THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Risk Estimation of Groundwater Drawdown in Subsidence Sensitive Areas.

JONAS SUNDELL

"*Uncertainty is an uncomfortable position. But certainty is an absurd one*"

-Voltaire

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Building with subsidence damages in central Göteborg.
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ABSTRACT

Groundwater drawdown induced ground subsidence is a severe problem in many regions around the world. Leakage of groundwater into a sub-surface construction, resulting in drawdown and subsequent subsidence, can lead to immense damage costs on buildings and installations in urban areas. To reduce the risk for damages safety measures can be implemented. Safety measures include design change of the construction, sealing of fractures in bedrock and permeable formations in soil, and infiltration of water to maintain stable groundwater heads. However, such measures can be very expensive and extensive investigation programs are therefore commonly realized as a basis for decision support on the need for safety measures. Since the sub-surface consists of heterogeneous and anisotropic materials which cannot be investigated in its entirety, decisions on safety measures have to be taken under uncertainty. In this thesis, a generic framework is presented on how to assess the risk for groundwater drawdown induced subsidence (Paper I). As specific tools for modelling uncertainties in the groundwater drawdown – subsidence – damage chain, a method for probabilistic modelling of bedrock levels and soil stratification (Paper II) and a method for probabilistic modelling of ground subsidence at the city scale (Paper III) are presented.

Keywords: groundwater leakage, groundwater drawdown, urban hydrogeology, pore pressure reduction, soft soil, subsidence, settlement, risk assessment, probabilistic, uncertainty quantification, geostatistics, spatial variability.

LIST OF PUBLICATIONS

This thesis includes the following publications, referred to by Roman numerals:

Appended to the thesis

I. Sundell, J., Rosén, L., Norberg, T., Wladis, D., & Alén, C. (2015b). *A framework for risk assessment of groundwater drawdown induced subsidence*. Paper presented at the International Symposium on Geotechnical Safety and Risk (ISGSR2015), Rotterdam, the Netherlands. http://ebooks.iospress.nl/book/geotechnical-safety-and-risk-v

II. Sundell, J., Rosén, L., Norberg, T., & Haaf, E. (2015a). *A probabilistic approach to soil layer and bedrock-level modelling for risk assessment of groundwater drawdown induced land subsidence.* Engineering Geology. doi: http://dx.doi.org/10.1016/j.enggeo.2015.11.006

III. Sundell, J., Haaf, E., Norberg, T., Alén, C., Karlsson, M., & Rosén, L. (2016). *Probabilistic modelling of groundwater drawdown induced land subsidence at the city scale.* Submitted to Georisk

Division of work between the authors

In publication I, Sundell, Rosén and Norberg formulated the structure of the five modules. Wladis contributed to the formulation of the groundwater module and Alén to the subsidence module. Rosén suggested the organization of the risk assessment process and described the modules for risk estimation and risk evaluation. Sundell formulated the description of the cause-effect chain, the first three modules and was the main author of the paper.

In publication II, all authors formulated the objective of the paper. Norberg devised the mathematical foundation for converting empirical distributions to normal z-scores. Haaf implemented the stochastic model and contributed to the formulations of the chapters. Sundell elaborated the concept of the modelling process, performed the kriging interpolations and was the main author of the paper.

In publication III, Sundell and Rosén formulated the objectives of the paper. Haaf implemented the stochastic model, performed the sensitivity analysis and contributed to the formulations in all chapters. Alén and Karlsson contributed with expert knowledge in subsidence modelling. Sundell developed the method, performed the ANOVA analysis, defined the probability density functions of the parameters, elaborated the model process and was the main author of the paper.

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ACKNOWLEDGEMENTS

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The initial idea of this research project originates from a study of an underground bike- and pedestrian passage under the nowadays-constructed national highway 50 in Motala. I worked as a hydrogeologist and Anders Bergström as a geotechnical engineer. Together we analysed the risk of groundwater drawdown induced subsidence. When we communicated the potential subsidence risk to the project management, it was decided to build a bridge instead of the passage.

Anders and I continued on method development for probabilistic risk analysis, see Bergström and Sundell (2012), together with three master thesis students, Victoria Tisell (2013), Minyi Pan (2013) and Elyas Hashemi (2012). In the meantime, I contacted Professor Lars Rosén on the idea of expanding the study to a PhD-project. Lars and I developed the project proposal further together with support and ideas from my colleagues and managers at COWI, Sonja Blom, Yvonne Andersson-Sköld, Thomas Lindblad and Ulf Sundquist.

I would like to express my deepest gratitude to my supervisors Professor Lars Rosén and Associate Professor Tommy Norberg for inspiring discussions, constructive feedback and extensive support. I would also like to thank Professor Claes Alén, PhD David Wladis, Assistant Professor Mats Karlsson, Professor Lars O Ericsson and Professor Åsa Fransson for fruitful discussions. I also wish to thank the project's reference group for constructive feedback on an early stage. I'm also grateful to my colleagues at COWI and Chalmers who have assisted me with data, support and inspiring discussions.

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Jonas Sundell
Gothenburg, April 2016

1 INTRODUCTION

This chapter gives a background to the work with examples on infrastructure projects with subsidence damages worldwide and in Sweden. A framework for risk assessment and management is suggested and the concept of two major project risks related to taking or not taking action is introduced.

1.1 Background

With increasing global urbanization follows a demand for improved infrastructure services such as roads, railroads, sewage and electric power. This creates land-use conflicts when space for infrastructure has to compete with space for buildings and recreation. Therefore, infrastructure services are increasingly located beneath the land surface, see e.g. Huggenberger and Epting (2011).

Complexity and uncertainties in sub-surface projects can be substantially higher compared to constructions on the ground surface. When constructing a house or a bridge on the surface, it is possible to build with routine designs based on properly tested materials with known properties (Rempling et al., 2015). Sub-surface projects are on the other hand constructed in poorly known materials formed and impacted by complex geological and anthropogenic processes (Lundman, 2011).

Uncertain and variable ground conditions in sub-surface construction result in a wide range of risks. These include failure of the construction with potential consequences such as loss of life and personal injury; economic damages and loss of credibility for those involved; risk of not meeting standards for functional design, operational ability and quality standards; risk of significant delay; and risk of significant increase in costs (Reilly & Brown, 2004). In addition to these risks, sub-surface construction can affect its surrounding environment. This includes advantageous aspects such as conservation of natural and urban landscape and possible reduction of noise and pollution (Rönkä et al., 1998). Sub-surface constructions can also cause negative effects on the environment due to leakage of groundwater into constructions with subsequent groundwater drawdown. Negative effects include dewatering of wells, springs and streams (Attanayake & Waterman, 2006), contamination propagation (Hernández-espriú et al., 2014) and biodegradation of wood foundation (Vatovec, 2007). Groundwater drawdown is a severe issue in areas with compressible materials and buildings sensitive for subsidence. Since a groundwater drawdown from a sub-surface construction can affect very large areas (square kilometers), see e.g. Burbey (2002), Huang et al. (2012), the damage cost in a city with many buildings and installations can be immense (Persson, 2007).

Groundwater drawdown induced subsidence is a severe problem in many regions around the world. In Shanghai, China, the whole city is affected, with subsidence magnitudes of up to two meters (Xue et al., 2005). In Mexico City, extraction of groundwater has caused more than 9 meters subsidence with severe consequences on building foundations, sewer drainage and transport systems (Ortega-Guerrero et al., 1999). In Bangkok, the whole metropolitan area is affected by subsidence mainly caused by groundwater extraction with damages on buildings and tunnels (Phien-wej et al., 2006). Groundwater drawdown induced subsidence is also an issue in Scandinavia with observed damages in Stockholm, Gothenburg and Oslo, see Karlsrud (1999) and Olofsson (1994).

In Sweden, there are several planned and ongoing infrastructure projects in urban areas such as; the railway tunnel Stockholm City Lane, the utility tunnel City Link for high voltage cables, the Stockholm Bypass of European highway E4, and the West Link, a railway tunnel under central Göteborg. The risk for subsidence damage in these projects is managed by implementing extensive investigation, modelling and communication programs.

To reduce the risk for damages, actions can be taken to implement further investigations to reduce uncertainties or safety measures to increase redundancy in the system. This includes additional geotechnical and hydrogeological investigations for more precise predictions, sealing and grouting of tunnels, inspection, stabilization of buildings and their foundations, and infiltration of water to maintain groundwater heads. As already mentioned, decisions on these actions need to be taken under uncertainty. Implementation on these actions is associated with two major project risks:

1. *The risk of <u>not taking</u> action <u>when there is a risk</u> of harmful groundwater drawdown and subsidence.* If the drawdown causes damages, the contractor is, by Swedish law (Swedish Environmental Code 1998:808 chp. 16), responsible for the costs and consequences of these damages. Except for direct costs for the contractor, indirect negative consequences for victims and for society as a whole can occur.
2. *The risk of <u>taking</u> action <u>when there is no risk</u> of harmful groundwater drawdown and subsidence.* This is risk is associated with unnecessary costs for measures not needed.

These two project risks create a need for efficient decision support regarding necessary safety measures. Such decision support needs to deal with the different sources of uncertainty in the system. Uncertainty can be defined as any deviation from the unachievable ideal of complete deterministic knowledge (Walker et al., 2003). There are different sources of uncertainties including: (1) context and framing of the boundaries of the system to be modeled, (2) input data and external forces that drive the model, (3) structural uncertainty due to incomplete understanding and simplified descriptions of modeled processes, (4) parameter uncertainty as well as (5) model uncertainty (Refsgaard et al., 2007). The nature of uncertainty is commonly categorized into aleatory (due to inherent variability) and epistemic (due to imperfect knowledge) uncertainty. Epistemic uncertainty can be reduced by improved knowledge whereas aleatory uncertainty cannot be reduced. There are different strategies to deal with the uncertainties, such as: ignoring, choosing conservative scenarios, using the observational method or by quantifying uncertainties (Christian, 2004). For complex systems, it can be difficult to use the same strategy for all sources of uncertainty.

For a complete risk assessment and understanding, the whole cause-effect chain of groundwater drawdown induced subsidence needs to be understood, see Figure 1 and Figure 2. This chain is initiated with leakage of groundwater into a sub-surface construction in bedrock (1a) or soil (1b). It continues with reduction of groundwater piezometric heads due to the leakage (2). The drawdown reduces pore pressure in compressible deposits (3) and causes subsidence (4). The extent of the subsidence damages (5) depends on the sensitivity of the constructions founded on the compressible deposits. The consequences depend on (among other things) the cost (6) associated with the damage. In this process, the consequences are determined by the interaction between geotechnical and hydrogeological conditions and the sensitivity of the constructions at risk. To cause damage, several conditions need to be fulfilled jointly: groundwater drawdown affecting pore-pressure in compressible soils below constructions sensitive to subsidence. Thus, the cause and effect chain implies that several processes in the system need to fail in order to cause system failure.

