CHALMERS
UNIVERSITY OF TECHNOLOGY

Comparison of Modelling Strategies for Ground Settlements due to Groundwater Drawdown

Multi-criteria analysis for comparison of three software packages

Master’s thesis in Infrastructure and Environmental Engineering

LINNEA JOHANSSON
FRIDA ÖGGER

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis 2021

Comparison of Modelling Strategies for Ground Settlements due to Groundwater Drawdown

Multi-criteria analysis for comparison of three software packages

LINNEA JOHANSSON
FRIDA ÖGGER

Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Geotechnics Research Group
Chalmers University of Technology
Gothenburg, Sweden 2021

Comparison of Modelling Strategies for Ground Settlements due to Groundwater Drawdown
Multi-criteria analysis for comparison of three software packages
LINNEA JOHANSSON
FRIDA ÖGGER

Supervisors: Linn Ödlund Eriksson, Sweco
Ezra Haaf, Department of Architecture and Civil Engineering
Pierre Wikby, Department of Architecture and Civil Engineering
Ayman Abed, Department of Architecture and Civil Engineering
Examiner: Lars Rosén, Department of Architecture and Civil Engineering

Master's Thesis 2021
Department of Architecture and Civil Engineering
Division of Geology and Geotechnics
Geotechnics Research Group
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

Comparison of Modelling Strategies for Ground Settlements due to Groundwater Drawdown
Multi-criteria analysis for comparison of three software packages
LINNEA JOHANSSON
FRIDA ÖGGER
Department of Architecture and Civil Engineering
Chalmers University of Technology

Abstract

When performing construction projects below the groundwater level, groundwater leakage into the construction can occur, which can lead to settlements. This Master's thesis aims at comparing three different software packages for calculation of settlements caused by groundwater drawdown in an aquifer situated below compressible soils. The different software packages used are: a stochastic settlement model that considers creep effects and parameter uncertainties, the Soft Soil Creep model available in Plaxis 2D and the Chalmers model with creep available in GS Settlement. To evaluate the appropriateness of them, settlement calculations for both 1D and 2D soil models are performed, together with a multi-criteria analysis (MCA).

The 1D modelling results show that all three approaches exhibit the same elastic- and elasto-plastic behaviour. For comparison of the creep behaviour between Plaxis 2D and GS Settlement, differences arise due to model formulations. GS Settlement seems to predict lower creep settlements than Plaxis for stress states around the preconsolidation pressure. For drawdowns that highly exceed the preconsolidation pressure, GS Settlement instead predicts higher settlements compared to Plaxis. The stochastic settlement model does not include creep effects, but the additional deformation is captured by the parameter uncertainty interval for drawdowns near the preconsolidation pressure and higher. When comparing 2D effects of consolidation, the ability for the stochastic settlement model to capture the additional settlements predicted by Plaxis 2D is ambiguous.

The results in this thesis highlight the differences between the three software packages. The MCA shows that the stochastic settlement model has a good capability in handling spatial uncertainties, but is disadvantageous due to the low level of intuition. Plaxis can handle complex geometries, but the calculation is time demanding. GS Settlement is more intuitive with lower calculation effort required, but lacks the ability of performing calculations with complex geometries. The MCA further emphasises that the ability to implement the theoretical framework of a groundwater drawdown together with modelling a drawdown over a large area is considered of high importance. To make it less subjective, further prerequisites which define the features of the project is needed. Hence, this comparison can serve as a support for future projects to achieve a versatile analysis in a structured way.

Keywords: Ground settlements, Groundwater drawdown, Soft clays, Plaxis 2D, GS Settlement, Analytical modelling, Multi-criteria analysis.

Acknowledgements

This Master's Thesis was written at the Division of Geology and Geotechnics at Chalmers University of Technology during the spring semester 2021.

We would like to express our sincere gratitude for the wide-spread commitment and support during this final semester of our studies. Our thanks goes to Ezra Haaf at Chalmers for supervising and guiding us in structuring the work. We would also like to thank Pierre Wikby at Chalmers for his supervision and assistance at every stage of this thesis. Our gratitude extends to our supervisor Ayman Abed at Chalmers for his encouragement and support in the modelling process, and to Linn Ödlund Eriksson at Sweco for her supervision in the project and guidance within the fields of geotechnics and hydrogeology. We are further grateful for the support from our Examiner Lars Rosén at Chalmers, who provided us with knowledge and experiences in the multi-criteria analysis. We would likewise thank Jonas Sundell at the Swedish Transport Administration, for his insightful suggestions in shaping our method and results. At last, we are thankful for the valuable help from the employees at Sweco for sharing their competences.

Linnea Johansson & Frida Ögger
Gothenburg, June 2021

Contents

List of Figures

List of Tables

Nomenclature

Roman letters

a	Regression parameter	[-]
a_0	Constant describing the improved modulus curve	[-]
a_1	Constant describing the improved modulus curve	[-]
b	Regression parameter	[-]
b_0	Factor ≤ 1	[-]
b_1	Factor ≥ 1	[-]
c'_{ref}	Reference cohesion intercept	[kPa]
C_c	Compression index	[%]
C_s	Swelling index	[%]
C_α	Secondary compression index	[%]
E	Young's modulus	[kPa]
e	Void ratio	[-]
e_{init}	Initial void ratio	[-]
h_{init}	Location of the groundwater level for lower aquifer	[m]
h_{new}	Location of the groundwater level after lowering	[m]
k	Permeability	[m/s]
K_0^{nc}	Lateral earth pressure for normally consolidated soils	[-]
k_i	Initial permeability	[m/s]
M	Shape parameter dependent on K_0^{nc}	[-]
m'	Modulus number at stress levels above the limit stress	[-]
M^*	Parameter related to the aspect ratio of the ellipsoid	[-]
M_0	Compression modulus for $\sigma'_v \leq \sigma'_c$	[kN/m^2]
M_L	Compression modulus for $\sigma'_c \leq \sigma'_v \leq \sigma'_L$	[kN/m^2]
p'	Mean effective stress	[kPa]
r	Creep parameter	[-]
R^2	Coefficient of determination in statistics	[-]
r_s	Time resistance number	[-]
t_{ref}	Reference time	[days]
u	Pore water pressure	[kPa]
w_n	Natural water content	[%]

Greek letters

α_s	Creep parameter or secondary compression index	[-]
$\alpha_{s(max)}$	Coefficient of secondary compression at the apparent preconsolidation pressure	[-]
β_{α_s}	Coefficient of change in coefficient of secondary compression with compression	[-]
β_k	Coefficient of change in permeability with compression	[-]
γ	Unit weight	[kN/m^3]
γ_w	Unit weight of water	[kN/m^3]
γ_{sat}	Saturated unit weight	[kN/m^3]
γ_{unsat}	Unsaturated unit weight	[kN/m^3]
κ^*	Modified swelling index	[-]
λ^*	Modified compression index	[-]
μ	Mean value	[-]
μ^*	Modified creep index	[-]
ν'_{ur}	Poisson's ratio for unloading and reloading	[-]
ϕ'	Friction angle	[°]
ψ	Dilatation angle	[°]
ρ	Density	[kg/m^3]
σ	Standard deviation	[-]
σ	Total normal stress	[kPa]
σ'	Effective stress	[kPa]
σ'_c	Preconsolidation stress	[kPa]
σ'_L	Limit effective stress where the modulus curve begins to increase	[kPa]
σ'_v	Effective vertical stress	[kPa]
σ'_{vc}	Vertical preconsolidation stress	[kPa]
σ_t	Tensile strength	[kPa]
τ_{fu}	Undrained shear strength from vane test	[kPa]
ε_p	Volumetric strain	[%]

Abbreviations

CRS Constant rate of strain
FEM Finite element method
MCA Multi-criteria analysis
OCR Overconsolidation ratio
SGU Geological Survey of Sweden
SS Soft Soil
SSC Soft Soil Creep

1

Introduction

1.1 Background

During underground construction projects, there is a risk of leakage of the groundwater into the construction. If the construction work has to be performed in a dry environment, the water must be pumped or prevented from leaking in. In areas with soft soils, this might lead to settlements, which cause damages on structures and consequently, high costs. The magnitude of a damage depends on the size and duration of the groundwater drawdown, the geotechnical conditions and the sensitivity of the damaged object (Merisalu et al., 2020). The full process of how risk of damages arises due to leakage into underground construction is explained by Sundell et al. (2015). The cause-effect chain is presented in Figure 1.1.

