic model developed by the Swedish transport administration in conjunction with compiling the preconditions of the project for the legal hearing in the land- and environmental court (STA, 2013). This stratigraphic model is a simplification of reality and includes three continuous layers: an upper layer of course grained material (often filling, sand and dry crust clay), an intermediate layer of clay and a bottom layer of course grained material (till or glaciofluvial). The model is based on data of mapped bedrock outcrops, drillings and CPT-soundings. The resolution of the model was 10x10 meters. Information regarding the density of the stratigraphic units is covered in section 0. The vertical stress (σ_v) is calculated for each grid point of the stratigraphic model. At each of these grid points, the stresses of the soil are calculated in a vector with a resolution of 0.1 m.

The undisturbed groundwater levels for the lower confined aquifer within the model area was determined from groundwater observations. The observations constitute groundwater level measurements conducted in 91 observation wells before the start of the project in 2015. The measurements constitute time series with varying resolution (every month to year) and length (a few measurements in a year to several years starting from 1970). Groundwater levels in the upper open aquifer is assumed to be equal to the upper edge of the clay.

The changes in groundwater levels in the lower confined aquifer were determined based on expert elicitation. Hydrogeologists involved in the tunnel-project with knowledge of the hydrogeological conditions in the area assessed the resulting groundwater drawdown (*GWD*) of the different risk-reducing measure alternatives. Only measure alternative 0,1 and 4 are subjected to groundwater drawdown since infiltration is considered to counteract any drawdown caused by leakage for alternative 2 and 3. The drawdown is also the same for alternative 0 and 4. This means that groundwater drawdown was assessed for two scenarios in total: scenario 0 and 4 where the sealing strategy constituted a grouting design in accordance with the original sealing strategy for the tunnel, and scenario 1 with a grouting design that fulfills the leakage requirements in the legal permit. The groundwater level was assessed in 71 locations, 49 inside and 22 outside the model area. The pointwise groundwater level observations constituting both the undisturbed groundwater levels and the groundwater drawdown was in a next step interpolated to enable subsidence calculations for all grid points within the model area. The interpolation method used was inverse distance weighting (IDW) with barriers. The barriers constitute all areas with bedrock outcrops. To account for uncertainties in the subsidence simulation, it was deemed necessary to apply the assessed groundwater levels with a margin of error of ± 20 %.

Based on the interpolated groundwater levels (undisturbed and disturbed), the pore pressure profile (u) is calculated as a linear approximation between the pressure heads at the top and bottom of the clay layer. The effective stress (σ'_v) is calculated from the vertical stress (σ_v) and the pore pressure (u). The changes in pore pressure from the undisturbed to disturbed groundwater level conditions (Δu) governs the change in σ'_v which in turn governs the subsidence. As with σ_v, the σ'_v and u are simulated for each grid point and for each 0.1-meter vector segment. The σ'_v and u are calculated for steady state conditions. In order to enable an analysis of when the subsidence reaches a certain magnitude, the consolidation process in the clay was calculated from Terzaghi's one dimensional consolidation theory (Terzaghi, 1943) with a solution based on Fourier series (Taylor, 1948). This was carried out for the time (t): 1, 2, 4, 15 and 14 years from the initiated groundwater lowering. Based on these calculations, a function $t(s)$ is created where the time in years after initiated groundwater lowering is a function of the subsidence magnitude. The function is a linear interpolation between the five times and thus a rough simplification of the actual time-subsidence curve.

Data, data processing and statistical analysis

The variable data used as input for the subsidence calculations constitutes 164 samples from 50 locations along the tunnel. The data was not obtained specifically for this study, instead it origins from the geotechnical investigations performed before the start of construction of the tunnel (STA, 2013). The variable values from these samples are shown in (Fig. A1). The samples were divided into three groups (Group 1, Group 2, and Group 3) depending on the location of the samples. Group 1 constitutes the model area in the northern part of the tunnel, Group 2 the middle part, and Group 3 the southern part. As can be seen in the figure, the parameter values vary for the different samples and some parameters indicate a vertical trend with higher values along depth. Assessing the quality of the geotechnical data is outside the scope of this article. However, for future implementation of this model we recommend using high quality data and manual evaluation of the oedometer test results to make sure that the defined PDFs are reliable and