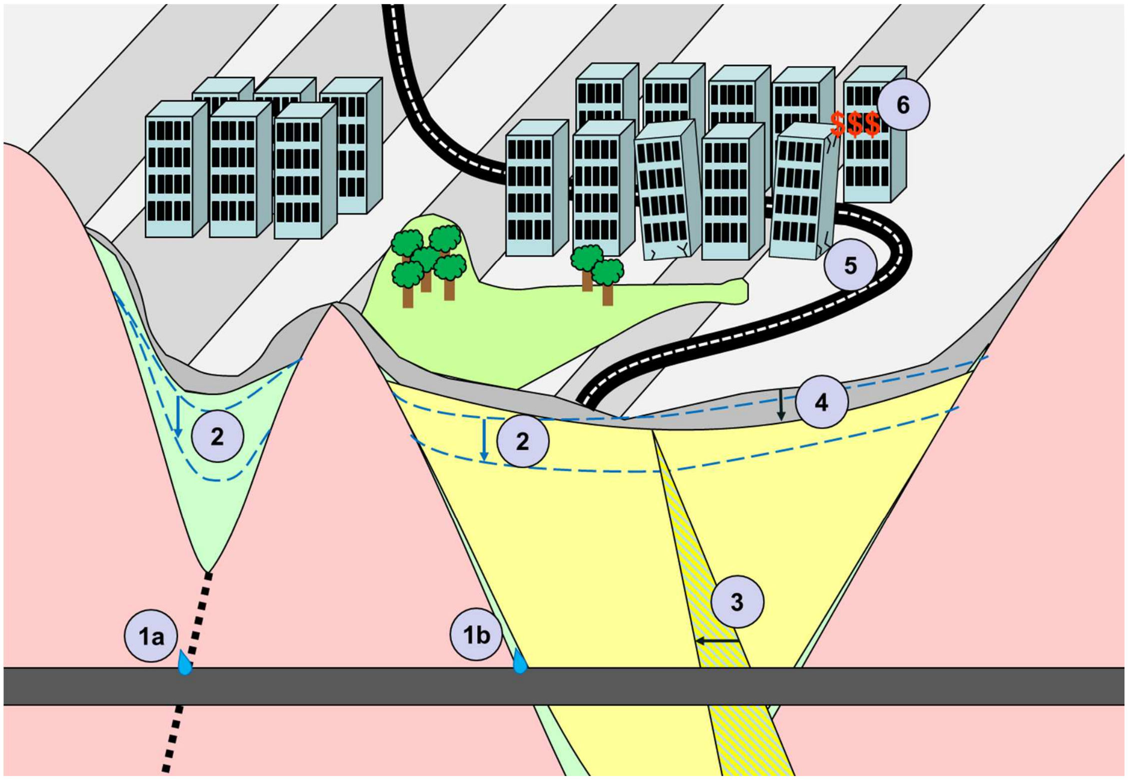

Figure 1 The different processes in the chain for groundwater drawdown induced subsidence damages. The pink area illustrates bedrock, green: coarse grained material, yellow: soft clay and grey coarse grained filling material. The hatched line at 1a illustrates a fracture zone in the bedrock.

Much research at Chalmers has been directed at the different parts of the cause-effect chain, with special emphasis on improved understanding of processes, reduction of uncertainties and suggestion and design of safety measures. This includes e.g. a method for describing the lithology of bedrock using probabilistic approaches (Rosenbaum et al., 1997), which can be used for groundwater modelling. Thörn and Fransson (2015) present a new methodology for hydromechanical testing of rock fractures. This method can reduce uncertainties of hydraulic properties in rock. Butrón et al. (2010) introduce a new concept for design and evaluation of grouting which can reduce the risk for leakage into a tunnel.

To understand the propagation of leakage and reduction of piezometric head in bedrock to aquifers in soil, hydrogeological models can be a useful tool. On this issue, LeGrand and Rosén (2002) argue that money can be saved by better use of existing hydrogeological knowledge. Svensson (1984) suggest a method for fitting probability density functions (pdf) to groundwater head observation time series for prediction of extreme values. Persson (2009) continues this research track by also including methods for estimating pore pressure. This is an essential part of the cause-effect chain since a reduction of pore pressure drives the subsidence. Persson

(2007) connect hydrogeological methods to geotechnical engineering, which is necessary for describing groundwater drawdown induced subsidence. Mossmark (2014) describes how hydrochemical processes are affected by leakage of groundwater into tunnels. Gustafson (2012) provides a review of the knowledge base on hydrogeology in crystalline bedrock with explanations on practical methods for site investigations, layout and design and operation of tunnels and underground facilities.

Research in geotechnical engineering and subsidence in soft soil has a long tradition at Chalmers. Sällfors (1975) presents methods for evaluation of the stress-strain curve. These methods are today the basis for industry standards in Sweden. Alén (1998) suggests probabilistic calculation methods of geotechnical problems and subsidence in particular. Novel investigation methods for behavior of creep in clay are presented in Olsson (2013). Going from investigation methods to calculation methods of creep, Sivasithamparam et al. (2015) suggests a method for modelling in anisotropic soft soils.

Except for methods aimed for a better understanding of various soil processes, research is also focused on methods for risk assessment, see e.g. Göransson et al. (2014), Brinkhoff et al. (2015) and Lindhe et al. (2009). Furthermore methods for cost benefit analysis (CBA) of safety measures, see e.g. Söderqvist et al. (2015), Malm et al. (2015) and Lindhe et al. (2011). Zetterlund (2014) advanced the concept of CBA and suggest a method based on Value of Information Analysis (VOIA), for prioritization of investigations in rock engineering investigations.

All these studies can be useful for a risk assessment of the subsidence damage chain. Nevertheless, none of these take account of the whole cause – effect chain. Persson (2007) does this to a certain extent with analytical methods, Heterogeneous soil conditions and damage costs are however not assessed.

Also in research outside of Chalmers, there is a gap in taking account of the entire cause-effect chain. There are, of course, many studies that are useful for the understanding of individual aspects, see Section 2. There are also studies that cover the relationship between groundwater drawdown and ground subsidence on a city-scale, see e.g. Galloway and Burbey (2011), Hung et al. (2012), Modoni et al. (2013) and Shen et al. (2013). These studies however, focus on the evaluation of historical observations of groundwater drawdown and subsidence and not on predictions of future events.

In the research project presented in this thesis, the purpose is to embrace the whole cause – effect chain in method development on useful tools for decision support. Although the individual publications only cover some aspects, they originate from a need for improved risk assessment of the entire system. This reasoning is different from studying individual aspects and then assessing how they can be useful for the whole system of groundwater drawdown induced subsidence. In addition, the chain has to be evaluated with interdisciplinary approaches that combine the fields of hydrogeology in bedrock and soil, geotechnical engineering and risk assessment.

1.2 Risk assessment

Risk is often defined as a combination of probability and consequence of a hazardous event, see e.g. Kaplan (1991). As mentioned in Section 1.1, the cause-effect chain for groundwater drawdown induced subsidence is characterized by different sources of uncertainties. Examples of uncertainties include hydrogeological and geomechanical properties, conceptualization and model representation. These uncertainties need to be carefully addressed when assessing the risk for groundwater drawdown and subsidence damages.

In risk assessment in practice, uncertainties can rarely be quantified based on existing data only, and therefore need to be addressed to a larger or smaller degree by expert opinions and judgements. Figure 2 illustrates a framework (presented in Publication I) for risk assessment and management, developed in accordance with the ISO standard on risk management (ISO, 2009) and the work by Aven (2012) and Lindhe (2010). In this figure, risk estimation is a part of the initial risk analysis step. The risk analysis also includes the scope definition and identification of hazardous events. In analogy with e.g. a fault tree model, which is a common risk method for structuring a causal risk analysis, see e.g. Lindhe et al. (2009), the cause-effect chain includes several hazardous events. These events need to occur jointly to cause damage on buildings and installations (top event).

Risk analysis with probabilistic methods may, for example, conclude that a permanent leakage into a tunnel (hazard) can cause damage costs valued at 2 MSEK (consequence) with a probability of 0.05. Although this conclusion gives an overview of the general risk for subsidence damage, the decision support on what safety measures to prioritize is very limited. Evaluation of alternatives to reduce the risk are done in the risk evaluation step of the risk assessment, see Figure 2. Risk evaluation can be performed in several ways. One approach is to define tolerability criteria, reflecting acceptance levels of affected stakeholders and regulations from authorities. An example of a tolerability criterion is that a certain level of subsidence (for example 2 cm) is accepted to occur at a certain level of probability (for example maximum five percent), see Publication III. Tolerability criteria can also be defined on other levels in the chain, for example by assigning acceptable damage cost to the buildings. Quantitative tolerability criteria of damage costs have not been applied on Swedish infrastructure projects as far as the author knows. Instead, tolerability criteria on leakage and groundwater drawdown for infrastructure projects are typically defined. Although tolerability criteria are defined for other levels in the cause-effect chain than the last, they have to be based on an estimation of the actual consequence. This means that tolerability criteria are based on the risk (costs for subsidence damages) but defined for intermediate parameters of the risk (leakage, groundwater drawdown or subsidence magnitude). When a acceptance tolerability criterion is used, the safety measure that best (considering e.g. cost and/or reliability) meet the criterion should be chosen. Safety measures can e.g. be analysed with cost-effectiveness analysis where the safety measure that can meet the acceptance criterion to the lowest cost should be recommended (economic analysis of alternatives in Figure 2).

Another approach to risk evaluation is cost benefit analysis (CBA), see Publication I. In a CBA, the expected risk reduction (reduced costs for damages), i.e. the benefit, of a safety measure is compared with the cost for implementing the measure. The criteria for CBA is maximum net benefit, which can result in a recommendation to accept extensive damages if this turns out to be the most profitable alternative.

In practice, successful risk evaluation has to comply with norms and regulations in society, making a combined, third, approach possible, and in many cases realistic. An example of this approach can be to define criteria tolerability criterion, as in the first method. Among the alternatives that can meet this criterion, the one with highest profitability according to a CBA is recommended. The difference form the first method (using cost-effectiveness analysis) is that also the benefit of the risk reduction (and not only that the risk should be reduced to a certain level) is included, which means that a more expensive alternative can be recommended if motivated by its benefits.

A risk assessment of the cause-effect chain for groundwater drawdown induced subsidence needs to address issues in both space and time. A tunnel can be very long and geological conditions, sensitivity of constructions and associated damage costs, as well as stakeholder preferences, can vary along the length of the tunnel. Examples on how spatial conditions can be addressed in the initial parts of the cause-effect chain are described in Publication II and III. Time needs to be addressed since leakage rates can vary during the construction and operation phase. Both drawdown and subsidence are transient processes which create time for implementation of safety measures. This is further discussed in Section 5.

Although the result of a risk assessment may conclude that the expected net value (see Publication I) of a certain safety measure is 0.5 MSEK if it is implemented at a certain location and time, the risk assessment serves as decision support. The actual decision on risk reduction on risk control is taken after managerial review and judgements by considering both stakeholder values and the result of the risk assessment.

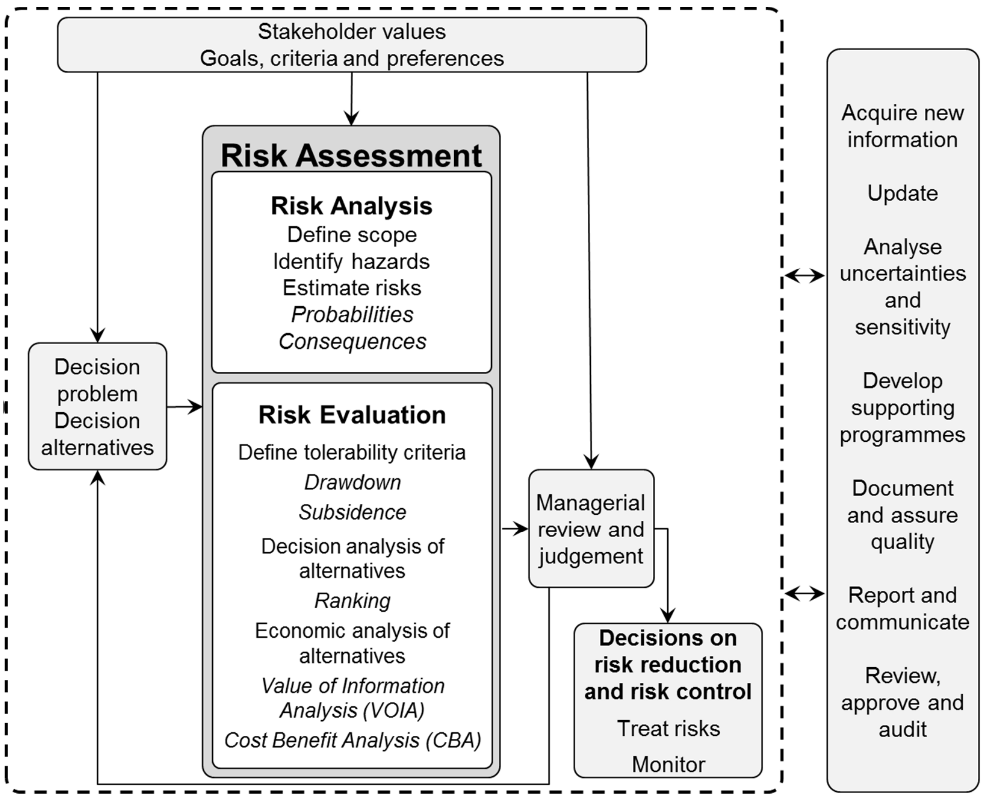

Figure 2 Framework for risk management modified after Publication I.