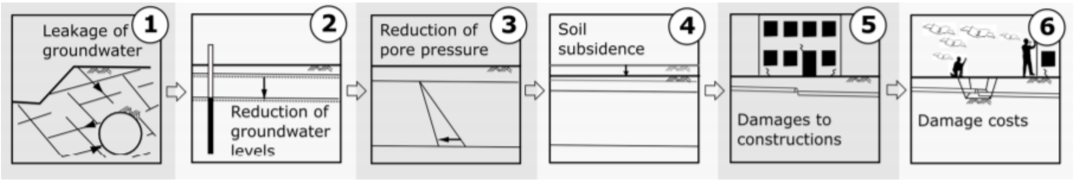


Figure 1.1: Cause-effect chain from leakage to damage (Sundell, 2018). Adapted with permission.

To quantify the risks, it is vital to have a well-functioning tool for prediction of settlements caused by changes in groundwater conditions. Today, analytical and numerical models have been extensively used in both research and by industry professionals in Sweden to perform settlement calculations due to groundwater drawdown. Material models and mathematical programs have been developed continuously but there is a lack of studies that compare their appropriateness for estimating settlements due to changes in groundwater conditions. This could potentially meet a need to further interlink hydrogeological and geotechnical competences. Depending on the context of the underground construction project, it possesses varying prerequisites. This entails that different computational alternatives can be better suitable in different projects. To address this problem, a multi-criteria analysis together with a comparison of settlement prediction between the alternatives can be performed to obtain a comprehensive and structured comparison of models. This could further serve as a support in a risk assessment framework not to underestimate the risk and cause harm to the environment or not overestimate it and take too many precautions. A more precise prediction might reduce material use, which is beneficial both from an environmental as well as an economical point of view.

1.2 Aims and objectives

The purpose of this Master's thesis is to compare three different computational tools based on how suitable they are in predicting settlements caused by a groundwater drawdown in the lower aquifer. This will be achieved partly with a literature study to clarify the basic theories for how settlements are caused by groundwater drawdowns, partly with a multi-criteria analysis for a structured comparison of the performance of computational tools available. The first software package that is studied and practised is a statistical settlement model, which considers parameter uncertainties. It is part of a risk assessment framework developed by Sundell et al. (2019a) and has been supplemented with a creep model by Wikby and Andersson (2020). The next two software packages are Plaxis 2D with the Soft Soil Creep model and GS Settlement with the Chalmers with Creep model. The analysis will be achieved by setting up representative and comparable soil models inspired by the site characteristics of the Haga passage, which is a part of the West Link project in Gothenburg.

1.3 Limitations

The study is limited to examine the effect of pressure change in a lower groundwater aquifer situated below a layer of compressible soils. Furthermore, settlement is only examined for cohesive soils in the form of clay. The deformation in the fill and frictional soil layers situated above and below the cohesive clay soils will in this case be considered negligible. The study covers the entire settlement process; both consolidation and creep to best represent reality. A delimitation is made to evaluate normal to slightly overconsolidated clays, which is typical for clays at the Swedish west coast. The study will use a set of predefined drawdowns in the lower aquifer and implement them in the three computational alternatives for settlement prediction. Hence it is limited to not predict the magnitude of the drawdowns. Lastly, the whole cause-effect chain is not considered - it only covers the parts that processes 'reduction of groundwater levels' to 'soil subsidence', shown in Figure 1.1.

1.4 Research questions

The following research questions are to be answered in this thesis:

- How does the pore pressure profile in the clay change when the groundwater pressure head is lowered in the lower aquifer?
- What is required to perform modelling of groundwater induced subsidence in the stochastic settlement model, Plaxis 2D and GS Settlement?
- How do the stochastic settlement model, Plaxis 2D and GS Settlement perform when modelling coupled hydrogeological and geotechnical problems and how does their appropriateness differ depending on the scenario observed?

2

Theoretical background

2.1 Groundwater conditions

Groundwater fills up voids in underground permeable materials. The upper bound of the groundwater zone is referred to as the water table (Winter et al., 1999), and can be detected at different levels depending on confined or unconfined conditions (SGU, 2019). An unconfined groundwater aquifer is in direct contact with the atmospheric pressure while confined conditions implies that the water zone is fully saturated and overlaid by a low permeable soil layer, such as clay, called aquitard (Carlsson & Gustafsson, 1984). The aquitard enables the confined aquifer to have a pressure level above its upper boundary. This level is referred to as pressure head. A conceptual model that shows a soil section with the upper and lower aquifers is presented in Figure 2.1.

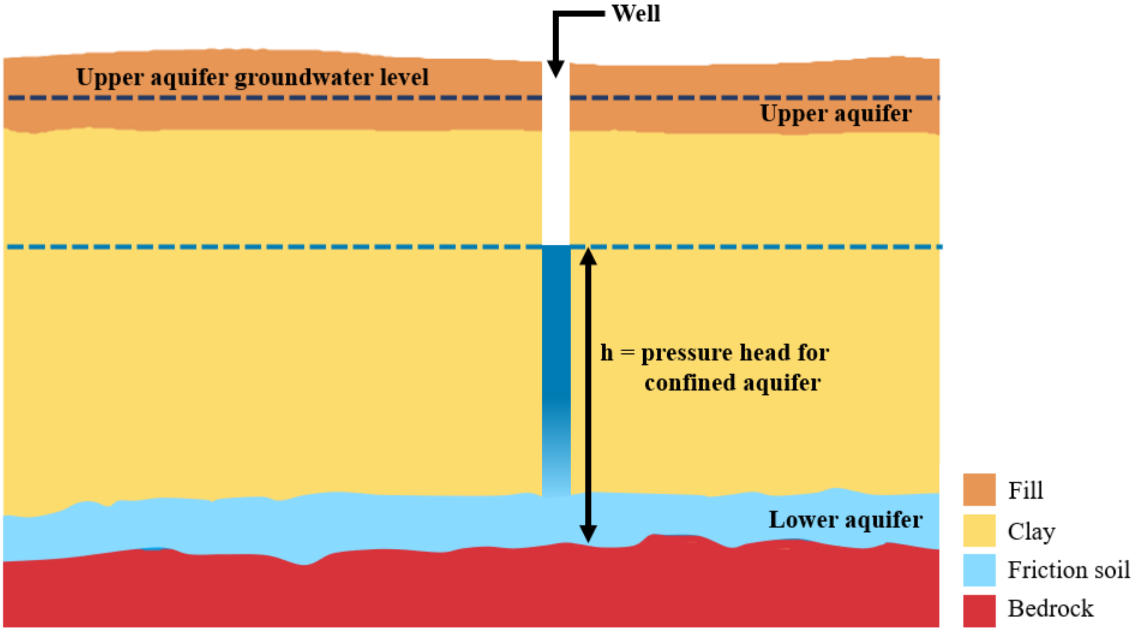


Figure 2.1: Schematic model of a soil profile illustrating the upper and lower aquifer.

The flow of groundwater is complex due to heterogeneity of the soil structure. The rate of flow is governed by the type of soil and its hydraulic conductivity together with the difference in pressure head, known as the hydraulic gradient. This phenomenon can be explained by Darcy's law, where the rate of water flow through a known medium is proportional to the difference in height of the water and inversely proportional to the length of the flow path (Fetter, 2014).

2.2 Stresses in soils

A soil structure can be interpreted as a skeleton made up of solid particles that surrounds continuous voids filled with water and/or air. The volume of the soil can change because of rearrangement of the soil particles, which will lead to transmission of stresses between the particles. For fully saturated soils the stresses can be explained by the principle of effective stress which was introduced primarily by Terzaghi (1923). It provides a relationship by three different stresses; total normal stress σ acting on a plane, pore pressure u that fills up the voids and effective normal stress σ' which is the stress that represent the interparticle forces. The relationship is $\sigma' = \sigma - u$ (Knappett & Craig, 2012).

2.3 Consolidation and creep

The process of when a fully saturated soil with low permeability undergoes a change in volume because of change in effective stress is called consolidation. There are a plethora of studies and literature describing the way in which soft soils behave during compression and consolidation and how it can be modelled. One of many theories is the one provided by Terzaghi that encompasses a one-dimensional consolidation process (Olsson, 2010), and is explained in more detail by for instance Knappett and Craig (2012) and Sällfors (2013).

