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A framework for Risk Assessment of Groundwater Drawdown Induced Subsidence

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Abstract. Sub-surface constructions generally involve drainage of groundwater, which can induce land subsidence in compressible soil deposits and cause extensive damage costs in urban areas. A probabilistic framework, in accordance with the risk management framework outlined by the International Standard Organization (ISO), for assessing risks of groundwater drawdown induced subsidence is presented here. The framework consists of five modules: (1) A stratified geostatistical (Kriging) procedure for probabilistic spatial analysis of soil layers. This module is necessary for a detailed understanding of the soil stratification, drainage paths, and their potential spatial variations; (2) A stochastic hydrogeological model capable of representing possible groundwater drawdowns for a specific sub-surface construction; (3) A stochastic subsidence model; (4) A model for estimating the economic consequences and calculating the risk, i.e. the expected cost, of groundwater induced subsidence; and (5) A module for evaluating the need for additional information to reduce the risk of erroneous decisions with respect to risk acceptance criteria based on economic Value of Information Analysis (VOIA), i.e. a cost-benefit analysis (CBA) of additional information collection alternatives for suggested strategies to reduce or control subsidence. The modelled land-area is represented by a grid with calculation points. When the three first modules are linked together in a Monte Carlo-simulation, it is possible to estimate the spatial distribution of probability of subsidence and evaluate the sensitivity to different model and parameter assumptions. An estimation of the risk of subsidence is performed by combining the probability of land subsidence with the locations and expected damage costs of existing buildings across the modeled area (module 4). With sensitivity analysis, significant weaknesses can be identified and robust safety measures at locations with significant risks for subsidence can be planned for. Uncertainties can be communicated by mapping and comparing different outcomes of the model, e.g. the expected value and the 95th percentile of the risk. Together with affected stakeholders the assumptions and the outcomes of the model should be discussed - both how well the model describes the system dynamics and how safety measures should be implemented.

Keywords. risk assessment, groundwater drawdown, subsidence, cost-benefit analysis, value of information analysis

1. Introduction

Construction of infrastructure in urban areas often involves tunneling and deep excavations. When building in urban areas founded on soft clay, it is necessary to consider the risk of land subsidence caused by drainage and subsequent drawdown of groundwater. If groundwater leaks into a tunnel overlain by clay deposits or other sediments with high compressibility, it can cause considerable reduction in pore-pressure and induce subsidence in the soil deposits.

Subsidence due to groundwater drawdown and associated damages to buildings and installations is a severe problem in many regions around the world, including cities in China (Xue et al., 2005), Las Vegas (Burbey, 2002) and Stockholm (Tyrén, 1968).

When planning for sub-surface infrastructure, decision-problems related to the risk for groundwater drawdown induced subsidence need to be assessed. In this paper, the risk is defined as a combination of the probability and the economic consequence of a groundwater drawdown induced subsidence that negatively affects the function of a construction.

This paper presents a generic framework in accordance with the ISO-standard for risk management (ISO, 2009) for risk assessment of groundwater drawdown induced subsidence. Moreover, examples are presented on how parts of the framework have been implemented in a case-study in Stockholm.

2. The Drawdown-Subsidence-Damage Chain

To assess the risk of subsidence, the complexity in the groundwater drawdown – subsidence – damage chain needs to be recognized. This chain represents a parallel system in which the interplay of various components determines the failure of the system and the extent of its consequences. The complex interaction between geotechnical and hydro-geological conditions, the built environment and preventive measures decides if there will be damages or not. If only one process has unfavorable conditions, other processes can compensate and hence not cause subsidence with negative consequences. If there is no leakage of groundwater into a construction, an almost infinite amount of water in the aquifer, a firm soil, or proper foundation of all constructions, there is no risk for subsidence with negative consequences. But if disadvantageous conditions exist in all parts of the system there is a risk for excessive subsidence damages. In order to cause subsidence with negative consequences, all parts of the system needs to have a certain amount of weakness.

Since a groundwater drawdown can affect a large area, it is important to decide on what scale the system should be studied. Typically, groundwater models used for predicting the extent of a groundwater drawdown are conducted for large areas (square kilometers), whereas calculation of ground subsidence with compression parameters obtained from sampling points are only assumed to be valid for small areas close to the sampling point itself.

The complexity of the system and the large areas to be assessed call for a modelling approach that can couple a hydrogeological groundwater flow model with a geotechnical soil mechanic model, and perform calculations for large areas within reasonable calculation time. In order to prioritize risk reduction measures and the need for additional information at different locations, an uncertainty and sensitivity analysis of the model has to be conducted.