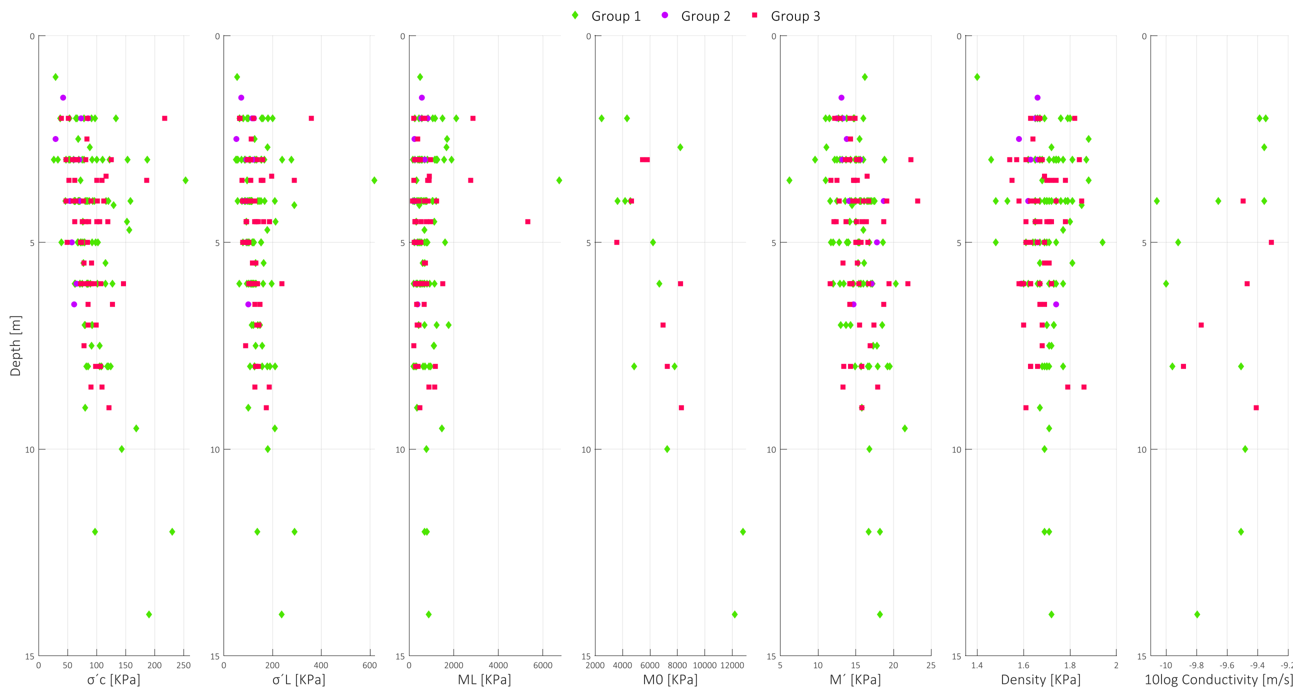

Fig. A1. Scatter plots of σ'C, σ'L, ML, M0, and M', density and hydraulic conductivity for the 164 samples.

reasonable.

Before the PDFs for the subsidence calculations are defined, the dependencies between parameters needs to be addressed. The first dependency necessary to account for is the current effective stress (σ'_v) and the pre-consolidation stress (σ'_C) which together defines the over consolidation ratio (*OCR*). Since σ'_C represents the maximum value of an historical effective stress, σ'_v cannot be higher than σ'_C, thus $OCR > 1$. With this condition, all *OCR* values < 1 must be evaluated. Other dependencies between compression variables exist because of the stress–strain relationship ($\sigma_L > \sigma'_C$ and $M_0 > M_L$) and some ratios (σ'_L/σ'_C, $M_L/\acute{\sigma}_L$ and M_0/M_L) must be used to avoid inconsistencies in the calculations. To make sure that $\sigma'_C > \sigma'_v$ and $\sigma'_L > \sigma'_C$, both *OCR* and the ratio σ'_L/σ'_C are conditioned by subtracting 1. The hydraulic conductivity (k) and density (ρ) for the clay and the course material are in this study assumed to be independent from the other variables. If the variable or quota is normally distributed, the mean value (μ) and the standard deviation (σ) is determined. If not, the data is transformed by the natural logarithm to normally distributed values. The normality of the various parameters were evaluated with the Anderson-Darling goodness of fit test (Anderson & Darling, 1954).