Consolidation occurs due to increase in effective stress and generation of excess pore pressure of the same magnitude as the applied load. This generation of excess pore pressure can for example be caused by a reduction of the pressure head. Over time, difference in excess pore water between different pressure zones will cause a flow of pore water in order to approach equilibrium. Subsequently, the soil will experience a compression. The compression behaviour of a soil is strongly linked to its stress history. If the present effective stress in a soil is the largest that the soil has experienced, it is said to be normally consolidated. An overconsolidated soil, on the other hand, has been exposed to higher stresses in the past. The term overconsolidation ratio (OCR) is used to classify whether a soil is normally consolidated or over consolidated. It is expressed as the ratio between the maximum stress that the soil has been subjected to, known as the preconsolidation pressure, and the current stress state (Knappett & Craig, 2012).

After the dissipation of the excess pore pressure there is still a possibility for the soil to deform but at a slower pace, referred to as secondary compression or creep (Sällfors, 2013). While primary consolidation is controlled by the dissipation of excess pore pressure and Darcy's law, secondary compression or creep is instead controlled by soil viscosity (Leroueil, 2006). It is defined as a time dependent decrease in volume during a constant stress. According to Larsson (2008) the separation of primary and secondary could be considered as imaginary, since the secondary compression is present during primary compression as well. If the current stress state constitutes 80 percent of the preconsolidation pressure, there is reason to consider creep (Larsson, 1986). Creep is generally characterized by the slope of the primary consolidation curve when plotting strain over time and the most common form of it is expressed in terms of strain or void ratio (Olsson, 2010). The creep can be described by various parameters depending on the constitutive model, further explained in Section 2.5.

2.4 Influence of groundwater drawdown

Variations of pressure heads in the upper and lower aquifers can depend on several factors, for instance disturbance of the water balance due to man made interventions such as hardened surfaces, drainage or artificial infiltration (Berntson, 1983). Control of groundwater can be achieved through either techniques that aims at prevent groundwater from entering excavations, for instance a cutoff wall or barrier, referred to as *exclusion*, or techniques that monitors groundwater by pumping from a well, referred to as *dewatering* (Cashman et al., 2012). Exclusion methods are mostly used instead of dewatering in urban areas, to reduce risk of settlements. However, the idea of having a perfectly impermeable cutoff barrier is difficult to achieve and hence, one needs to assume that some water will leak into the excavation, causing pressure levels to be lowered in the surrounding area.

When the water is extracted from a confined aquifer it will result in a reduction in pressure head which extends radially (Thiem, 1906). Regardless if the well constitutes a physical well as in dewatering, or an excavation as in the case of exclusion (when water leaks), the water table adjacent to the well will appear as a downward cone known as the cone of depression. How much the surrounding clay will be affected depends on the magnitude of drawdown in the confined aquifer as well as the properties of the clay materials (Carlsson & Gustafsson, 1984). Therefore, when the confined aquifer is subjected to a pressure decrease, it will generate various degrees of drawdown. The area that will experience a decrease in pressure head is also referred to as the influence area.

Reduction in pressure head will cause an immediate compression in the aquifer material while in clay, the deviation from the stable hydrostatic pressure will give a downward flow in the clay layer over time. Carlsson and Gustafsson (1984) explains this as leaking which can happen due to a drawdown of the pressure head in a confined aquifer. The aquitard will continue to drain until equilibrium, i.e. hydrostatic pressure, is reached. Since clays compress at a slower pace than coarse grained materials it will cause delayed compression (Cashman et al., 2012). If the thickness of the clay is relatively large it can take up to decades until this process is completed (Broms et al., 1976). Berntson (1983) conducted several tests on west swedish clays and found that for a 10 meter clay subjected to a pressure increase- or decrease of 15 kPa in the lower boundaries, it could show evidence of the pressure effecting the whole profile after a time period of 3 months. If the same pressure decrease was performed for a 20 meter thick clay, in the same time period some parts of the pore pressure will remain unaffected. Based on studies made by Blomén (2017) on several measurements, a typical soil profile can be assumed to have a 5 meter thick upper part where the pore pressure is not affected by drawdown in the lower aquifer.

2.5 Constitutive models

In analysing of soil behaviour there is a need for a constitutive model that links the states of stress and strain (Runesson, 2006). In the following section, the constitutive models used in this thesis are presented.

2.5.1 Soft Soil and Soft Soil Creep model

The Soft Soil Creep (SSC) model is a material model available in the Plaxis finite element software. Its outline is a further extension of the Soft Soil model which in turn is based on slightly similar principles as the Modified Cam Clay model, further explained in the Plaxis (2019) manual, since it treats primary loading and unloading/reloading differently. The distinction is made using a cap in the shape of an ellipsoid in the stress space. The cap represents the limit stress state that differentiates between unloading/reloading and primary loading. This boundary originally depends on the preconsolidation stress, but for the SSC model it is also time dependent (Waterman & Broere, 2004). Its full mathematical background can be found in the manuals provided by Plaxis (2019).

One of the apparent modifications made in the SSC model is the decoupling of M^* from the failure line. M^* does not relate to any kind of the critical state which formerly was the case of the Modified Cam Clay model. Instead it relates to the coefficient of lateral earth pressure at rest for normally consolidated soils, K_0^{nc}. M^* is then determined automatically by Plaxis once K_0^{nc} is entered if the friction angle is known. The modifications of the yield surface leads to the failure condition having to be imposed separately with a Mohr-Coulomb failure criterion (Amavasai & Karstunen, 2017). Therefore, it is also possible to assign an effective cohesion intercept and a friction angle, Plaxis manual (2019) recommends the critical state friction angle. To avoid traction, tension cut-off is implemented.

The different modes of loading in the SSC model is explained by the modified compression index λ^* and modified swelling index κ^* which is determined in a semi-log scale. It can be linked to the compression and swelling indexes C_c and C_s as explained by Amavasai and Karstunen (2017). Olsson (2010) brings up another approach for evaluation of λ^* and κ^*, where they instead are related to the oedometer modulus M_0 and M_L by the following expressions:

$$\lambda^* = \frac{1.1 \cdot \sigma'_{vc}}{M_L} \tag{2.1}$$

$$\kappa^* \approx \frac{2 \cdot \sigma'_v}{M_0} \tag{2.2}$$

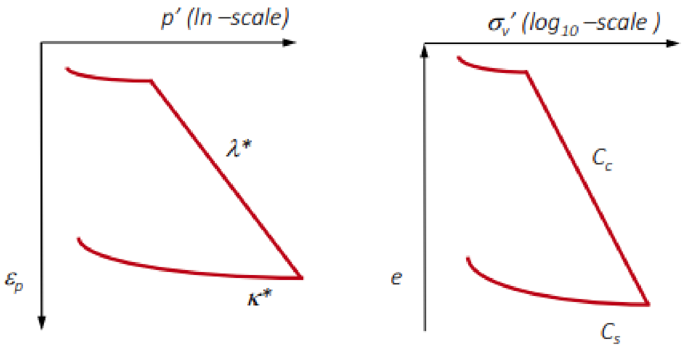


Figure 2.2: Definition of the compression and swelling index $\kappa^*$and λ^* (Amavasai & Karstunen, 2017). Reprinted with permission.

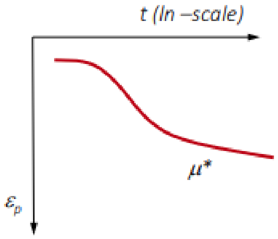


Figure 2.3: Definition of the creep index μ^* (Amavasai & Karstunen, 2017). Reprinted with permission.

The creep part of the model is explained by the creep index, μ^* and creep is assumed in both the normally consolidated region as well as the overconsolidated region (Amavasai & Karstunen, 2017). The parameter μ^* can be related to the one-dimensional creep index C_α (Plaxis, 2019) which can be determined empirically if water content is known by using values from Larsson (1997). Then it can be estimated by the following relationship proposed by Olsson (2010):

$$\mu^* = \frac{\alpha_s}{2.3} \tag{2.3}$$

Table 2.1: Basic parameters of the Soft Soil Creep model (Plaxis, 2019).