In Figure 1, the drawdown-subsidence-damage chain is illustrated for the case study in Stockholm. The soil-stratification profile is represented by: artificial man-made filling-material (a), clay (b), coarse grained glacial deposits (c) and crystalline bedrock. The coarse grained material (glacio-fluvial and glacial till deposits) forms a confined aquifer. The upper hatched line in Figure 1 illustrates the natural groundwater pressure level in this aquifer. A tunnel in the bedrock below the confined aquifer is planned for. Because the bedrock is fractured, the confined aquifer and the tunnel have hydraulic contact. A groundwater leakage into the tunnel can therefore cause a groundwater drawdown in the aquifer (the lower hatched line). This drawdown can initiate a subsidence process in the clay with the potential to damage constructions located founded on the clay layer.

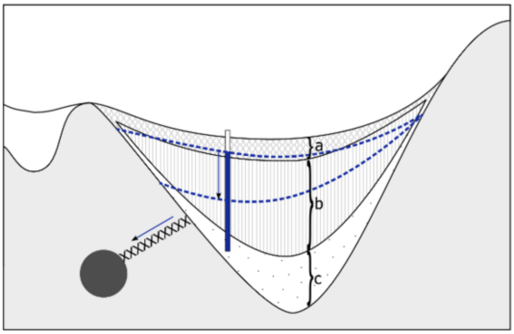

Figure 1. Conceptualization of soil stratigraphy and groundwater drawdown.

3. Generic Framework

The generic framework for risk assessment includes a risk analysis step, including the definition of the scope of the analysis, identification of potential risk objects, and estimations of probabilities of different magnitudes of subsidence. In the forthcoming risk evaluation step, tolerability criteria based on the sensitivity of the constructions at risk and the acceptance level of involved stakeholders is set. Possible risk reduction alternatives that meet the requirements are evaluated using a cost benefit analysis (CBA) approach.

The framework was developed in accordance with the ISO-standard for risk management and according to the view of risk management provided by Aven (2012), see Figure 2. It consists of five different modules: (1) a stratified geostatistical (Kriging) procedure for probabilistic spatial analysis of soil layers; (2) a stochastic hydrogeological model capable of representing possible groundwater drawdowns for a sub-surface construction; (3) a stochastic subsidence model; (4) a model for estimating the economic risk, i.e. the expected damage cost, of groundwater induced subsidence; and (5) a module for evaluating the need for additional information to reduce the risk of erroneous decisions with respect to risk tolerability criteria and economic analysis. The first three modules are used for estimating the probability of subsidence of different magnitudes in a risk analysis. The fourth and the fifth modules are used for evaluating possible options with respect to risk reduction (increased safety) and costs for implementation.

The first three modules are exemplified here by a case-study of subsidence in Stockholm. The modules are combined in a grid-cell pattern resulting in a map of the subsidence over the studied area. Although specific models are used for the case-study, the purpose of this article is not to give detailed recommendations on how groundwater drawdown or subsidence should be modelled but to formalize a process on how the entire drawdown-subsidence-damage chain can be considered in a risk assessment. It is important that the entire chain is considered, but depending on local conditions, details in the modelling need to be adjusted.

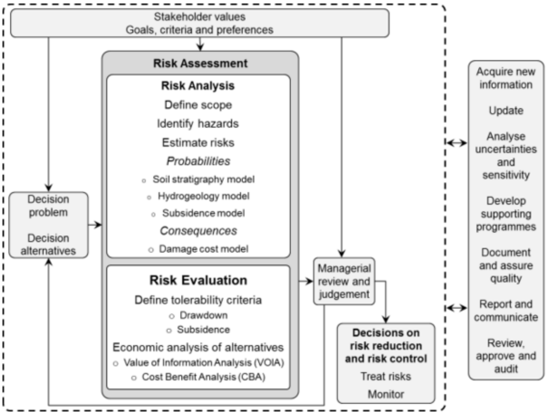

Figure 2. Generic framework.

4. Module 1 – Probabilistic Soil Stratigraphy Model

Knowledge of where compressible sediments are located and how thick they are is essential for estimating subsidence risk. The first module consists of a probabilistic method for coupled bedrock-level and soil stratigraphy modeling to detect compressible sediments. A detailed description of the method will be given in future publications. In the brief summary that is presented below, the model is adopted for conditions where it is possible to simplify the soil strata to three different layers.

First, a bedrock-level model is constructed from three sources of information: (a) geotechnical drillings reaching the bedrock; (b) drillings not reaching the bedrock; and (c) mapped bedrock outcrops. Input data for a probabilistic bedrock-level model is generated by a stepwise Kriging procedure. From the bedrock-level and the surface-level a soil-thickness model is generated.