As a next step, any spatial trends among the samples were investigated. The analysis focused on finding any differences between the three groups defined for the samples. The statistical method of ANOVA was used for this analysis. The null hypothesis is that the mean value among the groups is the same. The null hypothesis is rejected or not rejected with a significance level of 5 %. If there is a significant difference among the groups, the Bonferri-method (Dunn, 1961) is used as a post hoc test to point out which of the groups that should be excluded from the analysis. If the null hypothesis is rejected, only data from the remaining areas was used for the determination of PDFs. If the null hypothesis cannot be rejected, differences between the groups cannot be distinguished and all samples was assumed to belong to the same population and thus used for the determination of PDFs. Result from the variance analysis is shown in Table A1. The null hypothesis (equal means among groups) was only rejected for the variable density where the data from area 2 was excluded. For the quota M_0/M_L and the hydraulic conductivity, a *t*-test was carried out since no data for the variable M_0, and hydraulic conductivity was available from area 2. For the remaining variables and quotas, all data available was used for defining the PDFs.

As a final step in the statistical analysis, the existence of any vertical trends was investigated with linear regression. A determination coefficient (R^2) close to zero indicates a lack of vertical trend. A value of R^2>0.05 is assumed to indicate a vertical trend, i.e. the depth explains more than five percent of the variability for this variable. If R^2 is considered, the mean value (μ) and the standard deviation (σ) is determined based on the linear regressions residuals to make sure that the variance is equal in size at any vertical interval. The probability density distributions and the regression coefficients are presented in Table A2. It was only the variable density that showed no significant trend with depth ($R^2 = 0.0019$). Density was therefore only transformed with the natural logarithm. Remaining variables and quotas all showed a vertical trend. The mean value (μ) and the standard deviation (σ) is thus determined based on the linear regression's residuals for these. The PDFs for the transformed and logarithmic data are

Table A1
results from the variance analysis. Column two and three shows the p-value for the null hypothesis (equal means among groups).

Variable	ANOVA 1–2	ANOVA 1–3	Excluded area
ln (OCR-1)	0.96	0.57	None
ln ($\acute{\sigma}_L/\acute{\sigma}_c$-1)	0.35	0.78	None
ln ($M_L/\acute{\sigma}_L$)	0.31	0.41	None
ln (M_0/M_L)	–	0.9	None
ln $\acute{M}$	0.98	0.73	None
ln (Density)	0.04	0.14	2
log10 (k)	–	0.11	None

Table A2
Determination coefficients mean value and standard deviation for the PDFs, as well as the regression coefficients for the variables and quotas.

Variable	R^2	PDF		Regression coefficients	
		μ	σ	a	b
ln $\acute{M}$	0.13	0	0.15	0.03	2.58
ln (OCR-1)	0.13	0	0.9	−0.16	0.27
ln ($\acute{\sigma}_L/\acute{\sigma}_c$-1)	0.05	0	0.62	−0.07	0.54
ln ($M_L/\acute{\sigma}_L$)	0.06	0	0.51	−0.06	1.87
ln (M_0/M_L)	0.14	0	0.54	0.07	2.08
ln (Density)	0	0.53	0.05		
log10 (k)	0.13	0	0.28	−0.03	−9.36