Parameter	Description	Unit
λ^*	Modified compression index	-
κ^*	Modified swelling index	-
c'_{ref}	Effective cohesion	kN/m^2
ϕ'	Friction angle	°
ψ	Dilatancy angle	°
σ_t	Tensile strength	kN/m^2
ν'_{ur}	Poisson's ratio for unloading and reloading	-
K_0^{nc}	Coefficient of lateral earth pressure for normally consolidated soils	-
M	Shape parameter dependent on K_0^{nc}	-

2.5.2 Chalmers model with and without creep

The Chalmers model is used for settlement calculation of fine grained soils such as clay and silt (Novapoint, 2021b). The model is implemented in GS Settlement, and can be applied both with and without creep.

Alén (1998) developed a model which is based on the hypothesis that the time dependent deformation in clay can be described by the three different phenomena: consolidation, elastic/plastic deformation and creep deformation. The consolidation process is dependent of the permeability k of the soil, the elastic/plastic deformation is governed by the compression modulus M and the creep deformation depends on the creep parameter r. The model of Alén was further developed by Claesson (2003), who improved the compression modules and the creep number. The improvement makes the calculation result less sensitive to small variations in the applied load for values close to the preconsolidation, shown in Figure 2.4. The parameters a_0 and a_1 are set to 0.9 and 1.1 respectively when modelling IL oedometer tests, and 0.8 and 1.0 respectively when calculating settlements for full-scale conditions, since the strain rates during primary consolidation are higher for IL oedometer tests than for thick soil layers in field (Claesson, 2003). M_0 and M_L can either be evaluated through a conventional oedometer test or through empiricism as explained by Olsson (2010).

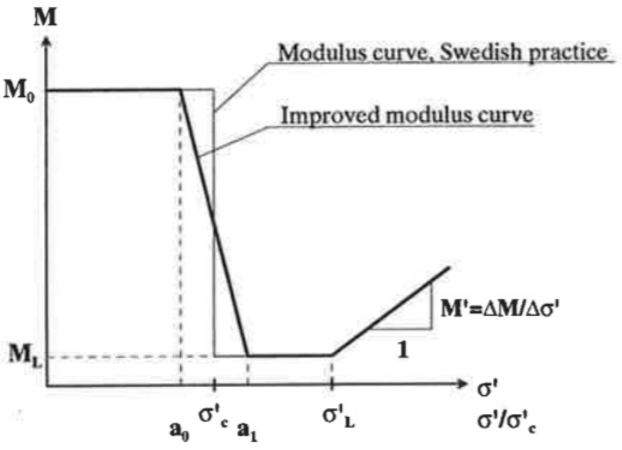


Figure 2.4: Swedish practice of modulus curve and the improved curve proposed by Claesson (2003). Reprinted with permission.

Claesson (2003) refers to the creep parameter r as the time resistance number r_s, defined as the inverse of α_s. The parameters r_0 and r_1 are shown in Figure 2.5 with the corresponding b_0 and b_1 values. b_0 is evaluated from the relationship between the in-situ stress and the preconsolidation pressure, which is the inverse of OCR, leading to $b_0 \leq 1$. The parameter b_1 is relevant for describing the creep behaviour when modelling both IL and full-scale conditions (Claesson, 2003). The creep resistance is generally very large in the overconsolidated range and falls markedly when the effective stress reaches the preconsolidation pressure. After the preconsolidation pressure is reached, the creep resistance increases almost insignificantly (Havel, 2004).

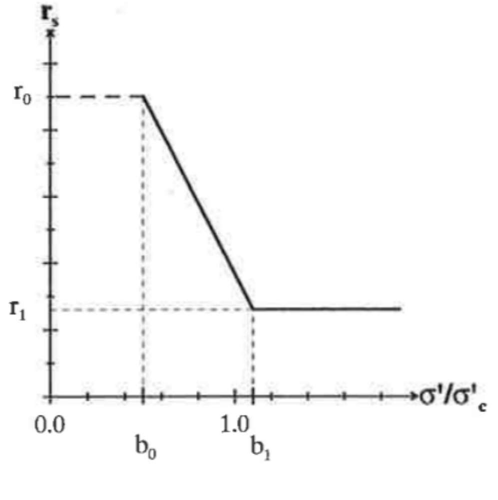


Figure 2.5: The time resistance number model (Claesson, 2003). Reprinted with permission.

The permeability parameters in the Chalmers model is k_{init} and β_k where, according to Larsson et al. (1997), k_{init} is the initial (natural) permeability and β_k is the coefficient of change in permeability with compression. All parameters used in the Chalmers model without creep (Novapoint, 2021b) are presented in Table 2.2 below.

The same parameters are used for the Chalmers model with creep, in addition to the parameters in Table 2.3.

Table 2.2: Parameters of the Chalmers model without creep (Novapoint, 2021b).

Parameter	**Description**	**Unit**
Soil weight	Total unit weight of soil	kN/m^2
M_0	Oedometer modulus for stresses below $a_0\sigma'_c$	kN/m^2
M_L	Oedometer modulus at stresses between $a_1\sigma'_c$ and σ'_L	kN/m^2
m'	Modulus number at stress levels above σ'_L	-
a_0	Factor ≤ 1	-
a_1	Factor ≥ 1	-
σ'_c	Preconsolidation stress	kN/m^2
σ'_L	Above σ'_L the modulus increases with increasing stress	kN/m^2
k_{init}	Permeability at initial conditions prior to loading	kN/m^2
β_k	Permeability reduction coefficient	-

Table 2.3: Additional parameters for the Chalmers model with creep (Novapoint, 2021b).

Parameter	**Description**	**Unit**
t_{ref}	Reference time; often 1 day	years
b_0	Factor ≤ 1	-
b_1	Factor ≥ 1	-
r_0	Time resistance at $b_0\sigma'_c$	-
r_1	Time resistance at $b_1\sigma'_c$	-

2.5.3 Analytical model with a probabilistic assessment of uncertainties

The stochastic settlement model implemented as a code in the Matlab software is an analytical way of predicting settlement. It is part of a framework developed in a study by Sundell et al. (2019a) and further explained by Sundell et al. (2019b). The framework serves as a tool for evaluating and quantifying risks related to settlement from groundwater drawdown and comprises partly of a stochastic settlement model. The outcome of the study provided a probabilistic assessment of subsidence prediction with a spatial distribution. This was achieved through a Monte Carlo analysis, which is a method that involves random numbers in a calculation that has the structure of a stochastic process (Hammersley & Handscomb, 1964). Within geotechnics, the stochastic input parameters could be e.g. compression modules and creep parameters, which are simulated in order to obtain numerous scenarios of ground settlement.

The model implemented by Sundell et al. (2019a) and (2019b) is elasto-plastic and as a further development, Andersson and Wikby (2020) supplemented the model to also consider long-term settlements by incorporating creep effects. The code developed by Andersson and Wikby (2020) assumes drainage at both boundaries, which can be considered unrepresentative in the case of a pressure decrease in the lower aquifer. To better describe the consolidation process, Xie et al. (2012) took into account one-sided drainage which only allowed the water to drain at the lower boundary.

The settlement prediction in the code is accomplished by using the Embankco model as a frame model implented in the programming tool Matlab. Embankco is a finite difference computer program for long term settlements in soft soil. It was developed by Université Laval and Swedish Geotechnical Institute, in commission of the Swedish National Road Administration (Larsson, 1986). The main purpose was to provide a calculation program for settlements in fine grained soils due to additional loading from embankments (Larsson et al., 1997). The time dependent consolidation process in Embankco is built upon the classical theory of consolidation explained by Larsson and Sällfors (1986). It has a with further re-adjustment of the pore pressure caused by the effects of creep (Alén, 1998).

To further reduce the uncertainties, a statistical analysis is made that determines which parameters that reveals a strong vertical trend towards depth and parameter dependency. The methodology used for determination of dependency among parameters is further described by Sundell et. al (2019b) and in Section 3.2.1. The parameters used are described in Table 2.4. Compressibility parameters can be obtained from oedometer tests according to Swedish standards or approximated through empirical relationships (Larsson et al., 1997). Creep parameters can either be evaluated from IL oedometer tests, or empirically based on the specific soil type and natural water content w_n.