1.3 Aim and specific objectives

The overall aim of this thesis is to

> *Develop methods for estimating risks of groundwater drawdown induced subsidence in infrastructure projects, taking into account the entire chain of events from groundwater drawdown to land subsidence. These methodologies*

> *should serve as a clear and cost-effective decision support for implementation of safety measures.*

To fulfill the overall aim, there are three specific objectives:

> *Develop a framework for risk assessment of groundwater drawdown induced subsidence*
>
> *Develop a method for probabilistic modelling of bedrock levels and soil stratification*
>
> *Develop a method for probabilistic modelling of groundwater drawdown induced subsidence on a city-scale that utilizes the bedrock and soil stratification model*

In a later stage of this research project, the mentioned methods will be combined with VOIA, see e.g. Zetterlund et al. (2011), for economic valuation of subsidence consequences and safety measures. VOIA is a cost-benefit analysis that provides a comparison of the benefits of increased knowledge and safety measures to reduce risks of inappropriate decisions against the costs for new information and measures.

This project provides novel research to better predict the risk of harmful subsidence caused by groundwater drainage. More accurate risk predictions will make decision making more efficient, reduce costs of subsidence problems, and improve communication of the risks to stakeholders, authorities and contractors.

1.4 Scope of work

The overall aim of this thesis is achieved through theoretical studies and method development with continuous application in case studies. The methods for probabilistic modelling of bedrock levels and soil stratification and subsidence are applied on a case-study in Stockholm; City-Link tunnel, which is a planned utility tunnel in bedrock for power-lines. The work is presented in Publication, I, II and III.

Figure 3 illustrates how the three publications relate to each other. Publication I provides a framework for risk assessment of the cause-effect chain for groundwater drawdown induced subsidence. This publication relates to the first specific objective. Publication II and III are necessary components for estimating risks in the cause-effect chain. Risk estimation is an essential component of the risk analysis compartment included in the presented framework in Publication I.

Publication II provides a basic geometric structure of bedrock and soil layers for analyzing risks in the cause-effect chain. This is necessary for adding additional groundwater and subsidence modules when estimating risks in the chain. The City Link Tunnel case study has provided data to the model. Publication II relates to the second specific objective.

In Publication III, subsidence magnitudes due to certain groundwater drawdown magnitudes are analyzed probabilistically. The method estimates risks in the second (pore pressure) and the third (subsidence) part of the chain. The model in Publication II provides soil and bedrock geometry for the simulations of subsidence. The City Link case study provided data. Publication III relates to the third specific objective.

This thesis includes a theoretical background of the cause-effect chain for groundwater drawdown induced land subsidence in Section 2. In Section 3, a theoretical background to on Kriging and probabilistic groundwater modelling is given. An overview of the publications and the main findings is presented in Section 4. Section 5 comprises a discussion of the result and how the research is planned to continue in further studies.

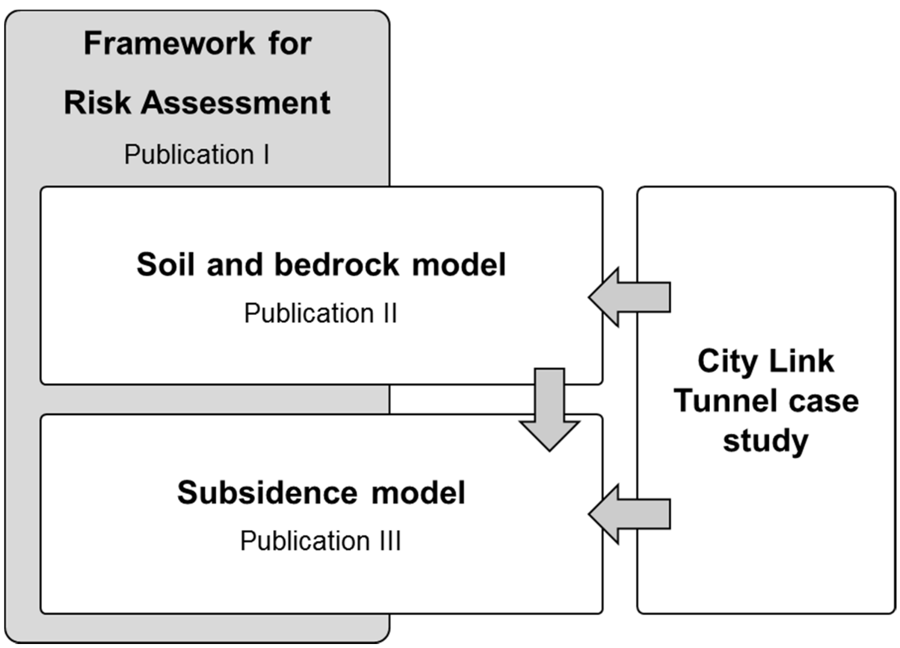

Figure 3 An illustration on how the three publications relate to each other and the case study.

2 THEORETICAL BACKGROUND OF THE CAUSE-EFFECT CHAIN

The whole cause-effect chain for groundwater drawdown induced subsidence damages needs to be understood for a relevant risk estimation of the same. This chapter describes the different parts of this chain starting with groundwater leakage into the construction, resulting in groundwater drawdown, subsidence and, in the end, damages on constructions.

As described in the introduction, the magnitude of the consequences is determined by the interaction between hydrogeological conditions in soil and bedrock, geotechnical conditions in the soft soil and the sensitivity for subsidence of the constructions at risk. In this cause-effect chain, see Figure 1 and Figure 4, several conditions need to occur jointly to cause damage. There has to be a groundwater leakage into the construction to cause a groundwater drawdown. Depending on the magnitude of the leakage, hydrogeological conditions in soil can compensate so that the extent and magnitude of the groundwater drawdown and reduction of pore pressure are limited. For a case with extensive groundwater drawdown, the geo-mechanical properties in the soil materials can compensate, preventing substantial subsidence. Finally, the extent of the damages, and thereby the damage costs, determine the vulnerability of the constructions for subsidence. Consequently, the cause and effect chain implies that several processes in the system need to fail in order to cause system failure.

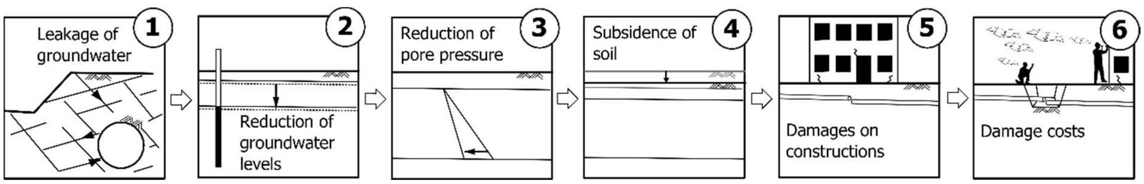

Figure 4 The cause-effect chain for groundwater drawdown induced subsidence damages.

How critical these processes are, can vary between projects and sites. This implies that the full range of different aspects of the cause-effect chain need to be properly understood for each individual sub-surface project. Since preconditions in geology and built environment vary between projects, it is important to understand these for planning of safety measures. In this chapter, a theoretical background to the different processes in the chain is given.

2.1 Geometry of bedrock and soil

A sound understanding of the geometry of bedrock and soil is essential for all parts in the cause-effect chain. This understanding needs to be based on the geological and anthropogenic processes on the bedrock and soil within the modeled area. Knowledge of this history can help or focus ideas on characteristics of the hydrogeological and geomechanical system. In Paper II, a method for probabilistic modelling of bedrock- and soil-layer levels is suggested. A geological model gives information on continuity of stratigraphy between boreholes and helps to understand spatial variation, see Figure 5. If the geological model is parametrized, it can be combined with a hydrogeological and/or geomechanical model for spatial modelling of groundwater flow and subsidence respectively.

For major infrastructure projects it is common that the sub-soil is evaluated based on an extensive investigation program. In addition, there typically exist a large amounts of historical observations from previous projects in urban areas. Although large amounts of investigations are available, only a very small fraction of the soil volume that will be constructed or affected by the construction can be observed. Broms (1980) suggests that 1 in 1,000,000 by volume can be investigated. With geophysical investigation methods it is however possible to cover larger areas but the ambiguities and uncertainties can be immense (Kearey et al., 2013). Since the investigations are characterized by uncertainties, there is a need for estimations of the representativeness of the samples regarding the volume of the construction. Such estimations can be based on a combination of knowledge of local geological conditions, previous experiences and statistics. Because of this need, the problem changes in character, from mechanical linking of borehole information to a transdisciplinary problem that includes uncertainty estimation.

Several structured interpolation procedures for building geological models, e.g. Asa et al. (2012), Bourgine et al. (2006) or Chung and Rogers (2012), are based on the geostatistical method Kriging (Matheron, 1963), see Section 3.1. The basis of Kriging is the variogram, which describes the relationship between distance and variability of a variable in space. Kriging provides a probabilistic approach by which a weighted average and an uncertainty estimation are calculated at each interpolation point. There are many methods based on Kriging with different approaches on how the input data are managed, how different data types are managed, and how dependencies between different geological layers are considered.

A common method for estimating the probability of the presence of a soil type in a grid cell is indicator Kriging, see e.g. Sidorova and Krasilnikov (2008) and Deutsch and Journel (1997), using indicators to represent material categories. Other approaches, based on Markov chain analysis, have been used for modelling of categorical data in geology, see e.g. Rosen and Gustafson (1996), Rosenbaum et al.

(1997), Norberg et al. (2002) and Carle and Fogg (1997). Spatial simulation of material categories in comparison to an approach with continuous layers can be beneficial in very heterogeneous environments with complex layering. The method presented in Paper II is based on an assumption of continuous layers. As mentioned in the paper, this assumption is suitable for the geological setting in the case-study in Stockholm and similar settings and on the regional scale studied here. In addition, the assumption of continuous layers simplifies modelling in terms of transformation of data between different software, since only a few two dimensional matrices needs to be transferred instead of multiple three dimensional matrices in high resolution.

For the hydrogeological system, it is also necessary to model structures in bedrock - since dominant fractures can transport more water. To model fracture planes in bedrock geometry another approach than presented in Paper II is needed. Zetterlund et al. (2011) describes how the probabilistic method T-PROGS (Carle, 1999) can be used for modelling of different structures in rock mass. This method is based on Markov chain analysis for estimation transition probabilities from one material to another and indicator kriging for performing the spatial estimation of material distributions across the modelled volume. The locations of major fracture zones are crucial for the flow of groundwater in bedrock. Since fracture locations can be simulated, this approach could be appealing for further studies of the hydrogeological part of the system. An example of one realization with T-PROGS for a 2 meter deep soil layer is presented in Figure 5a. Other methods for simulation of fracture network include e.g. FracMan (Dershowitz, 1992) and 3DEC (Itasca Consulting Group, 2012).