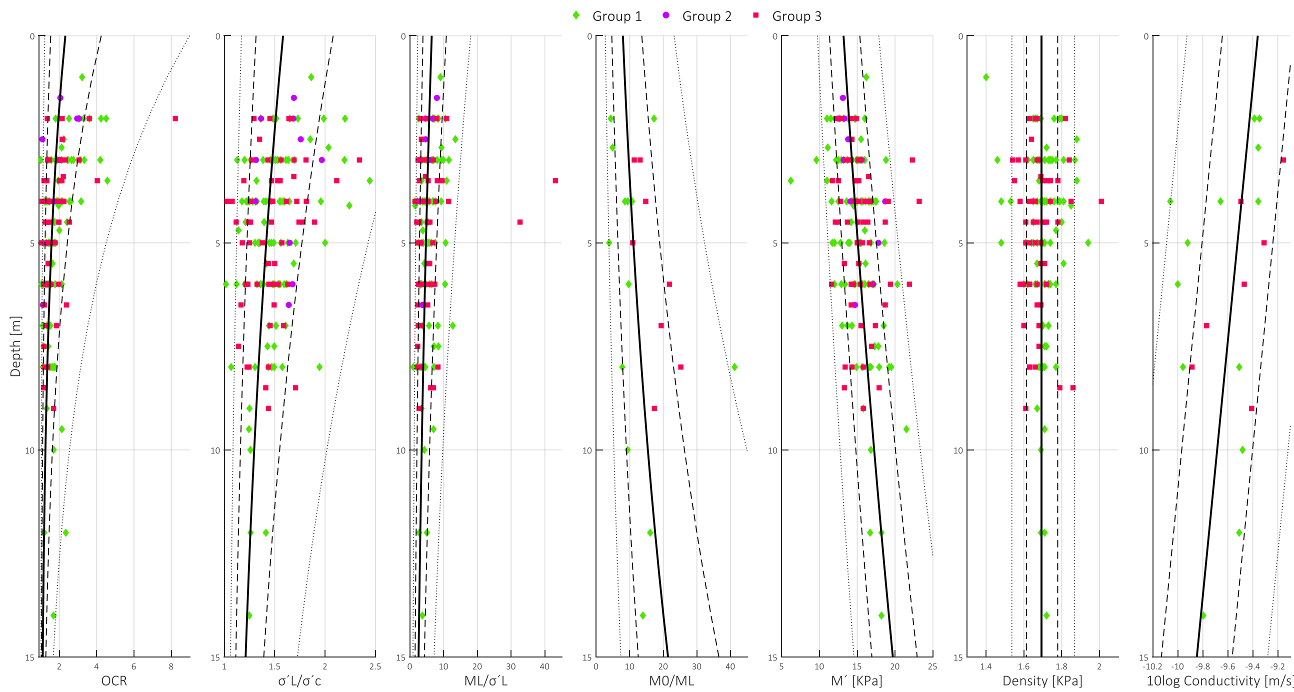

Fig. A2. Graphs constitute scatter plots of transformed compression variables and factors for OCR, σ'L/σ'C, ML/σ́L, M0/ML, M', density and hydraulic conductivity. The dashed lines indicate the standard deviation and the dotted lines two standard deviations (95 percentile interval) for future observations.

illustrated graphically in Fig. A2.

Simulation of subsidence

The various variables for the subsidence calculations are simulated in a sequence as follows. Based on the stratigraphic model and the undisturbed groundwater level, u och σ'_v are determined along the vertical vector every 0.1 m. The *OCR* is simulated by transforming the values simulated from the PDF ln (OCR-1) by the natural logarithm and by adding 1. σ'c is determined by multiplying σ'_v with *OCR*. In the same manner, σ'_L is determined by multiplying σ'_c with the PDF for the quota σ'_L/σ'_c, M_L is determined by multiplying $\acute{\sigma}_L$ with the PDF for the quota $M_L/\acute{\sigma}_L$ and M_0 is determined by multiplying M_L with the PDF for the quota M_0/M_L. remaining variables are simulated directly from the PDFs. Δu is determined for $t = 1, 2, 4, 15$ and 40, based on the assessed groundwater drawdown for the measure alternatives.

The magnitude of subsidence is calculated in each grid point with a simple one-dimensional elasto-plastic compression model by Larsson and Sällfors (1981). The model is based on variables evaluated from constant rate of strain (CRS) oedometer tested clay samples. Three cases of stiffness (equation 4–6) with different compressions modules as a function of the effective stress are evaluated in the model. Which case that was used depends on how σ'_v and $\Delta\sigma$ related to $\sigma'c$ and σ'_L according to following conditions:

$$if\,\sigma'_v + \Delta\sigma < \sigma'_c then\,\delta(z) = \frac{\Delta\sigma}{M_0} \tag{A.1}$$

$$if\,\sigma'_c < \Delta\sigma + \sigma'_v then\,\delta(z) = \left(\frac{\sigma'_c - \sigma'_v}{M_0} + \frac{\sigma'_v + \Delta\sigma - \sigma'_c}{M_L}\right) \tag{A.2}$$

$$if\,\sigma'_v + \Delta\sigma > \sigma'_L then\,\delta(z) = \left(\frac{\sigma'_c - \sigma'_v}{M_0} + \frac{\sigma'_L - \sigma'_c}{M_L} + \frac{1}{M'}\ln\left(1 + \left(\sigma'_v + \Delta\sigma - \sigma'_L\right)\frac{M'}{M_L}\right)\right) \tag{A.3}$$

The subsidence in each grid point was determined by integrating the solutions for equation 4–6 along the vertical vector in accordance with following equation:

$$s = \int_0^{z_{max}} \delta(z)dz \tag{A.4}$$

Appendix B. . Risk expectancy

This section presents the resulting risk expectancy for the categories buildings, gardens, pipes, and paved surfaces, for all risk mitigation alternatives and with the discount rate 0, 1.4 and 3.5 %. The risk expectancy are presented in Figs. B1-B5.