Table 2.4: Parameters for the analytical model with a probabilistic assessment of parameters (Larsson et al., 1997).

Parameter	**Description**	**Unit**
Soil weight	Total unit weight of soil	kN/m^2
M_0	Oedometer modulus for stresses below σ'_c	kN/m^2
M_L	Oedometer modulus at stresses between σ'_c and σ'_L	kN/m^2
m'	Modulus number at stress levels above σ'_L	-
σ'_c	Preconsolidation stress	kN/m^2
σ'_L	Above σ'_L the modulus increases with increasing stress	kN/m^2
w_n	Water content	-
k_{init}	Permeability at initial conditions prior to loading	kN/m^2
β_k	Permeability reduction coefficient	-
$\alpha_{s(max)}$	Creep index at the apparent preconsolidation pressure	-
β_{α_s}	Change in coefficient of secondary compression in normally consolidated settings with compression	-

2.6 Computational tools

The following subchapters describes the three different computational tools, used in this thesis, that are available for modelling.

2.6.1 Stochastic settlement model

The stochastic settlement model is implemented in the programming software Matlab. Its outline is described in Section 2.5.3.

2.6.2 Plaxis 2D

Plaxis is a software for finite element analysis of deformations, stability and groundwater flow in geotechnical engineering (Plaxis, 2019). It uses numerical methods, which are highly suitable for solving complex geotechnical problems by using mathematical models to describe the behaviour of the soil. It is, however, often problematic to obtain a direct solution to the models and therefore the finite element method (FEM) can be used to approximate a solution. The main idea behind FEM is the division of a continuum into elements delimited by nodes. Each node can have various degrees of freedom that relates to discrete values of the unknowns in the boundary value problem to be solved.

The software has different packages and the one used for this thesis is Plaxis 2D (Plaxis, 2020). For simplicity, Plaxis 2D will be further referred to as Plaxis in this thesis. When modelling the soil behaviour, a constitutive model should be determined, i.e. Soft Soil or Soft Soil Creep, which are described in Section 2.5.1. The model can be divided into different soil layers with varying input parameter data and flow conditions. Pressure levels can be assigned for the whole model or for the different soil layers. Regarding the finite element mesh, different sizes of the mesh can be implemented when modelling, and it can be chosen between 6-node or 15-node triangular elements. The 6-node triangle gives a second order interpolation for displacements, whether 15 nodes provides a fourth order interpolation. When a node becomes active, an initial displacement is estimated through a stressless predeformation of the recently activated element so that it fits the deformed mesh from the previous step (Plaxis, 2020). The results of the final structure can be shown in a figure of the model or in charts as e.g. total displacements and excess pore pressure.

2.6.3 GS Settlement

GS Settlement (in this thesis further referred to as GS) is an application in the GeoSuite Toolbox that is used for time-dependent settlement calculation. The program is based on the general finite element program GEOnac (Olsson, 2010) and it assumes one-dimensional settlement calculations with uniaxial stress and vertical pore water flow. However, a calculation can consist of more than one calculation point, with different x and y coordinates, and can then be assumed as lightweight 'pseudo 3D' (Novapoint, 2021a).

Constitutive models used for the clay are Chalmers without creep and Chalmers with creep, described in Section 2.5.2. In the program different soil layers with varying soil parameters can be inserted. The pressure level is by default at the ground surface and the pore pressure is hydrostatic. This can be changed manually over time by adding new times with other pore pressures. Furthermore different boundary conditions can be assigned for the boundaries between the soil layers (Novapoint, 2021a). On a stress chart tab sheet the stress changes over depth can be shown before calculating. A max time period should be determined for the calculation, and different times and depths can be added as well. The results are shown as graphs where e.g. excess pore pressure and displacements over time or depth can be chosen, and can also be exported to text files for further analyses.

2.7 Multi-criteria analysis

Multi-criteria analysis (MCA) is a tool that describes different objectives in a decision making process and compares the adequacy of the outcomes according to several parameters (Dodgson, Spackman, Pearman, & Phillips, 2009). This means that different criteria in models or methods can be evaluated according to how well they represent reality. When performing an MCA, the objectives must first be identified. The next step is to identify alternatives that may make the objectives achievable. Once the alternatives are defined, it should be determined how to compare their propriety of attaining the objectives. In this step the criteria, which must be measurable and serve as performance measures, are defined. Thereafter the alternatives are analysed with a chosen MCA-technique, e.g. scoring and weighting stages. In scoring, the expected consequences of each alternative gets a certain score for its suitability for the different criteria stated. The scoring can be done according to a global scale, where it is predefined what the high or low score implies. Another method is the use of a local scale, where the alternatives are scored relative to each other by identifying the best performing option and the worst performing option. Weighting defines the relative valuations for each criterion, between the top and the bottom of the scale. A total rate over all the alternatives is stated and the conclusion of which alternative that should be chosen can be made.

3

Method

In the following chapter, the method of this thesis is described in detail. Firstly, the problem was defined and thereafter a literature study was performed to acquire information about the subject. The case study of Haga passage in Gothenburg was chosen, with site description and data analysis presented in Section 3.1. Investigation of the stochastic settlement model, Plaxis and GS was performed and thereafter the modelling process started, further explained in Section 3.2. In parallel with the modelling process, the multi-criteria analysis was performed. The MCA process is described in Section 3.3. A flow chart over the method is presented in Figure 3.1 below, where grey boxes relates to the MCA and white boxes to the modelling process.

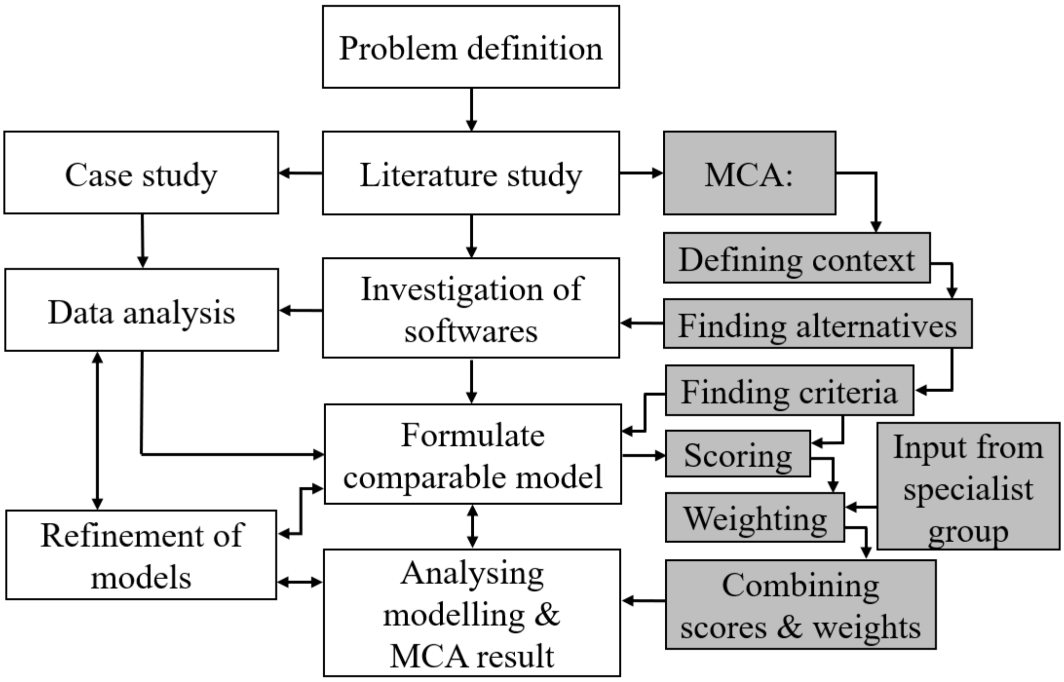


Figure 3.1: Methodology flow chart.

3.1 Case study

To make it possible to carry through the comparison between the different computational alternatives, data retrieved from the surroundings of the Haga passage in the West Link project, has been used. The data has been provided by The Swedish

Transport Administration. Currently, the project is in the construction phase and will consist of an eight kilometers long railway line, of which six kilometers are in tunnel (Swedish Transport Administration, 2018). It should be emphasised that the case study is based on hypothetical scenarios for groundwater drawdown.