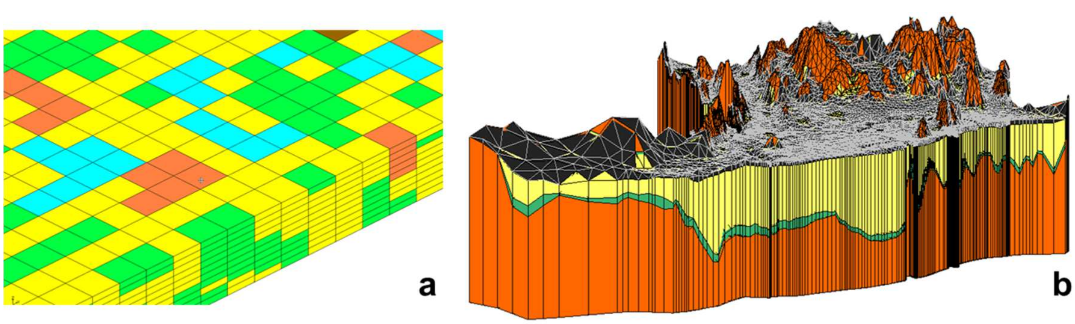

Figure 5 Two different approaches for soil stratification modelling. The left image (a) shows on one realization with T-PROGS resulting in discontinuous layering, green: coarse grained material, yellow: clay, orange: silt, blue: glacial till, and, brown: peat. The right image (b) is based on the modelling approach presented in Publication II with continuous layering, black: coarse grained filling material, yellow: clay, green: coarse grained material, and, red: bedrock. Note that the two models are based on different data and that the scales are different for the two images.

2.2 Leakage into a sub-surface construction

The cause-effect chain starts with a disturbance of the present state hydrogeological conditions when constructing below the groundwater table. Constructions in soil as well as in bedrock can cause leakage of groundwater that propagates in the cause-effect chain. In addition to reducing possible negative impact on the surrounding environment, it is also of interest to reduce inflow for ensuring the function of the construction. How the leakage propagates to drawdown of groundwater piezometric heads is described in Section 2.3. In this section, the leakage conditions in bedrock, see Figure 6, is described together with strategies for investigation, analysis and reduction of the leakage.

Sweden is dominated by crystalline bedrock. In this material, groundwater flows in secondary porosity fractures formed through repeated periods of tectonic activity. Primary porosity is negligible from a practical point of view. The hydraulic conductivity of crystalline bedrock depends on its fracturing and weathering, see e.g. Lachassagne (2008). Fracture conditions are dependent on tectonic history whereas weathering is dependent on the bedrock's mineralogy and history of chemical, physical and biological processes, see e.g. Pidwirny (2012). Weathering effects decrease with increased distance from land surface major fractures and fracture zones, which leads to a reduced permeability. This trend of reduced permeability with greater depth from land surface is also a result of reduced fracture apertures since rock stress increases at greater depths (Gustafson, 2012).

Although some estimations can be made on the hydraulic conductivity of the bedrock depending on depth below surface and the location of fracture zones, the hydraulic conductivity can vary several orders of magnitude. From a model-based view, the hydraulic conductivity depends on the scale of the problem that is analyzed. Gustafson (2012) divides the scale into three different levels: The small scale with analysis of point inflow from individual fractures (1), the medium scale where blocks between 3-30 meters can be assumed as a stochastic continuum (2), and the large scale where the rock is assumed as a homogeneously porous medium.

Starting with the small scale, Thörn (2015) describes the impact of fracture geometry on the inflow. Zetterlund et al. (2011) present a method for stochastic simulations of rock mass characteristics for grouting purposes along tunnel sections on the medium scale. The observation method (Peck, 1969), where grouting is designed preliminary in a design phase and additional measures are decided based on observations in the construction phase, see e.g. Spross and Larsson (2014), is also performed on the medium scale. For the large scale, Wladis and Gustafson (1999) studied how the hydraulic conductivity varies based on data from the well archive provided by the Swedish Geological Survey (SGU).

Consideration of scales is of course of relevance when estimating the inflow. However, depending on what phase the project is in and the consequence of the leakage, different scales are of relevance. An early stage risk assessment for groundwater drawdown induced subsidence on the city-scale would start with the large scale and continue the analysis on the medium scale when more information becomes available. The small scale is of interest when the tunnel inflow of individual fractures can be significant and critical.

The most common technique to reduce the inflow into a bedrock construction is to seal the water-bearing fractures by grouting. In this process, boreholes are first drilled into the rock mass, then grout is injected under pressure to fill the fractures (Stille, 2015). Depending on the impact on the construction and the surrounding environment, the acceptable leakage ratio varies between projects but also along different parts of a tunnel construction.

Figure 6 Frozen leakage water from fractures in bedrock in a tunnel under construction. The photo is taken close to the tunnel entrance. Photo: COWI AB.

In Sweden, the tradition has been to control environmental impact of groundwater drawdown by regulation of inflow. Inflow is typically regulated in a permit for water extraction decided by a (Land and Environmental) court. This means that the possible environmental impact has to be propagated down to an acceptable leakage. Since leakage is the first part of an often complex cause-effect chain, this is of course difficult and characterized by uncertainties. There is, however, a possibility that this trend is about to change. In the recent case for Bypass Stockholm, the Land and Environmental Court at Nacka Tingsrätt, case M 3346-11, regulates acceptable changes in groundwater heads rather than leakage.

2.3 Groundwater drawdown

This section gives an introduction to groundwater flow, water balance and conceptualization methods of groundwater systems in cities. Later, Section 3.2 gives an introduction to probabilistic groundwater models. In this thesis, the term "aquifer" is defined as a groundwater bearing unit in soil or bedrock with greater permeability than clay deposits, regardless of its practical potential for utilizing or storing groundwater. Clay deposits are considered aquitards.

When evaluating the possible extent and magnitude of groundwater drawdown it is important to analyse the water balance between infiltration, storage and runoff. A leakage into a construction causes a discharge and reduces the storage in affected aquifers. This leads to a reduction of groundwater piezometric heads which also can reduce pore pressure in soft soils and cause consolidation settlements, see Section 2.4 and 2.5 respectively. As mentioned in the introduction, the reduction of heads can cover large areas at great distances from the construction.. For the case studies in Paper II and III, the possible extent of groundwater drawdown for the planned tunnel is up to 1 km. For long tunnels, this large area creates challenges both for a hydrogeological investigation but also for the other parts of the cause-effect chain. A discussion of scale issues in the cause-effect chain follows in Section 5.

A hydrogeological investigation on a large, city scale includes several challenges. The hydrogeological system in a city is often very heterogeneous due to variation of anthropogenic disturbance of the water balance. These disturbances include covering of soils leading to increased surface runoff and reduced infiltration, groundwater flow barriers due to constructions, leakage into constructions, leakage from water distribution and sewage systems, and infiltration of water compensating for leakage into constructions. An understanding of the hydrogeological system in a city can be obtained by studies of groundwater observation time series, measurements of leakage in tunnels and pipes and, comprehensive modelling approaches that include groundwater, surface water and the hydraulic effects of constructions.

For a sound understanding of an urban hydrogeological system, traditional field tests are also needed. For any hydrogeological field test, such as pumping test and slug-test, it is important to connect the test environment and other sources of information when evaluating parameters and representativity of the test. This is even more important in cities due to the mentioned large scale and the heterogeneous environment. For planning and evaluation of field tests, the soil-stratification model presented in Paper II has been of great benefit for the hydrogeological investigations of the City-Link tunnel in Stockholm, see Sundkvist (2015). In the planning phase, the model was used for finding representative locations for investigation wells. When evaluating the field tests, the soil stratification model was used for conceptualizing the hydrogeological system and connect the test results with individual aquifers. After the conceptualization, a numerical groundwater model based on the soil stratification model and the field investigation was realized (Wladis & Borgström, 2015). In the case-study, the potential area for groundwater drawdown due to the planned tunnel was decided, based on a conservative reasoning with the test-results, models, experiences from previous projects and potential damage. Further ideas on how to improve groundwater modelling with probabilistic models is presented in Section 3.2.

Figure 7 Infiltration utility under construction in central Stockholm. Three infiltration wells (foreground) and cabinet for regulation of infiltration flow. Photo: COWI AB.

A common strategy to compensate for leakage and insufficient grouting for maintaining of groundwater levels is infiltration of water into the aquifers, see Figure 7. In Sweden, infiltration of water as a safety measure in infrastructure projects is regulated in rulings in legal court in conjunction with permits for drainage. Although infiltration is a safety measure, construction and operation of infiltration wells can be expensive, complicated and cause damages itself. Likewise, determining the extent of drawdown from a construction, detailed information on the functioning of an infiltration well can first be given in its operation phase. Infiltration wells can be an expensive safety measure. If they are installed as a safety measure but it is later found that they are not needed, their installation costs bring economic loss to the project. If the need for infiltration is first observed during the construction phase, there is a critical time period to design and put functioning infiltration wells into operation before the drawdown causes damages. Infiltration of water can also cause too high groundwater levels, which can lead to e.g. flooding of basements. It is also discussed whether infiltration of water can increase the content of oxygen and cause decomposition in buildings' wood foundation (Björdal, 2016).

2.4 Reduction of pore pressure in soft soils

The reduction of groundwater piezometric heads in soil layers also gives reduced pore pressure (Δu). Reduction of pore pressure in soft soils is essential in the cause-effect chain since this leads to consolidation settlements, see Section 2.5. Similar to the groundwater drawdown process, the reduction of pore pressure is a transient procedure. Pore pressure variation in a clay profile depends on the hydraulic conductivity of the clay layer itself and materials in adjacent layers, drainage conditions and water balance between infiltration and drainage.

In the case-study in Paper III, steady-state conditions and groundwater drawdown in confined groundwater aquifers below clay layers only is assumed. Groundwater in open groundwater aquifers above the clay layer are not likely to be drained due to the low hydraulic conductivity in the clay and high infiltration. With these assumptions, the pore pressure is assumed to vary with a straight line between the pressure at the bottom and the top of the clay layer. This means that no reduction of pore pressure occurs in the topmost part of the clay layer. This also means that the reduction of pore pressure in the bottommost part of the clay layer corresponds to the same pressure reduction as the reduction of groundwater head in the confined groundwater aquifer (see Paper III for details). Similar assumptions are made in e.g. Persson (2007).

Other assumptions such as hydrostatic conditions between open and confined groundwater aquifers could be reasonable if drainage paths in the clay layer are assumed to be created by penetrating constructions and previous investigation drillings. In accordance with this assumption, artesian pressure conditions are however not possible. Since artesian pressure has been observed in some of the case-study areas this assumption is not valid for these areas.

For heterogeneous soil and drainage conditions, the pore pressure profile in the clay volume can vary significantly, see e.g Berntson (1983). Precise information of pore pressure conditions can however be difficult to estimate for the whole clay volume if a large area is covered. For the case-studies in Paper II and III, only a few estimations of pore pressure with CPT (cone penetration tests) and spare measurements of piezometers in the clay volume are available. Therefore, it is necessary to estimate the pore pressure based on information from groundwater observation wells.

As mentioned previously, the reduction of pore pressure in the clay due to a groundwater drawdown is a transient process. Even if a groundwater drawdown in a coarse-grained confined aquifer unit reaches steady-state conditions relatively fast, it can take much longer until steady-state conditions are reached in the clay volume. The transient process is commonly calculated with Darcy's law, see e.g. Muir Wood (2004). Estimating the transient reduction of pore pressure is necessary to analyse the consolidation process properly, see Section 2.5.

2.5 Subsidence in soft soil

Consolidation settlement in soft soils occur as a result of dissipation of pore pressure. In Paper III, a method for probabilistic calculations of groundwater drawdown induced subsidence on a city scale is introduced. This section gives a theoretical background to the subsidence process. In addition, in Paper III uncertainties in soil property estimates are quantified and represented by probability density functions. This chapter gives further details on uncertainties in property estimates and subsidence modelling in soft soils.