Second, a three layer soil model is constructed, including the following materials: (a) coarse grained/filling material below the surface; (b) clay; and (c) coarse grained glacial material above the bedrock. Since the layers are dependent of the total soil thickness, the layer thicknesses are transformed to proportions of the total soil thickness. As Kriging requires data to have a Gaussian distribution, the proportions are converted from probabilities (P) to standardized normal quantiles (z).

In a Monte-Carlo (MC) simulation, a spatial distribution of the bedrock level is simulated together with the transformed standard normal quantiles for the soil-layer proportions. From the iterations, the probability for clay at each grid-cell is calculated. The results of the case-study are maps showing the expected value and the 95th percentile of the thickness of compressible sediments at specific locations.

Applied on the case study in Stockholm, the resulting model was found to be geologically reasonable and validated to be in good agreement with a reference dataset. The case-study shows that the method can efficiently handle large amounts of data.

5. Module 2 – Probabilistic Hydrogeological Model

The soil-layer model is used for obtaining a detailed understanding of the geology in the area.

This understanding, together with information of drainage conditions and groundwater recharge, is necessary for conceptualization of the groundwater flow system. The conceptual understanding of the groundwater flow system is summarized in a conceptual model. Based on this model, the construction and parameterization of a groundwater model can then take place from which calculations of critical parameters can be estimated, e.g. groundwater drawdown. In the groundwater-modelling phase, three different types of uncertainty are considered: conceptual-, model-, and parameter uncertainty.

Depending on the local conditions, different types of models can be used, from qualitative reasoning, calculations with analytical methods to more complex numerical models, see e.g. Fetter (2001). If a too complex numerical model is used, it might be difficult to find and analyze weaknesses in the underlying conceptual understanding and in the numerical model itself (Konikow & Ewing, 1999). Therefore, it is important to complement a complex numerical model by more simplified and transparent analyses. A combination of models, whether numerical or analytical, provides means for evaluating the different types of uncertainties.

The basis for this approach of uncertainty evaluation is that different models use different assumptions in terms of e.g. initial and boundary conditions. Also, the translation of the conceptual model into a calculation model may vary between different models. When using a set of models, it is possible to evaluate how the computation of a critical parameter, e.g. tunnel inflow, varies with different model approaches accounting for both conceptual and model uncertainty. Discrepancies between the results provide an indication of the relative importance of the different approaches, in terms of e.g. initial and boundary conditions, to the final result. This approach has proven to be an important tool to corroborate or to reveal a lack of conceptual understanding in the Stockholm case study.

Based on this approach, the model uncertainties among the used models can be evaluated, i.e. the uncertainty caused by the limitations in the mathematical models used to simulate the physical system imposed by the simplifying assumptions.

No probabilistic groundwater model was conducted for the case study. In future research, methods for evaluating parameter uncertainties in groundwater models will be studied. Parameter uncertainties are caused by measurement errors in the data, incomplete knowledge of spatial or temporal variations, and heterogeneities that have not been detected during data collection. Parameter uncertainties can be evaluated by stochastic simulations see e.g. Dagan (1982), or geostatistically where simulated spatial distributions are fitted to the data, see e.g. Glasgow et al. (2003). From a large number of realizations, the uncertainty in the model predictions based on the parameter uncertainties can then be evaluated from cumulative probability distribution functions of the model results. One tool that will be evaluated to improve this module is The Model-Independent Parameter Estimator Estimation and Uncertainty Analysis – PEST (Doherty et al., 2010), in combination with MODFLOW for evaluation on model-parameters and predictive uncertainty.

6. Module 3 – Probabilistic Subsidence Model

The first two models are necessary for describing the location and magnitude of compressible sediments and the additional action - groundwater drawdown - which drives the subsidence process. In the third module, the subsidence is calculated in a probabilistic model.

Since a groundwater drawdown from a long tunnel can cover a large area, potentially square kilometres, methods able to perform probabilistic calculations with reasonable calculation time are necessary. It is not expected that very complex methods, such as three dimensional finite element methods, can fulfil this aim.

On the case-study of the soil-layer model in Stockholm, a common Swedish analytical calculation method (Sällfors, 2001) has been adjusted for making it possible to conduct probabilistic calculations. The calculation method is based on evaluation results from Constant Rate of Strain (CRS) tests (Larsson & Ahnberg, 2005) on soil samples. 79 samples from 38 locations were evaluated in the case-study. Before assigning probability density functions (pdf) of the parameters for the simulation, it was investigated with variogram analysis and ANOVA if any correlation exist in space, to interpreted geology or to urbanization rate. Since no such correlations were found (Ramm & Collinder, 2014), all sampling points were used for assigning pdf for every calculation point.