In the surrounding area of Haga passage, the topography is varying with a soil stratigraphy consisting of fill, clay, friction material and bedrock. The surface layers over the area are shown in Figure 3.2 where yellow parts imply clay, orange parts imply friction material and red parts imply outcropped bedrock.

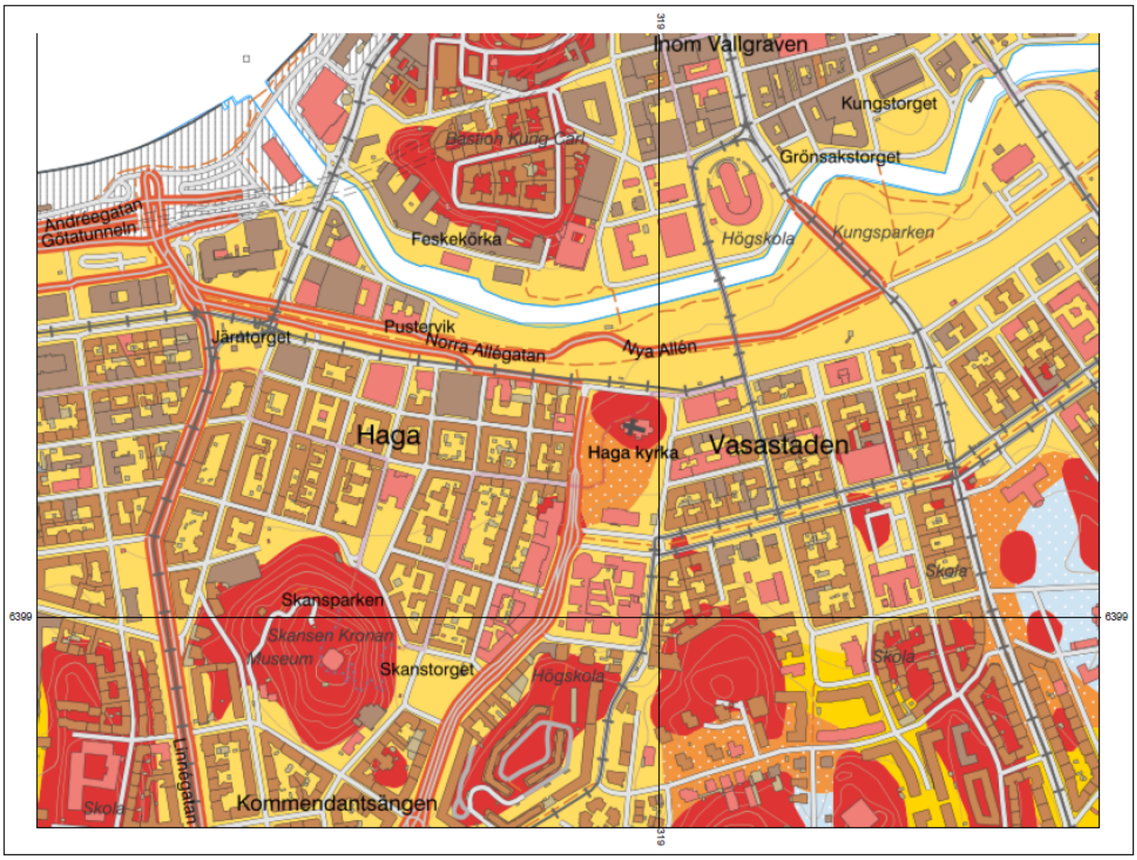


Figure 3.2: Soil type map over the Haga area in Gothenburg, Copyright SGU (2021).

In the northern part of the area, the fill differs between thin layers under areas of vegetation and thicker layers of about 6 to 7 meters where the canal Vallgraven used to be before it was moved. Along some streets in Haga and Vasa the fill under the hardened surfaces consists mainly of gravel with fragments of bricks and is generally 1 to 2 meters thick. The soil layer can be up to 60 meters in the northern part of the area, but generally decreases to the south, with a thickness of 2 to 4 meters by the church of Haga. Moreover, segments of outcropping bedrock exist in the southern part. Since there is a large variability in the soil thickness three different soil sections will be used in this thesis, further explained in Section 3.2. Under the clay layer a frictional soil layer of generally 0.5 to 2 meters is present and consists mainly of sand and gravel, followed by bedrock (Högsta & Sanell, 2014). The section chosen for the Haga area is shown in Figure 3.3.

Figure 3.3: Map over the Haga area with the chosen section. Copyright Google Earth (2021).

The clay has a density that increases with the depth. The density in the top clay has a value of approximately 1.6 t/m^3 and remains constant downwards to a level of 21 meter below ground surface. Further down it increases linearly with depth and reaches a density of 1.9 t/m^3 40 meters below ground surface. Regarding the stress history of the soil, it is slightly over-consolidated as many clays in the Gothenburg region. When it comes to the hydrogeological characteristics of the site, the main focus in the case study is put on the properties of the clay. CRS tests have been executed on the clay in the surrounding area of the Haga passage. Based on these tests performed at different depths, the hydraulic conductivity is estimated to range between $3 \cdot 10^{-10}$ m/s to $8 \cdot 10^{-10}$ m/s. For the pressure levels, both the upper and lower aquifer shows a consistent gradient from south towards north, which coincides with the slope of the ground surface.

3.2 Model setup

As mentioned in Section 3.1, data from Haga passage provided by the Swedish Transport Administration was used for the modelling. The soil properties were evaluated from CRS tests and Incremental Loading oedometer tests. It was vital that regardless of computational method, the soil properties remain the same and that they are comparable to each other.

Three different characteristic sections were established. The upper soil profile consists of a 2 meter thick filling layer serving as the upper groundwater aquifer followed by a clay layer of varying thickness. In the bottom, there is frictional soil that serves as the lower aquifer. The thickness of the clay layers varies in the three different sections with 5, 10 and 15 meters. Initial pressure levels have been set equal to the top of the clay layer for both upper and lower aquifer. The initial pore pressure has an hydrostatic increase with depth. For the Plaxis and GS models, it was possible to assign an upper zone that was assumed unaffected by the pressure decrease in the lower aquifer, as explained in Section 2.4. The magnitude of this zone was set to 5 meters for the profiles with 10 and 15 meters of clay, while for the 5 meter model this zone was assumed to make up for one third of the clay layer, i.e. down to a depth of 3.67 meters. The deviation from the assumption of a 5 meter upper aquifer in the 5 meter model had to be made in order to achieve a change in pore pressure in the clay. Otherwise, it would have been completely drained.

The calculation time was set to 30 years since the excess pore pressure requires time to consolidate. The pressure decrease was assumed to be permanent. To better understand how the stress state appears for the sections, stress charts is shown in Figure 3.4. The stress charts are a result of the assumed pressure levels together with the expected unaffected upper zone.

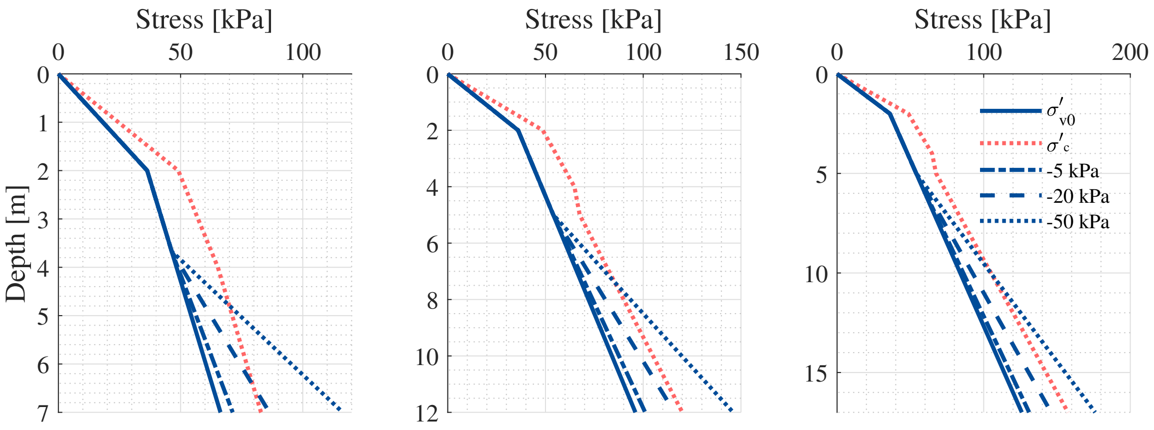


Figure 3.4: Stress chart for 5, 10 and 15 m section with different drawdown scenarios.