The theory of deformation of porous medium soils containing water within its voids is based on the principle of effective stress *(σ')*, introduced by Terzaghi (1923). This principle states that the total stress, *(σ)*, consist of the sum of the effective stress (inter-granual stress carried by the soil skeleton) and the pore pressure *(u)*. To a certain extent, the deformation process in clay can be compared with other materials such as steel or concrete. With a reduction of pore pressure in clay, the stress increases in vertical direction *($+\sigma_v$)*. This causes an axial compression *($-\varepsilon_v$)* but also a (small) lateral change *($\Delta\varepsilon_h$)*. A similar process occurs for a metal cylinder. When a vertical force pushes the cylinder, the stress increases in the same direction as the force, resulting in a vertical compression but also a horizontal expansion. The relationship between axial compression and lateral expansion gives the Poisson's ratio, $\upsilon = -\frac{d\varepsilon_h}{\varepsilon_v}$.

Since materials expand and compress in different directions depending on the direction of the force, the stress-strain relationship is three-dimensional. Often, stress-strain is simplified to a one-dimensional relationship with the same direction as the force. The initial condition in this relationship is linear elastic. In this condition, the strain *(ε)* is proportional to the stress *(σ)* and Hook's law, $\varepsilon = -E * \sigma$, holds (where E is Young's modulus defined as the ratio of the stress along an axis to the strain). An essential feature of the elastic phase is that the material is left in its original condition when it is loaded and unloaded. In addition, there is a one-to-one relationship between stresses and strain in the elastic phase.

Since the reduction of pore pressure is a transient process, consolidation of soft soil is also a time dependent procedure. This time dependency together with the mentioned principles for the elastic phase, forms the basis for Terzaghi's equation of one-dimensional consolidation under constant total stress (Terzaghi, 1943): $\frac{\delta u}{\delta t} = c_v\left(\frac{\delta^2 u}{\delta z^2}\right)$, where z is depth and c_v is the coefficient of consolidation. The coefficient of consolidation can be expressed as: $c_v = \frac{M * k}{\gamma_w}$, where M is the modulus and γ_w is the unit weight of water.

When transferring the elastic phase of soft soils according to Swedish practice, Young's modulus can be compared with the primary compression modulus, M_0, see Larsson and Sällfors (1986). As discussed in Olsson (2010), the methods for estimating this parameter give results with significant uncertainties. In Paper III an empirical assumption for estimation of M_0, is used, see Larsson et al. (1997). Since the compression is very small and reversible in the elastic phase, the estimation of M_0, is however less critical in comparison to estimation of parameters in the subsequent plastic phase.

When a material yields, it goes from elastic to plastic conditions. If only one dimensional condition is considered, the transition phase from elastic to yielding is often simplified to a point. For soft soils, this point corresponds to the preconsolidation pressure *(σ'_v)*. In Sweden, the industry standard for estimating the preconsolidation pressure follows a graphical method introduced by Sällfors (1975).

In this method, piston samples of clay are evaluated with constant rate of strain (CRS) rate of 0.7 %/hr. This method is also used in Paper III. Other methods for estimating the preconsolidation pressure in one-dimension are described in e.g. Casagrande (1936) or Burmister (1952).

As mentioned in Paper III, one of the main uncertainties in estimation of soil properties is model uncertaintity when laboratory measurements are transformed into design properties (Kok-Kwang & Kulhawy, 1999). Since different possible methods are possible when the phase from elastic to plastic conditions is transformed to the single point of preconsolidation pressure, the estimation includes this model uncertainty. The evaluation is also dependent on temperature and strain rate, see e.g. Sällfors and Tidfors (1989) and Claesson (2003). This dependency is related to the uncertainty of measurement errors caused by equipment, procedural-operator and random testing effects. Plastic deformations are irreversible, greater than the elastic phase and brings the material into new conditions. Due to this, the modelling of the transformation phase is crucial when calculating subsidence.

When plastic conditions are reached after the yield point, the strain increases and plastic hardening occurs until a new yield condition is created, see e.g. Olsson (2010). Due to this hardening, the transition phase between elastic and plastic conditions is moved along the direction of the applied stress (for one-dimensional problems). Except for irreversible deformations, this process increases the preconsolidation pressure. This means that if the soil is reloaded and loaded again with a stress between the old and the new, increased, preconsolidation pressure, the deformation will be in the elastic phase.

As with the elastic part, plastic deformation is a time dependent procedure when pore pressure is reduced. In Paper III, a simplified one-dimensional method that calculates subsidence after infinite time has been used, see Larsson and Sällfors (1986). This method is simplified in many different ways, since it is one-dimensional and ignores time dependencies and creep processes. Yet, the purpose of Paper III is not to suggest a method for precise calculation of subsidence but a useful tool for risk estimation of groundwater drawdown induced subsidence on the regional scale. It is possible that a refined calculation method would reduce uncertainties in the result, but to benefit from a precise model robust soil estimates are also needed. In Paper III, the samples in the case study show great variation in the soil property estimates. Due to this large variability, it is however not likely that refined calculation methods would change the identified risk areas significantly.

In addition, it is likely that probabilistic calculations of subsidence with refined models would be computationally demanding. The model in its present state for the case-study in Paper III already takes a few days to compute. Nevertheless, calculation methods that consider time dependencies would be useful from a risk estimation perspective since this would make it possible to plan for safety measures before harmful subsidence occurs.

2.6 Damages on constructions

The extent of subsidence damages depend on its magnitude but also on the sensitivity of the constructions. Buildings built by brick are in general more sensitive than armed structures in concrete and long buildings are more likely to be damaged than shorter (Karlsrud, 2015). Most damage on buildings involves cracks (Korff, 2009). Bonshor and Bonshor (1996) identify three crack types due to different deformation modes; sagging, hogging and local, see Figure 8. In sagging, there are greater deformations at the center of a building than on the sides. This causes wide cracks at the bottom and narrow cracks at the top of a building. Hogging causes large deformations on the sides and small at the center of a building, which leads to wide cracks at the top and narrow cracks at the bottom of a building. Local deformations are typically caused by close-by subsurface construction work.

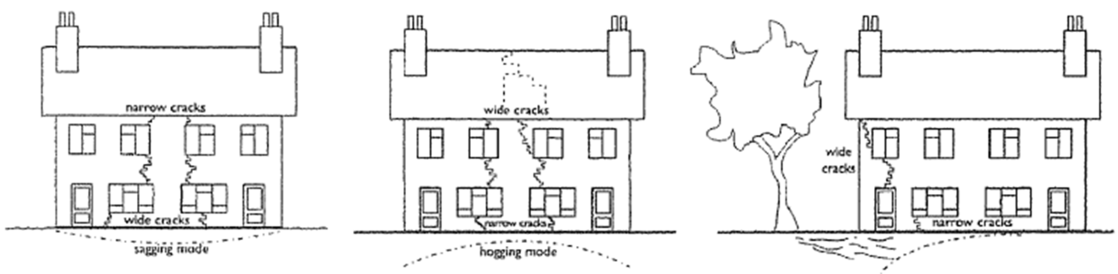

Figure 8 Deformation modes: sagging, hogging and local (Bonshor & Bonshor, 1996).

The severity of a damage depends on its effect on the function and appearance of a building and on the associated repair procedure and cost. Korff (2009) and Cooper (2008) have compiled literature reviews of classification systems for deformation damages on buildings. These include both qualitative and quantitative descriptions. Qualitative aspects relate to aesthetics, serviceability and stability damages with risk for collapse, see e.g. Driscoll (1995). Quantitative descriptions are based on settlement quantities (downward displacement), differential settlements (difference in settlements between two points on a building), deflection ratio (quotient between relative deflection and distance between two reference points) or angular distortion (measure of shearing distortion of a structure) (Boscardin & Cording, 1989).

In Paper III it is assumed that subsidence quantities below two centimetres are not likely to cause damages. For an unlikely worst-case scenario, the differential settlements are also two centimetres. A reasonable assumption of the minimum width for a building in Stockholm, the site for the case study, is 10 meters. This results in a maximum relative deflection of 1/500. If it is further assumed that the building is not tilting, the angular distortion also corresponds to 1/500. Son and Cording (2005) have compiled qualitative estimations of damage levels with angular distortion and lateral strain (quotient of horizontal displacement and length between two reference points). The span for where slight damages are observed is set to angular distortions between 1/700 and 1/300. The worst-case situation for angular distortion is within this limit. Since most buildings are wider than 10 meters, differential settlements are likely to be lower than the maximal settlement and since lateral strain can occur, the two centimetre limit is a reasonable limit for damage.

As mentioned in the beginning of this section, the sensitivity of different buildings varies. Tisell (2015) classified the sensitivity of individual buildings in Stockholm depending on their foundation. Buildings classified as sensitive are founded directly on soft soil or have wood foundations. Buildings founded on coarse grained materials, friction piles or with reinforced foundation are classified as non-sensitive. In addition, buildings with a basement floor founded directly on soil are also classed. The presented risk maps in Publication II and III are combined with this information in Sundell and Rosén (2016), see Figure 9. Here, the 95th percentile for where the groundwater pressure level of the confined aquifer saturates at least 1 m of the clay thickness (Publication II) corresponds to area D. Area A, B and C corresponds to risk areas for 0.5, 1 and 2 m groundwater drawdown respectively (Publication III). By combining these sources, monitoring, safety measures and further investigations can be prioritized to locations where there is a risk for both groundwater drawdown induced subsidence and sensitive buildings.

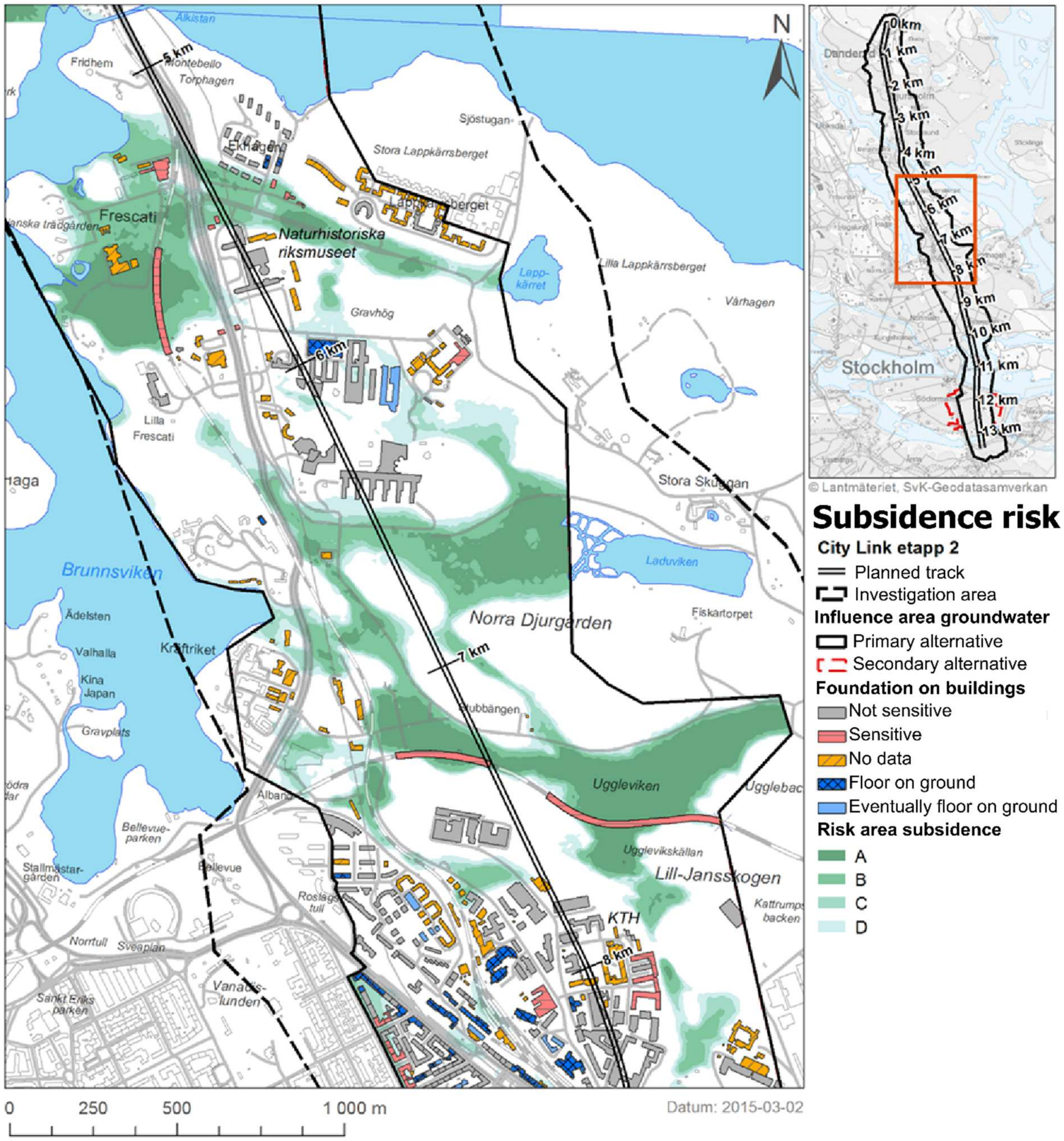

Figure 9 Risk areas for subsidence (A-D) together with a classification of sensitivity for different foundation types.