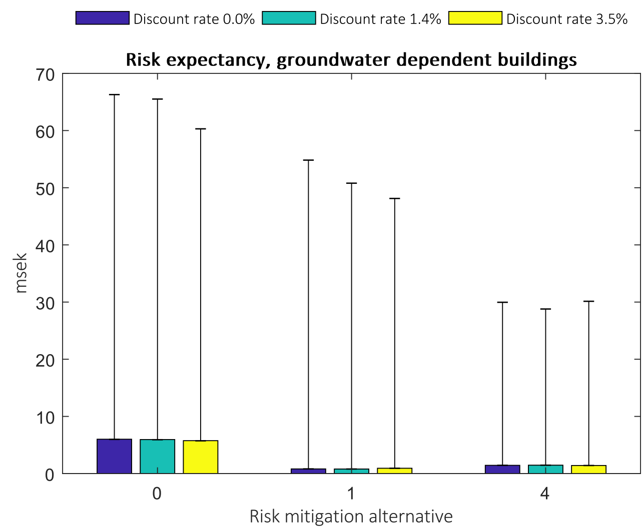

Fig. B1. Risk expectancy for buildings for the risk mitigation alternatives 0, 1 and 4, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

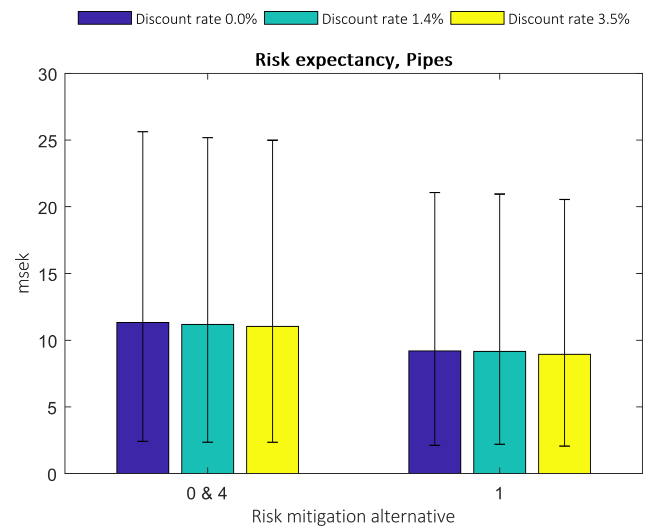

Fig. B3. Risk expectancy for pipes for the risk mitigation alternatives 0(4) and 1, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

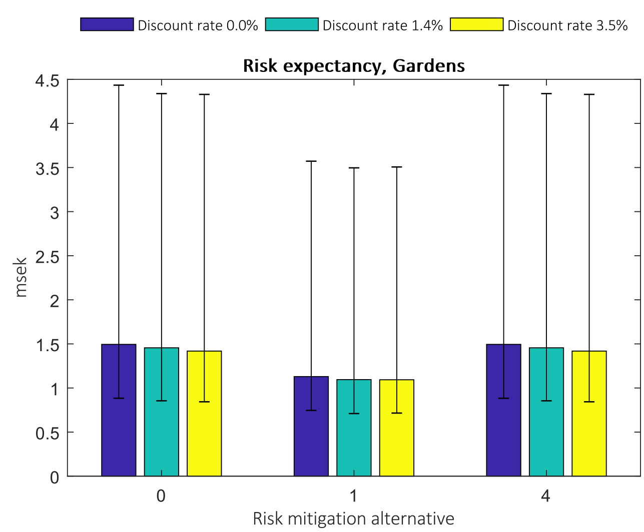

Fig. B2. Risk expectancy for garden areas for the risk mitigation alternatives 0 and 1, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