To realise the comparison of the three computational tools, the following calculations were made:

1D modelling

- Analysis of waterflow theoretical frameworks

- Analysis of the elasto-plastic behaviour
- Generation and dissipation of excess pore pressure over time
- Generation and dissipation of excess pore pressure with varying drawdowns
- Ground settlements with varying drawdowns
- Ground settlements with varying clay layer thickness
- Influence of upper undisturbed zone

2D modelling

- Ground settlement prediction
- Generation and dissipation of excess pore pressure

3.2.1 Stochastic settlement model

For the subsidence prediction in the stochastic settlement model both one-dimensional (1D) and two-dimensional (2D) cases have been simulated, presented below.

1D model setup in the stochastic settlement model

The geometry in the stochastic settlement model was determined by setting up an input file with the required data. This included the ground level elevation, elevation of top of clay, thickness of fill and clay, location of the pressure level for lower aquifer (h_{init}) as well as location for upper aquifer. The pressure level for the lower aquifer after a decrease in pressure is referred to as h_{new}. The selected geometry for the three different sections are shown in Table 3.1.

Table 3.1: Input parameters describing the soil stratigraphy for the characteristic sections in the 1D case.

Clay thickness [m]	Ground level elevation [m]	Clay top elevation [m]	Fill thickness [m]	h_{init} [m]	Initial gw[1]-level of upper aquifer [m]	h_{new} 5kPa [m]	h_{new} 20kPa [m]	h_{new} 50kPa [m]
5	0	-2	2	-2	-2	-2.5	-4	-7
10	0	-2	2	-2	-2	-2.5	-4	-7
15	0	-2	2	-2	-2	-2.5	-4	-7

[1] Abbreviation for groundwater.

The soil parameters were determined based on statistical analysis from data retrieved from the Swedish Transport Administration, shown in Table 3.2. The outcome of the analysis were the regression variables a and b that are used to describe the function of each soil property. In addition, the mean μ and standard deviation σ were determined. The R^2 value is determined by regression in Excel. For values of $R^2 < 0.05$ there is no vertical trend, and the regression parameters are not taken into account. Dependencies and homoscedastic errors are considered by using ln(OCR-1), $\ln(\sigma'_L/\sigma'_c - 1)$, $\log_{10}(k_i)$ and $\ln(\rho)$. Although σ'_L and M_L reveal a strong linear dependency, they were assumed to be independent in order to not allow the modulus M_0 to fluctuate and instead take a value that matches well with the Plaxis and GS models.

Table 3.2: Soil parameters used in the simulation.

Parameters	$\boldsymbol{a}$	$\boldsymbol{b}$	$\boldsymbol{\mu}$	$\boldsymbol{\sigma}$	$\boldsymbol{R^2}$
ln(OCR-1)	-0.044	-0.928	0.081	0.776	0.274
$\ln(\rho)$	0.004	0.440	-0.007	0.027	0.699
$\log_{10}(k_i)$	-	-	-9.138	0.284	0.054
β_k	-	-	4.136	0.351	-
$\ln(w_N)$	-0.0124	4.3643	0	0.1168	0.613
$\alpha_{s(max)}$	-	-	0.0166	0.0044	0.0036
$\beta_{\alpha_s}/\alpha_{s(max)}$	-	-	0.4326	0.1378	0.049
$\ln((\sigma'_L/\sigma'_c) - 1)$	-0.009	-0.661	0.018	0.374	0.078
$\ln(M_L)$	0.0304	6.379	0	0	0.5848
$\ln((M_0/M_L) - 1)$	-0.010	2.077	0.019	0.361	0.092
$\ln(M')$	0.0099	2.3545	0	0.124	0.419

In order to study the elastic region of the model, the OCR was increased to 3 and the standard deviations were set equal to zero. The rest of the code remained unchanged. Creep was excluded by setting the standard deviations to zero and the creep parameters equal to zero.

2D model setup in the stochastic settlement model

For analysis of the 2D case, the stochastic settlement model was simulated for a list of points corresponding to the chosen cross section in the area of Haga, shown in Figure 3.3. The consolidation behaviour is still 1D, but the alignment of points allows it to be considered as 'pseudo-2D'. The points corresponds to locations with different clay depths. More specific, the thickness of clay ranged from 24 meter to approximately 3 meter and had the same setup as the 2D model analysed in Plaxis for the interfaces between the clay and the friction or fill material. The soil parameters were set as the same as for the 1D model shown in Table 3.2. The selected geometry is shown in Table 3.3.

Table 3.3: Input parameters describing the soil stratigraphy for three characteristic sections in the 2D case.

x[1] [m]	Clay thickness [m]	Ground level elevation [m]	Clay top elevation [m]	Thickness of fill [m]	h_{init} [m]	Initial groundwater level of upper aquifer [m]	h_{new} [m]
340	24.8	4.7	3.2	1.6	3.3	3.5	1.3
350	23.6	4.8	3.2	1.6	3.4	3.8	1.4
360	21.1	4.8	3.3	1.6	3.6	3.9	1.6
370	18.5	5	3.3	1.7	3.8	4.1	1.8
375.3	15.8	5	3.5	1.6	3.8	4.3	1.8
385.1	10.3	5.3	3.9	1.4	4.0	4.5	2
390	8.3	5.6	4.3	1.3	4.1	4.6	2.1
400	6.7	6	4.8	1.2	4.4	4.8	2.4
410	2.6	6.7	6.1	0.6	4.8	5.2	2.8

[1] Distance along the x-axis according to Figure 3.3

3.2.2 Plaxis model

For the modelling in Plaxis, both 1D and 2D cases have been simulated. The 1D scenarios were performed in order to make the results comparable with the 1D modelling in the stochastic settlement model and with GS.

1D model setup in Plaxis

Firstly, a one-dimensional model was considered, with no effects of varying stratigraphy taken into account. Therefore it was simplified to a soil pillar with a width of one meter. The constitutive model was set to SSC, in order to take into account creep effects. In the model setup it was assumed to be a 15 noded elements model and the mesh was set to *very fine*. The three models and their soil layers are shown in Figure 3.5. An upper zone unaffected by the pore pressure decrease in the lower aquifer was created, as explained in Section 3.2. For the 10 meter and 15 meter models this upper zone consists of the first 5 meters from the ground surface, whereas for the 5 meter model the zone was chosen to be one third of the clay layer. The input soil parameters for each soil layer have been evaluated from data provided by the Swedish Transport Administration and are presented in Table 3.4 and Table 3.5.

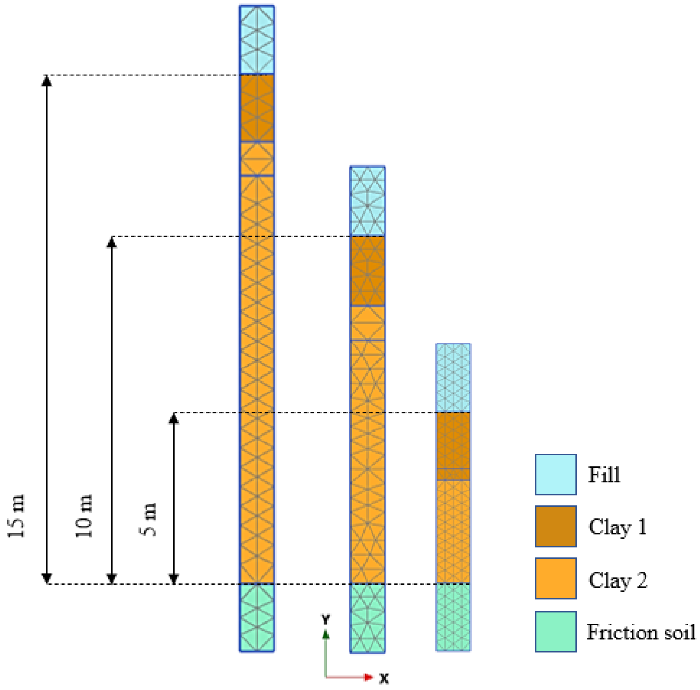


Figure 3.5: 1D models used in Plaxis.

Table 3.4: Clay 1, Soft Soil Creep model.