In Publication I, the economic consequences of subsidence damages are valued as restoration costs due to damages. This valuation can be based on historical records of damage costs. Since the valuation is based on historical records, damages and expected benefits of safety measures are valued *ex-post*. An *ex-post* valuation refers to known quantities as as if the specific effect of interest (such as damage due to subsidence) has already occurred. Other, indirect, costs can also be associated with subsidence, e.g. project delays and inconvenience for dwellers. Such indirect costs, by which peoples preferences on risk reduction can be reflected, are more difficult to quantify. Peoples preferences has to be valued *ex ante*, using e.g. studies of willingness to pay to avoid disturbances associated with subsidence damages. For further details on different valuation approaches, see e.g. Boardman et al. (2011).

Safety measures to prevent damages are also possible in this part of the cause-effect chain. Such measures can include fortifying of foundations. This measure is however likely to be very expensive and is feasible for individual buildings with a high risk for damages only.

3 METHODS

This chapter gives details on methods used in this thesis.

3.1 Kriging and variogram

Since kriging is an essential component of Paper II, the theoretical framework of kriging is introduced here. The primary advantage of Kriging is its ability to interpolate values from known data points and provide estimates of the uncertainty at all locations of the model domain. Kriging is commonly used to obtain an estimate with minimum error variance. When modelling with Kriging, a variogram is used to estimate the spatial correlation structure between the data. The variogram is also used in an interpolation process when values at unsampled sites are estimated by weighting the values of neighbouring data points. Moreover, a variogram can reveal the possible existence of anisotropy in different directions of a variable over the model field. From the known data points, an experimental variogram is calculated using Eq. (1):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{ij}=h} (v_i - v_j)^2, \qquad (1)$$

where *N(h)* denotes the number of pairs of points separated by a lag distance *h*. For each pair (*i* and *j*) with approximate distance h, the quadratic sum of the difference between the data values of these are calculated $\sum(v_i\text{-}v_j)^2$. The experimental variogram can then be described as the mean of the variance between the paired data values.

To facilitate interpolation, parameters of theoretical variogram models must be fitted to the experimental variogram. For the dataset in this study, four different variogram models were used: (1) Nugget effect, (2) Exponential, (3) Gaussian, and (4) Spherical.

A nugget effect describes a completely random variability within the shortest sampling intervals that neither depends on coordinates nor on the lag distance (Webster, 2008). Measurement and interpretation errors contribute to this variance. If the nugget effect is to be relevant, it has to be combined with other models. The nugget effect is defined by Eq. (2):

$$\gamma(h) = s, \qquad (2)$$

for h>0. The exponential variogram is defined by Eq. (3):

$$\gamma(h) = s\left(1 - e^{-3h/r}\right). \qquad (3)$$

The Gaussian variogram is defined by Eq. (4):

$$\gamma(h) = s\left(1 - e^{-3h^2/r^2}\right). \quad (4)$$

The spherical variogram is defined by Eq. (5):

$$\gamma(h) = \begin{cases} s\left(\frac{3h}{2r} - \frac{h^3}{2r^3}\right) & h<1 \\ s & h \geq 1 \end{cases}. \ (5).$$

For the case where $h = 0$, $\gamma(h)$ also equals 0. In equations 2-5, s and r denotes the sill (limit of the variogram value when h tends to infinity) and range (the distance when the difference between the variogram value and the sill is negligible) respectively, see Figure 10.

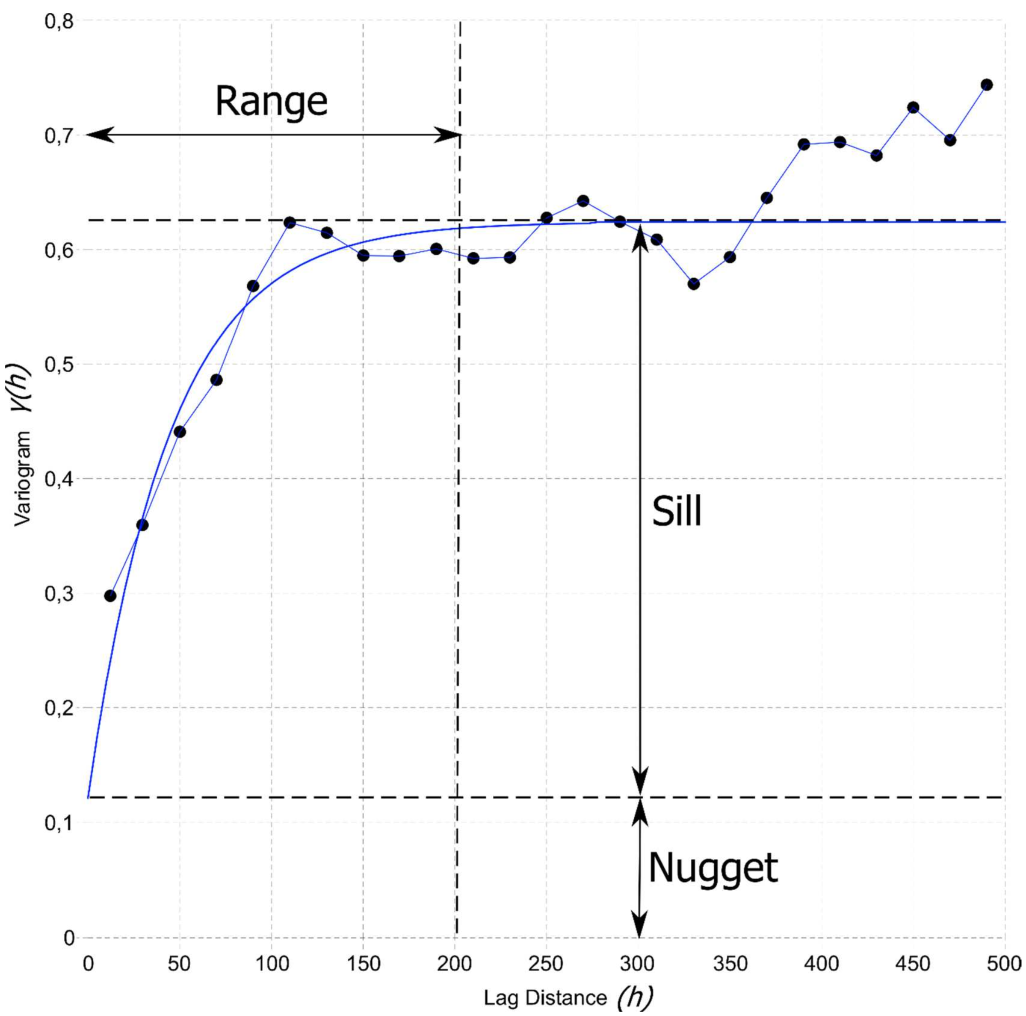

Figure 10 Variogram with, range, sill nugget and lag distance. Publication II gives illustrations on how the experimental variogram can fit to a theoretical variogram.

To fit a theoretical variogram model to the experimental variogram, the least-square (LS) method is used in Paper II. With this method, a formula for the modelled variogram is chosen so it minimizes the quadratic sum of the difference between the theoretical and experimental variogram. Examples on how modelled variograms can be fitted to experimental variograms can be seen in Publication II.

In Paper II, ordinary kriging is used with the modeled variogram to estimate values at unsampled locations. Ordinary Kriging estimates values at every point to be interpolated by Eq. (6):

$$\hat{v}_0 = \sum_i \; w_i * v_i, \qquad (6)$$

where:
v_i is the sampled value,
w_i is a weight factor calculated by means of the modelled variogram and the distance between v_i and v_0.

3.2 Groundwater modelling

Although no groundwater model is presented in this thesis, this section gives a suggestion on how groundwater modelling can be a useful tool for estimating the possible extent of groundwater drawdown for a planned sub-surface construction. This is planned for a future study in this research project.

The groundwater flow pattern depends on drainage and infiltration conditions, layering of porous and semi-permeable soil layers and fracture structures in bedrock. Groundwater flow in porous and fractured media can normally be assumed to be laminar, see e.g. Gustafson (2012). With this assumption, Darcy's law, $q = K\frac{\Delta h}{\Delta l}$, is valid. Darcy's law describes the proportional relationship between discharge rate *(q)* through a porous medium, its hydraulic conductivity *(K)* and the groundwater pressure gradient *(Δh/Δl)*. Darcy's law also forms the basis for the diffusion equation for transient flow, which finite difference groundwater model codes such as the commonly used MODFLOW (Harbaugh, 2005) is based upon. For three dimensions, this equation can be written as:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t}$$

where K_{xx}, K_{yy} and K_{zz}, are values of the hydraulic conductivity along the x, y and z coordinate axes, h is the piezometric head, W is the volumetric flux per unit volume representing sources and/or sinks of water, S_s is the specific storage of the porous material; and t is time.

Although it is possible to solve the diffusion equation in a groundwater model, it can be difficult to obtain reliable results. This is difficult since the groundwater flow system, particularly in a city, can be very complex and uncertain. Pieziometric heads are commonly obtained from groundwater observation wells. These are often measured during limited times in different projects without overall coordination. Hence, it can be difficult to find representative levels for the whole study area. Individual observations can also be affected by very local drainage conditions that is not of interest for the larger scale of the model. Estimation of hydraulic conductivity and specific storage can be even more difficult. Although there is a large variety of different investigation methods for these hydrogeological properties such as slug-tests, pumping tests or screening curves of soil fractions, these tests can be expensive and time consuming (especially pumping tests) or only representative for very small volumes (slug-test and screening curve). This means that a judgment on the representativeness of these properties is needed for estimating often heterogeneous soil- and bedrock conditions. In addition, estimations are needed for the conceptualization of the flow system in the limits of the model and on sources and sinks representing both known sources with uncertain conditions (e.g. road tunnels and rivers) and unknown sources (e.g. secret facilities, and leaking water distribution and sewage pipes), see Werner et al. (2012).

Different assumptions and conceptualizations of the system can be equally reasonable but give substantially different results when applied in a model. An example from a case study in Copenhagen showed that five different consultants reached substantially different conclusions on the vulnerability of a water supply, although all were given the same information (Refsgaard et al., 2005). A groundwater model can never give an exact prediction of what will happen in the future. Nevertheless, since scenarios can be invalidated, it can answer what will not happen in the future (Bredehoeft & Konikow, 2012). Information on where groundwater drawdown is not expected is also useful to prioritize monitoring and safety measures.