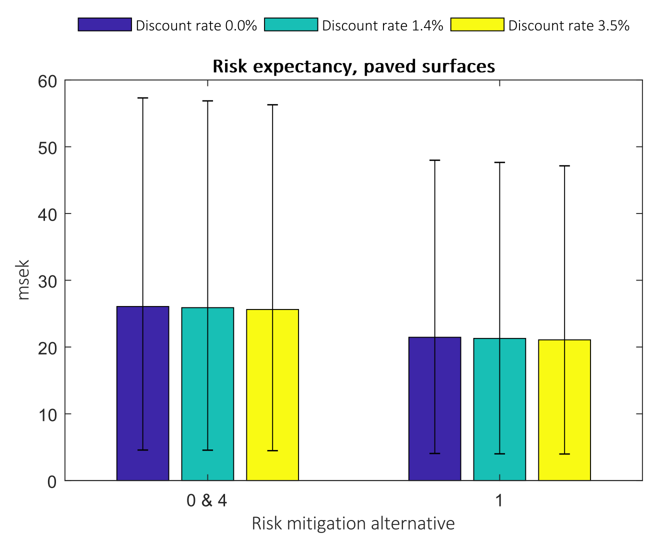

Fig. B4. Risk expectancy for paved surfaces for the risk mitigation alternatives 0(4) and 1, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

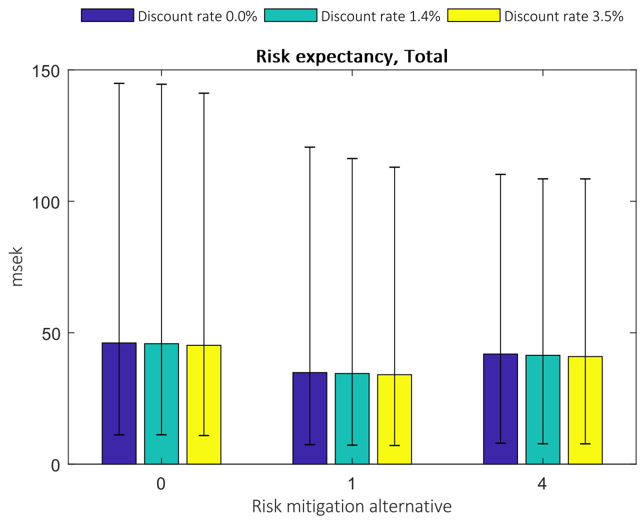

Fig. B5. Total risk expectancy for the risk mitigation alternatives 0, 1 and 4, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

Appendix C. . Implementation costs

This section presents the resulting implementation cost for the categories contract costs for building the tunnel (including excavation and grouting measures) and extra sealing measures in the form of concrete lining, costs for delays, costs for artificial recharge (installation, maintenance, and water usage) and costs for building reinforcements are presented in Figs. C1-C5 for all risk mitigation alternatives and with the discount rate 0, 1.4 and 3.5 %.

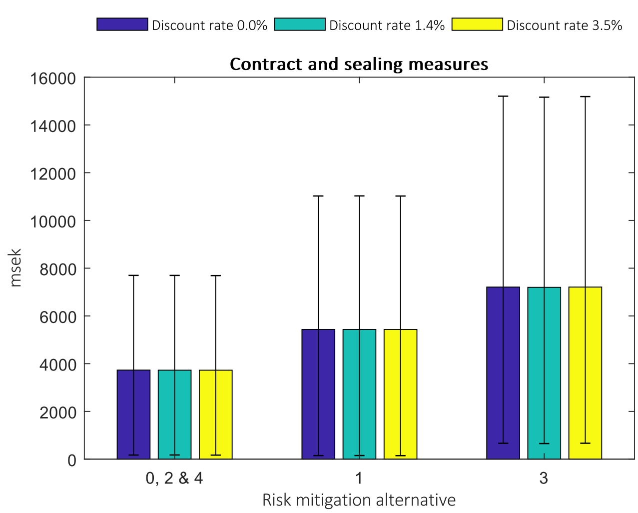

Fig. C1. Contract and sealing costs for the risk mitigation alternatives 0, 2 & 4, 1 and 3, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

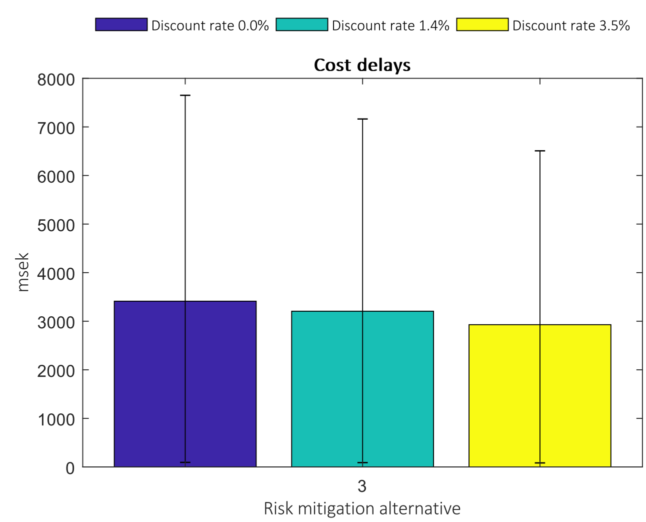

Fig. C2. Cost of delays for the risk mitigation alternative 3, for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