When the pdf of the parameters were obtained, a MC-simulation for the subsidence calculations was carried out simultaneously with the simulations for the soil layer model. No probabilistic groundwater model was implemented for the case study, instead, groundwater drawdowns of 0.5, 1 and 2 meters were used for describing the additional action. For each iteration at every calculation point a soil profile was first simulated, then the compression parameters were simulated and the ground subsidence calculated. This process was repeated for 1000 iterations at about 800,000 calculation points.

With the obtained calculation result, a risk map of where a groundwater drawdown could be expected to cause subsidence was created. The risk area was defined as calculation points were the 95th percentile of the simulations increases two centimetre subsidence.

In order to improve this module a more advanced one-dimensional finite difference model that considers creep is planned for. Moreover, the model is planned to be calibrated with history matching to subsidence observations. In many urban areas, it is common that relatively dense subsidence observations exist. In the cities Stockholm and Göteborg there are thousands of subsidence recording points. With history matching, it is expected that pdf for soil parameters that are valid for local areas could be found. This approach is expected to both reduce model and parameter uncertainties. Further, the module is planned to be improved by not being ended with an absolute number for what is an acceptable subsidence but by generating a pdf for land subsidence that in Module 4 will be combined with the sensitivity and economic value of the potential damage of the constructions founded on the clay in order to estimate the risk.

7. Module 4 – Risk Estimation

The probabilities estimated in Modules 1-3 are combined to a resulting pdf for land subsidence. In the simplest case, this pdf, f_s, is combined with a cost function representing the economic consequences of a subsidence, C_s. The risk of subsidence is then given by a summation based upon a traditional definition of economic risk:

$$R_s = \int C_s f_s ds \tag{1}$$

The economic consequences will primarily be based on avoidance costs, valued as restoration costs due to damages. The economic consequences are monetized following standard valuation procedures, see e.g. Hanley & Barbier (2009).

8. Module 5 - Risk Evaluation

The type of investigation or measure to be realized in a certain part of the area will be evaluated by means of Value of Information Analysis (VOIA) where the costs for collecting new information is weighted against the benefits of reduced risk of choosing an inappropriate alternative to control land subsidence. The result of the VOIA is – from an economic perspective - a selection of the most appropriate information collection alternative and safety measure to control land subsidence.

As described by e.g. Back (2006) VOIA is an approach for estimating the value of different data collection programs based on cost-benefit analysis (CBA) (IT-Corporation, 1997; McNulty et al., 1997). VOIA has been applied to geo-environmental problems since the beginning of the 1970s. The basic idea of VOIA is simple: the value of additional information is the change in expected total cost (or benefit) caused by the new information. In the present project the main benefit is defined as the reduced economic risk of inappropriate decisions.

A *prior analysis* is based on the present state of knowledge and results in an estimation of the net present value, Φ_{prior}:

$$\Phi_{prior\,i} = \sum_{t=0}^{T} \frac{1}{(1+r)^t} [B_i(t) - C_i(t)] \tag{2}$$

where B represents the expected deterministic and probabilistic benefits [monetary unit], i.e. the reduced risk, and C is the expected deterministic and probabilistic costs [monetary unit] of alternative *i,* representing e.g. alternative designs for controlling land subsidence. T is the time horizon [for years t] and r is the discount rate. The subsequent *preposterior* analysis is performed similarly, but is based on the information that is expected from the data collection program. This implies that the analysis is performed *after* (‘posterior’) the data collection program has been defined, but *before* (‘pre’) the data collection has taken place, and it results in a value of the preposterior objective function $\Phi_{preposterior}$. In the third step, the Expected Value of Information (EVI) is calculated:

$$\mathrm{EVI} = \Phi_{preposterior} - \Phi_{prior} \tag{3}$$

The benefit (B) of the new information is equal to the reduced economic risks of not choosing the appropriate design alternative (see above). There is only a value of information if the investigation has the potential to change the decision on e.g. what design to use for controlling land subsidence. Note that the EVI does not consider the data collection cost C_p. To do so, the Expected Net Value (ENV) is calculated:

$$\mathrm{ENV} = \mathrm{EVI} - C_p \tag{4}$$

9. Conclusion

This paper presents a novel framework for how the risk of groundwater drawdown induced subsidence can be assessed. Compared to existing methods known to the authors, the entire drawdown – subsidence – damage chain is considered more comprehensively here. Only by considering the entire process, the most appropriate information collection alternative and safety measure to control land subsidence can be selected. This paper outlines a work in progress and the major challenges of the subsequent work are (1) to adapt and couple the different models into a model-chain that is practically applicable and at the same time provide sufficiently accurate results; (2) to develop a step-wise procedure for quantification of the input variables to the VOIA (e.g. the reliability of information collection methods), and (3) to value consequence costs to properly reflect actual societal costs, including stakeholder preferences, of land subsidence.

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