Groundwater modelling is a mixture of expert knowledge of the hydrogeological system and history matching of available observations. When applying groundwater models in cities, it is common with large amounts of information that can give characteristics on the hydrogeological system. Such information includes observations from geotechnical drillings, wells in soil and bedrock, and existing sub-surface constructions. Even though much information exist, all this is obviously only historical data.

The lack of full access in time and space of the phenomena of interest creates a need for a model (Oreskes et al., 1994). One way to address uncertainties in prediction of groundwater drawdown is by probabilistic groundwater modelling, see e.g. Freeze et al. (1990). Such approaches are however criticized for only taking account for some uncertainties since the probability density functions (pdf) can be incorrect and other conceptual and numerical models than the one used are not included (Konikow & Ewing, 1999). One method for probabilistic modelling of highly parameterized models that cannot be estimated uniquely on the basis of a given calibration dataset (ill posed problems) is to combine MODFLOW with PEST (Doherty et al., 2010). PEST, Parameter ESTimation code, is a software package for parameter estimation and uncertainty analysis. The basic principle of PEST is to estimate properties (e.g. hydraulic conductivity and recharge) with regularized inversion where a best fit is defined by principles of least-squares minimization. To stabilize the numerical solution, two mathematical regularization techniques is be used in PEST: Tikhonov regularization and subspace regularization. In the first, "soft" information on acceptable deviation from what is geologically reasonable is combined with a measurement objective function, see Doherty (2003). For subspace regularization numerical stability is achieved through subtracting parameters or parameter combinations instead of adding information to the calibration process. The parameters or combinations to be subtracted are determined through singular value decomposition (SVD), see e.g. Moore and Doherty (2005). In this process, SVD first identifies where the most variation is and then defines the best approximation of the original data points using a reduced set of parameter combinations (Baker, 2005).

In a future study, it is planned to combine a probabilistic groundwater model with the methods for soil and bedrock stratification presented in Paper II and the subsidence model in Paper III. An initial step for this three-dimensional groundwater model is to distinguish different material types. This can include a separation of coarse-grained material from fine grained and fractured bedrock from non-fractured. After this, properties such as hydraulic conductivity and infiltration capacity can be assigned to the different materials. Different materials however, often exhibit significant heterogeneity and anisotropy. One method for addressing this issue is by modelling hydraulic conductivity fields. These are modelled by assigning pilot points of hydraulic property values to the different materials. Pilot points is a 2D scatter point set representing different locations within a material. Hydraulic conductivity values are then assigned to the points by minimizing the difference between model output and field measurements. Property values of continuous fields are then interpolated from the points (Doherty, 2003). A preliminary study of this approach for Göteborg has shown its feasibility although the error between the observed and calculated heads is relatively large (up to about 8 meters). Strategies to improve the model include: a finer grid resolution (from the present 50x50 meters) in areas with high gradients, shorter distance between the pilot-points and including more information on present drainage and infiltration conditions.

The probabilistic approach with PEST does not assess the problem with different possible conceptualizations of the system. This issue is currently studied in a master thesis project. The study is based on a case study for an esker used as groundwater supply for a small municipality. Available information for the study area includes data on ground-water level time series, hydrogeological properties and boreholes with information on soil stratification. From this data, different professional hydrogeologists will independently from each other set up assumptions for a groundwater model. The master student will then do the modelling. The modelling process and its outcomes will be self-reviewed by the experts according to NUSAP (Van der Sluijs et al., 2005) or a similar method where both quantitative and qualitative uncertainties are addressed.

4 THE PUBLICATIONS

This chapter summarizes the main findings in the three publications appended to this thesis. The importance of each publication in the cause-effect chain is motivated. In addition, it is described how the three publications are connected.

4.1 Paper I - Framework for risk management

The first paper (Sundell et al., 2015b) presents a structured framework for risk assessment and management based on the current ISO-standard (ISO, 2009) and the works by Aven (2012) and Lindhe (2010). Many of the suggested procedures in the framework are commonly investigated in planned Swedish infrastructure projects. Nevertheless, there is no framework that describes how the different investigations in the cause-effect chain can be linked together in a risk assessment. This paper aims to fill this gap for a structured approach in risk assessment.

Five different modules necessary for the risk assessment are introduced in this paper. The first three modules are connected to the cause-effect chain for groundwater drawdown induced subsidence and the processes introduced in Section 2. Module 1 emphasizes the need for a probabilistic soil stratigraphy model for estimation of the likelihood of compressible sediments at locations with constructions sensitive for subsidence. This model is further developed in Paper II. In module 2, suggestions for probabilistic groundwater modelling are introduced. It is also explained how module 1 can be used as part of groundwater modelling. In module 3, probabilistic subsidence modelling based on module 1 and probability density functions (pdf:s) from constant rate of strain (CRS) evaluated piston samples is introduced. This modelling is further developed in Paper III.

The first three modules can be included in a risk analysis where the probability of subsidence of a certain magnitude is estimated. In module 4, risk estimation, the calculated pdf for subsidence, f_s, is combined with a cost function representing the economic consequences of a subsidence, C_s. From these, the economic risk, i.e. the expected consequence cost, for subsidence can be calculated:

$$R_s = \int C_s f_s ds$$

In the fifth module, risk evaluation, i.e. whether or not a measure is cost efficient, is evaluated with VOIA, see e.g. Back (2006) and Zetterlund et al. (2011). VOIA is a form of cost-benefit analysis (CBA). The basic idea of VOIA is to value additional information as the change in expected total cost (or benefit) of the project due to new information. In the first stage of a VOIA, costs and benefits of the present stage of knowledge is evaluated in a *prior analysis*. In the second stage, a *preposterior* analysis is performed, based on the information that is expected from the data collection program. The preposterior analysis is performed *after* ('posterior') the data collection program has been defined, but *before* ('pre') the data collection has taken place. The Expected Value of Information (EVI) can then be calculated as the difference between the values of the preposterior and prior analysis. Note that EVI is always non-negative and bounded by the Expected Value of Perfect Information (EVPI). Note also that EVI equals zero if the data has no potential to reduce the total project cost.

The suggested framework in this paper aims at providing for more comprehensive evaluations of the economic value of safety measures. At the time of writing the paper, there was still a lot of work left for linking the different modules together. This is still the case but the interaction between the modules has been further addressed in Paper II and Paper III.

4.2 Paper II – Probabilistic simulation of bedrock levels and soil stratigraphy

As mentioned in Section 2.1, one essential part in describing the groundwater drawdown – subsidence - damage chain is a good understanding of the soil stratigraphy. This is essential since groundwater flow conditions are partly governed by geological materials and subsidence depends on the compressibility of materials. In this section a novel method for probabilistic modelling of soil stratigraphy and bedrock level is presented. In Paper II (Sundell et al., 2015a) a complete description of the method is presented.

The probabilistic soil stratigraphy method uses borehole logs with different types of information to build a model for bedrock levels and soil stratigraphy. Some boreholes reach the bedrock whereas others do not. Similarly, some boreholes contain information of the whole soil stratigraphy whereas others do not. The overall idea of the presented method is to utilize all available data that contains useful information of soil and bedrock stratigraphy in a probabilistic model. This was done by a combination of a stepwise kriging (see Section 3.1) procedure and statistical simulations in the R software environment (R Development Core Team, 2010). The modelling process is stepwise since this procedure takes account of different types of information and the dependencies between the different layers. If the layers would have been simulated independently from each other, it is likely that an unrealistic layering would have been the result.

Building a geologic soil stratification model in a city with thousands of boreholes can take a very long time, depending on the method chosen. Some methods are based on linking boreholes together, see e.g. Peterson et al. (2014), which could be necessary if a detailed model in a heterogeneous environment is needed. If fewer details are acceptable, e.g. ignoring information on embedded layers, the method presented in Paper II is an efficient approach. It is also common that models have to be updated continuously when new information is available, which gives additional reasons for an automated approach. The method in Paper II has proven to provide geologically reasonable results in real world applications. It has been applied on the city scale to case studies in both Stockholm (Sundell, 2015) and Gothenburg, Sweden (Sundell et al., 2016b). The method is useful and efficient in areas with relatively large amounts of available data and when the stratigraphy can be simplified to continuous layers. If this is not the case, other approaches, such as the ones presented in Section 2.1, could be considered.

4.3 Paper III – Probabilistic subsidence model on a city-scale

The third paper (Sundell et al., 2016a) continues from the work presented in Paper II by adding on a probabilistic subsidence module. First, a method for upscaling and quantifying variability in parameter values from soil samples to the scale of a hydrogeological model is presented. Second, a probabilistic method for calculating subsidence on a city-scale is introduced. Finally, a risk map describing areas where a groundwater drawdown with a certain magnitude can cause subsidence is presented. In Paper III (Sundell et al., 2016a) a complete description of the method is presented. The author would like to acknowledge Ramm and Collinder (2014) for their statistical study of clay parameters.

As stated earlier, if the whole cause-effect chain for groundwater drawdown induced subsidence is to be evaluated, different fields of study needs to be combined. One of these fields is geotechnical engineering. Geotechnical problems are often evaluated on the construction-site scale. This means that sampling and calculation methods are also developed for this scale. The risk for subsidence needs to be evaluated on the scale for a potential future groundwater drawdown. Since a drawdown from a tunnel can be extensive and cover a large area in a city, the term "city-scale" is used in the paper. On this scale, it is very expensive to sample with the same frequency as when dimensioning in construction projects. This creates a need for a method capable of calculating subsidence on a city-scale and probabilistic representation of uncertainties.

In this paper a novel method for probabilistic calculations of subsidence on the city-scale is introduced. The method is applied to a case study in Stockholm, Sweden with 79 evaluated constant rate of strain piston samples. In a first stage, compression parameters are transformed to normality and detrended against depth. Dependencies between the parameters are considered by finding the pdf of the quotient between the dependent and the studied parameter. Since the samples are spatially scarce, it is necessary to investigate if the parameters are dependent on a controlling factor that can be used for dividing the large area into smaller sub-areas. In this paper, it is investigated if the samples are dependent on the degree of urbanization (DU) for the sampling location. This dependency between the transformed parameters and DU is evaluated with ANOVA, see e.g. Marx and Larsen (2006). For the parameters with significant differences unique pdf:s for the different DU areas are used in the simulations of subsidence.

From the pdf:s of the parameters, DU areas and the probabilistic soil stratigraphy model presented in Paper II, subsidence is simulated with a simple but common Swedish method (Larsson & Sällfors, 1986). The result of the subsidence simulation is used to draw a risk map where areas with a low probability for subsidence are separated from areas where subsidence can occur with a higher probability. The risk area is defined as grid points where the 95th percentile of the simulations shows a land subsidence exceeding two centimetres. The two centimetre limit has been chosen as a conservative lower-level as when subsidence can damage a construction, see Section 2.6. This means that the risk in the maps is expressed at a constant level of both consequence (2 cm subsidence) and probability (95th percentile). The risk maps show locations where a risk (according to the simulations) for subsidence greater than 2 centimetres has a probability larger than five percent.

The significance of individual parameters to the calculated subsidence is evaluated with the Spearman rank correlation coefficient, see e.g. Bedford and Cooke (2001). Mapping the result of this sensitivity analysis, the parameters that are most significant for the simulated subsidence at a certain location can be seen.

The risk areas and the result of the sensitivity analysis can, together with information on sensitive constructions, be used for assisting decision-making regarding prioritization of risk reducing measures, monitoring and further investigations.