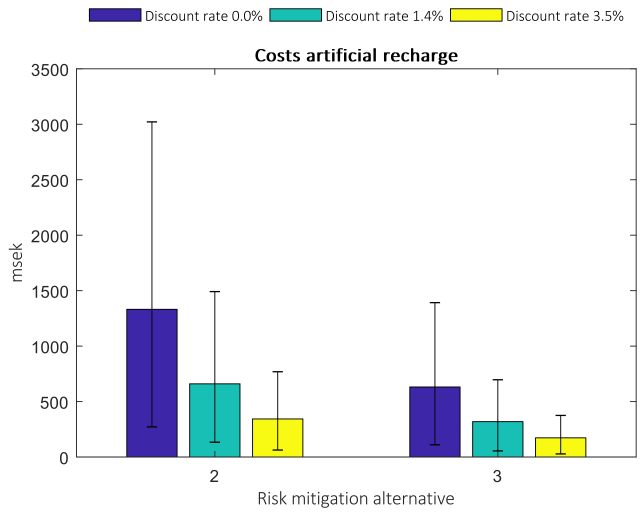

Fig. C3. Cost of artificial recharge for the risk mitigation alternatives 2 and 3 for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

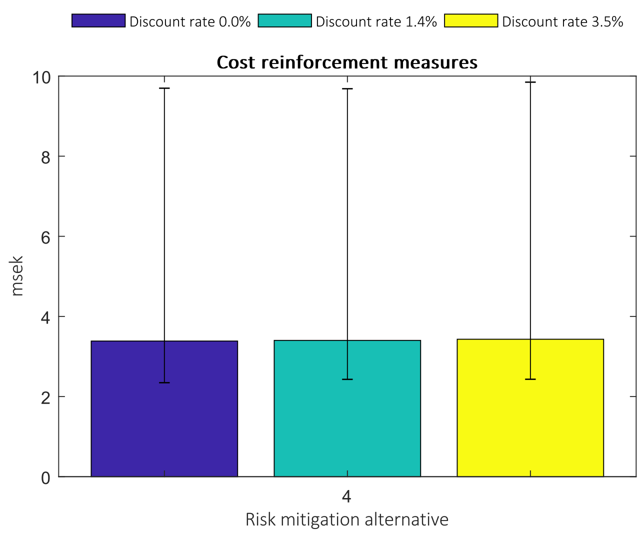

Fig. C4. Cost of reinforcement measures for the risk mitigation alternative 4 for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

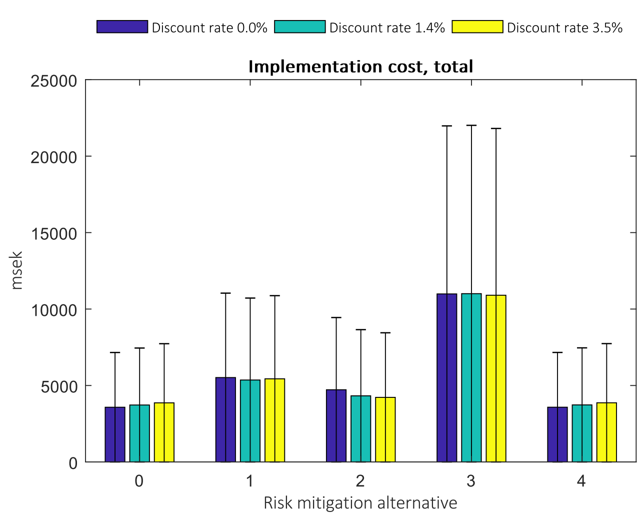

Fig. C5. Total investment cost for the risk mitigation alternatives 0, 1, 2, 3, and 4 for the discount rate of 0, 1.4 and 3.5 %. The bars represent the 50th percentile, and the error bars represent the 5th and 95th percentile.