5 DISCUSSION AND FURTHER INVESTIGATIONS

In this thesis, three novel methodologies for risk assessment, soil stratification modelling and subsidence modelling on the city-scale are presented in Paper I, II and III, respectively. The three papers focus on different phases in the cause-effect chain for groundwater drawdown induced subsidence. Nevertheless, all methods are connected to the overall aim of developing methodologies for reaching a transparent and cost-effective decision basis for estimating subsidence risks due to groundwater drawdowns in infrastructure projects.

As discussed in Section 2, different scales can be used when evaluating the links in the cause-effect chain. The scale of the problem is important to consider since different methods are appropriate for studies and evaluations on different scales. In Figure 11, a suggested division of scale for the different parts of the cause-effect chain is suggested.

As mentioned previously, Gustafson (2012) divides hydrogeological characteristics of the bedrock into three different scales: (1) a small scale where individual fractures are evaluated, (2) a medium scale with blocks between 3-30 meters, and, (3) a large scale where the rock is assumed as a homogeneously porous medium.

Blöschl and Sivapalan (1995) suggest a four level scale division of catchment hydrology, according to which the groundwater drawdown part of the cause-effect chain, can be grouped. This scale division starts with the small local scale with flow in macropores. It continues with hillslopes where the preferential flow occurs through high conductivity layers. The second largest scale is divided into catchments with different soil types and properties. Finally, the regional scale with large scale geological formations is considered. Pore pressure variability in clay deposits is also reasonable to group in a similar system. Mourgues et al. (2011) show how both large, basin scale and local scale phenomena affect a pore pressure profile. Instead of naming the second largest scale "catchment", it is more reasonable here to change the name to "deposit". This is because pore pressure is considered for the clay deposit which normally is on a smaller scale than a whole catchment area.

In geotechnical engineering, scales are commonly distinguished between micro-, meso-, and macroscale, see e.g. Guo and Zhao (2016). On the smallest microscale, the particles of the material are studied. The mesoscale describes samples of representative volume elements (RVE) that describe properties of a material. On the larger macroscale, boundary value problems (BVPs) are evaluated when engineering designs for constructions and adjacent buildings. When the scale is increased to a regional scale, the problem moves from being a geotechnical issue to a geological assessment of soil deposits.

For damages on constructions, it is more appropriate to change scale from length and area to severity. As described in Section 2.6, the severity of damages on constructions can be scaled into aesthetics, serviceability and collapse. Damage costs can be scaled into direct and indirect costs. Direct costs include e.g. reparation of damages meanwhile indirect costs include e.g. changes in market value of the buildings and the preferences of utilizers to avoid damages due to subsidence. When discussing indirect costs it is of course important to also consider positive aspects (benefits) of improved infrastructure services such as higher market value of buildings due to improved communication. The difference between the direct and indirect costs is assumed to vary between projects. Due to this assumption, they are placed parallel in Figure 11.

How the three publications are related to the parts and scales on the cause-effect chain is also illustrated in Figure 11. Publication I embraces the whole chain without going into details on scales. Publication II is relevant for the first four parts of the chain. The presented methodology is exemplified with a bedrock level and soil stratification model on a city-scale. With additional information on the characteristics of the bedrock and soil, the model can also be used for intermediate sized issues. Publication III relates to larger scaled subsidence problems. The applied methodology relating to assignment of probability density functions to geotechnical properties can however be applied to intermediate sized problems with significant heterogeneity.

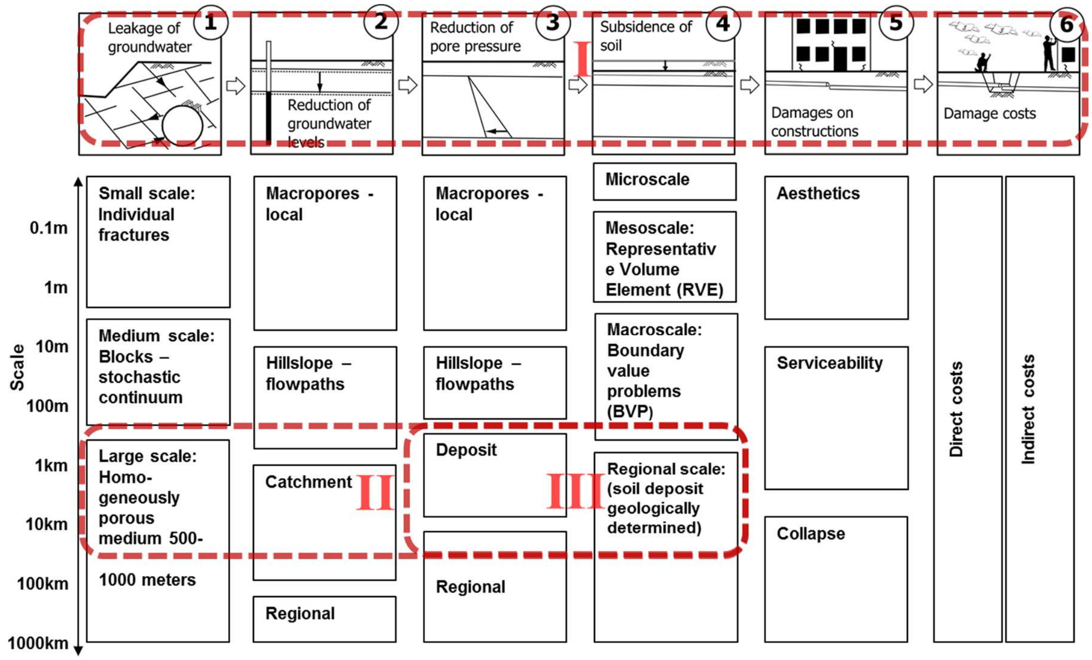

Figure 11 The cause-effect chain with a division of scales for each part. How publications I, II and III are related to this division is presented in the figure. The numbered scale axis is only relevant for the first four parts of the chain.

In addition to a division of the cause-effect chain into scales, time is also an important aspect. The processes in the cause-effect chain are transient with a sequential increase of groundwater drawdown and subsidence magnitude. As mentioned in Section 2.5, the subsidence process can also be divided into a reversible elastic phase with small subsidence magnitudes and an irreversible plastic phase with larger magnitudes. The process before the tipping phase from elastic to plastic is reached, is also time-dependent since the increased stress that drives this process is a result of the gradual increase of pore pressure over time. The need for safety measures is also time dependent since the subsidence process and hence the extent of damages increases over time. This time dependent process creates a time space for implementation of costly safety measures to be implemented before critical levels in the cause-effect chain is reached as suggested by the observational method. The methods presented in Paper II and III where risk areas for subsidence for certain groundwater drawdown magnitudes are useful tools in this procedure since safety measures can be implemented before critical groundwater levels are reached.

Decision support on the available time for implementation of safety measures would be significant improved if time-dependencies are included in the subsidence simulations in Paper III. Information of the time until critical subsidence levels are reached would give more precise information on the length of the acting space. This function is planned to be incorporated into the model.

From the positions of Publication I, II and III in Figure 11, it is clear that future focus in the research project now needs to be directed to the initial (leakage to groundwater drawdown) and last (damages and costs) phases of the chain. As mentioned in Section 3.2, it is planned to connect the methods in Paper II and III with a probabilistic groundwater model for evaluation of possible drawdown scenarios for a planned construction. This would improve the identification of the risk areas to give decision support on implementation of safety measures in areas with risk for both groundwater drawdown and subsidence. For the last phase, the presented and planned methods will be connected with estimations on potential damage and costs for buildings within the risk areas in a VOIA. Economic valuation would further improve decision support since the cost for additional information and safety measures should be valued against the benefit of reducing expected damage costs, i.e. the risk (due to better decisions and relevant risk reduction measures) as suggested in Paper I.

Although quantitative probabilistic methods (such as the ones presented in Publication I, II and III and planned for in further research) are used in risk analysis of groundwater drawdown induced subsidence, bias in sampling and lab-evaluation, different model conceptualizations or alternative numerical models are not taken into account. Since the reason for a model is a lack of full access to the phenomena of interest, it is the responsibility of the modeler to demonstrate the degree of correspondence to the real system and to delineate the limits of that correspondence (Oreskes et al., 1994). This is fulfilled in Publication II by comparing the modeled result with a reference dataset. In Publication III a future scenario is modeled. Since the future cannot be validated until it occurs, a discussion on the model's reliability and usefulness for decision support is given in Publication III. The method in Publication III has also been compared with calculation points with Swedish industry standard practice. This quantitative comparison shows that risk areas elaborated with the method in Publication III is able to capture points with a calculated subsidence greater than two centimetres (Sundell & Haaf, 2015). This comparison shows a good correspondence between the methods.

As stated in Publication III, decisions regarding risk-reducing measures need to be taken before the model can be validated against additional observations. For the decision-making on these measures, it is important to evaluate if the process representation is detailed enough to be useful for predicting the dominant modes of response in the system (Beven, 2007). Since all sources of uncertainty cannot be evaluated quantitatively, it is important to be reflective upon the quality of evidence (van der Sluijs et al., 2008). As mentioned earlier, a current master thesis study is evaluating the effect of professional assumptions on groundwater modelling. The study will let different professional hydrogeologists, independently from each other, set up assumptions for a groundwater model. The comparison will be made both by the experts' own self-evaluation of the assumptions and the modelled result and by comparing the result between the different experts' models, similar to work by e.g. Refsgaard et al. (2005).

Although multidisciplinary approaches are used to analyse the cause-effect chain, decisions on safety measures is not only a matter of technical understanding of a system and valuation of damage costs. Since stakeholders are affected by the consequences of subsidence damage, their preferences on risk and safety measures need to be considered. It is likely that the risk perception is considerably different between stakeholders potentially affected by damages and the contractor. An early involvement and transparent communication with stakeholders is therefore of great importance. Slovic (1987) argues that a key to successful risk communication is two-way communication between experts and stakeholders. In this process, both side has something valid to contribute and each side must respect the insights and intelligence of the other. If models should be used as a tool for decision support when interests on e.g. safety measures are in dispute, Saltelli and Funtowicz (2014) emphasize that transparency should be aimed for. A Swedish review by professional hydrogeologists of effects on groundwater conditions due to leakage into facilities constructed in bedrock found that data, methods and assumptions were often difficult to access (Werner et al., 2012). If this information is difficult to access and understand for stakeholders, communication fails. Transparency includes clear communication of uncertainties of the potential consequences for a planned groundwater drawdown. A communication of uncertainties is often mistaken for insufficient control. Communicating uncertainties would rather mean that the contractor is prepared for actions on many possible scenarios. By this approach, stakeholders' safety and trust for the contractor would rather increase.

With this licentiate thesis, improved multidisciplinary approaches for analysis and communication of risk have been presented. The overall aim to develop methodologies for risk estimation has been fulfilled by three different objectives:

- The first objective to develop a framework for risk assessment of groundwater drawdown induced subsidence is fulfilled by the presentation in

Publication I. This framework embraces the whole cause-effect chain for groundwater drawdown induced subsidence. By doing so, the most appropriate safety measure can be implemented. The presented framework also serves as a basis for connecting the other two specific objectives to the overall aim.

- The second specific objective to develop a method for probabilistic modelling of bedrock levels and soil stratification is fulfilled by the presentation in Publication II. The presented method is proven able to; efficiently combine different sources of information; handle large amounts of data; require little manual adjustments; easy to update, and; give a geologically sound result when applied on two case studies in Stockholm and Gothenburg.
- The third specific objective to develop a method for probabilistic modelling of groundwater drawdown induced subsidence is fulfilled by the presentation in Publication III. The result of the simulation is presented as risk maps where the 95th percentile of two centimetres subsidence is suggested as a tolerability criterion. The maps have been used for risk communication in the application for permit to drain groundwater in the City Link case study. If these maps are connected with information on the vulnerability of risk objects, such as buildings and installation, the maps are useful decision support form planning of safety measures, monitoring and additional investigations.

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