Appendix D. . Sensitivity analysis – Subsidence calculations

Based on the Monte Carlo simulations, a sensitivity analysis for the subsidence calculations and the risk cost was performed and the result is shown in Fig. D1. The figure shows the degree to which the geotechnical input parameters covariate with the risk cost for risk-reducing measure alternative 0 and 2 expressed in the form of correlation coefficients between − 1 and 1. The results from risk-reducing measure alternative 1,3 is not included but show similar result. There exist dependencies between the parameters used for the subsidence calculations. All parameters have a positive correlation to and are simulated based on σ'$_0$ resulting in negative correlation coefficients for the parameters. The correlation coefficients for the modulus are also negative since low modulus result in large subsidence. The parameter with strongest correlation is M_0. The parameter M' has a correlation at 0 since the case where Equation (A3) takes effect never arises in the example at hand.

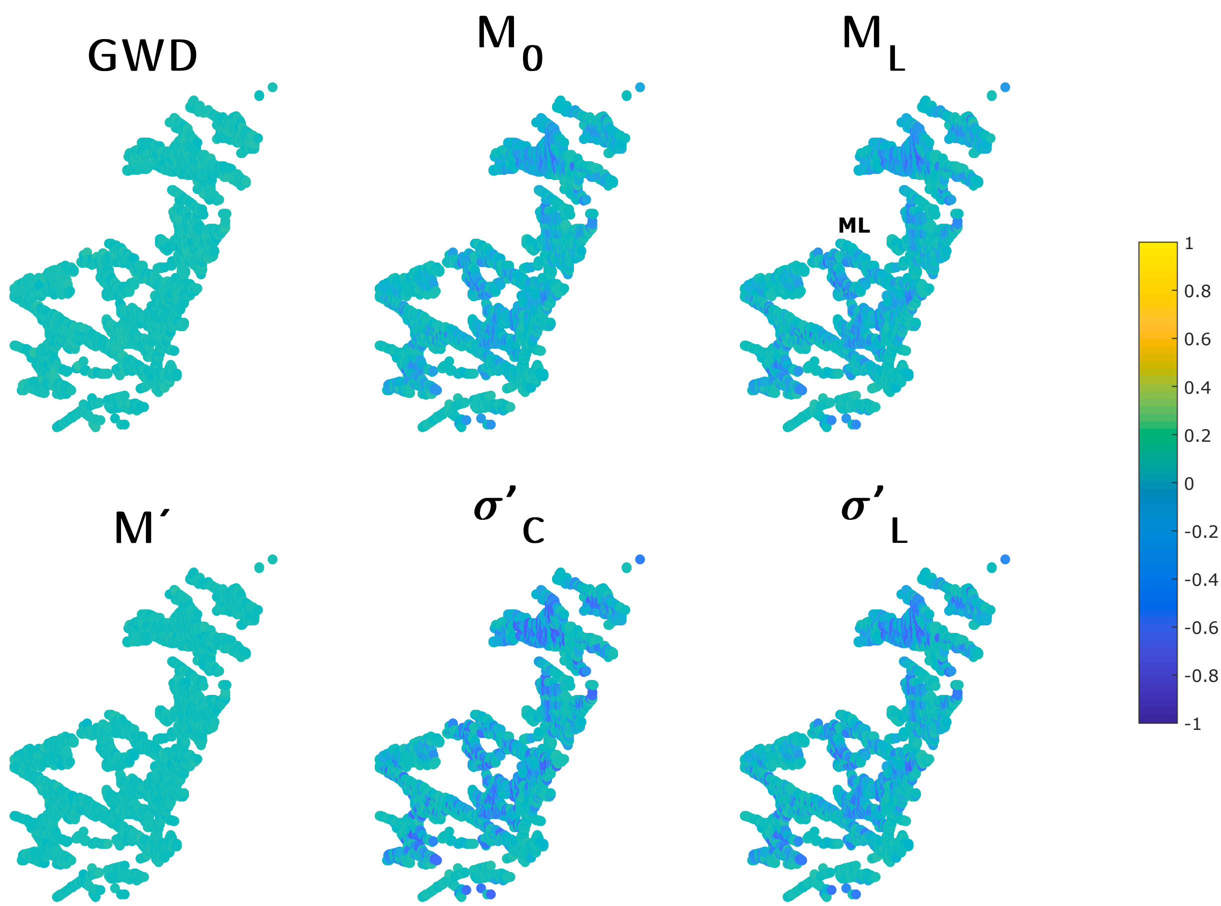

Fig. D1. Sensitivity analysis performed for the subsidence calculations for alternative 0, 2 and 4 with Spearman's rank correlation coefficients. The plotted points represent the location for an object at risk. Coordinates are not indicated due to the sensitive character of the information.

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