Parameter	Value	Unit
γ_{sat}	16	$\mathrm{kN/m^3}$
γ_{unsat}	16	$\mathrm{kN/m^3}$
μ^*	0.00571	-
k	$7.3 \cdot 10^{-5}$	m/day
λ^*	0.068	-
κ^*	0.017	-
c'_{ref}	2.2	$\mathrm{kN/m^2}$
ϕ'	30	°
ψ	0	°
ν'_{ur}	0.15	-
K_0^{nc}	0.5	-
M	1.60	-
OCR	1.35	-
e_{init}	1.15	-

Table 3.5: Clay 2, Soft Soil Creep model.

Parameter	Value	Unit
γ_{sat}	16	kN/m^3
γ_{unsat}	16	kN/m^3
λ^*	0.104	-
κ^*	0.024	-
μ^*	0.00571	-
k	$7.1 \cdot 10^{-5}$	m/day
c'_{ref}	2.7	kN/m^2
ϕ'	30	°
ψ	0	°
ν'_{ur}	0.15	-
K_0^{nc}	0.5	-
M	1.61	-
OCR	1.25	-
e_{init}	1.15	-

During the modelling stage, the consolidation analysis type was selected in order to consider excess pore pressure dissipation which leads to consolidation settlements. The two aquifer layers (fill for the upper aquifer and friction soil for lower aquifer) were assigned two different pressure levels, where the initial levels coincided with each other at a level of -2 meters (on top of the clay layer). As stated in Section 3.2, the upper part of the profile was assumed to not being affected by the drawdown. This was achieved by assigning the upper part of the soil with the water level corresponding to the upper aquifer. The drawdown of the lower aquifer was accomplished by creating a new water level at a desired depth and simply assigning it to the friction soil. This was done in a new construction stage with the analysis type consolidation and a given time period, as shown in Table 3.6. The time period was set as the following:

- 7 days for a 5 kPa pressure decrease
- 20 days for a 20 kPa pressure decrease
- 2 months (60 days) for a 50 kPa pressure decrease

In the subsequent construction stage, the new condition was left to consolidate during a time period of 30 years (10950 days). While deformation occurs due to drawdown, there is also creep going on meanwhile, that needs to be subtracted from the drawdown settlements. Therefore, a phase of background creep was created in order to reduce the too high settlements. Complete presentation of all the analyses with their related construction stages is shown in Table 3.6. The groundwater flow boundary conditions were set as closed in the vertical boundary (x direction) and open in the horizontal boundaries (y direction), in order to force a vertical flow of water.

Table 3.6: Calculation phases for 1D analysis in PLAXIS 2D.

Analysis type	**Phase**	**Duration [days]**	**Starts from phase**
K0 - procedure	Initial phase	-	-
Consolidation	Background creep	10950	Initial Phase
Consolidation	0.5 m drawdown	7	Initial phase
Consolidation	Consolidation	10950	0.5 m drawdown
Consolidation	2 m drawdown	20	Initial phase
Consolidation	Consolidation	10950	2 m drawdown
Consolidation	5 m drawdown	60	Initial phase
Consolidation	Consolidation	10950	5 m drawdown

In order to study the elastic region of the model, the soil model was simplified to a Linear-Elastic model. Young's modulus E was obtained from the oedometer modulus M_0 and Poisson's ratio ν and given a value of 3715 kPa according to a conversion equation provided by Knappett and Craig (2012).

2D model setup in Plaxis

Unlike the 1D modelling cases, the 2D case had a varying stratigraphy which enables the pore water to flow in both vertical and horizontal directions. The 2D modelling in Plaxis was modelled without creep, to make it comparable with the stochastic settlement model.

The model is based on the chosen section in Haga, shown in Figure 3.3. The stratigraphy was provided by the Swedish Transport Administration and imported to Plaxis. The stratigraphy of fill, soil layers, friction layer and rock have been assigned to the model, as shown in Figure 3.6. A close up of a cutout is presented in Figure 3.7. As for the 1D cases, an upper zone which is not affected by the pressure drop in the lower aquifer is modelled, here set to around 5 meters. It should be noted that the thickness of the upper zone will vary in the 2D analysis, due to the variation of the ground surface.

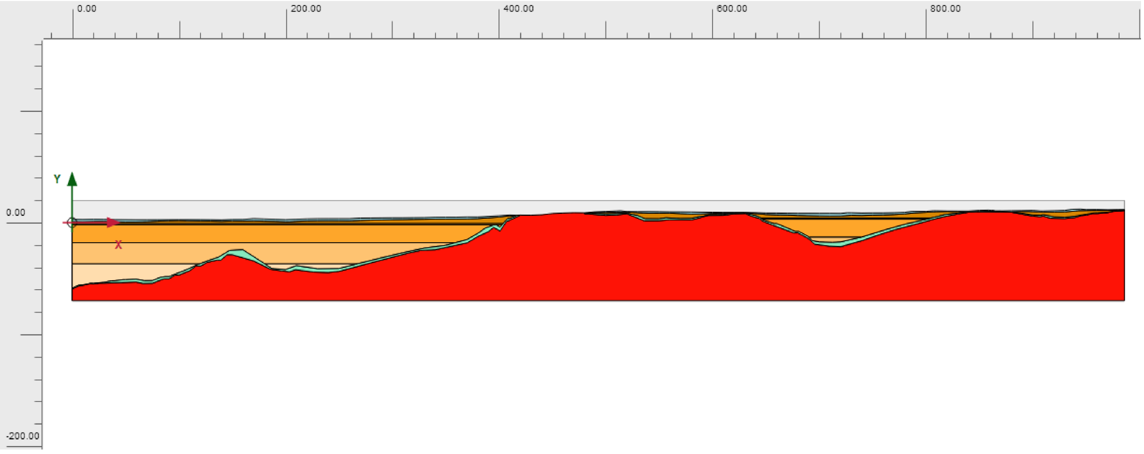


Figure 3.6: Soil stratigraphy of the chosen section in Haga.

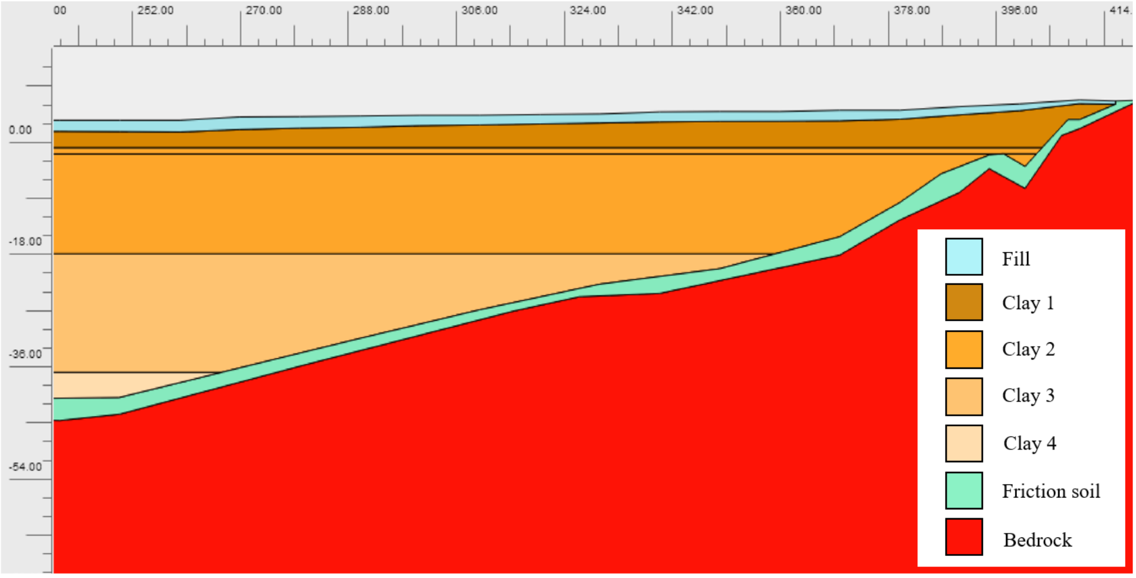


Figure 3.7: Close-up of the soil stratigraphy of the chosen section in Haga.

For Clay 1 and Clay 2 the same soil parameters have been used as in the 1D case (see Table 3.4 and Table 3.5), except that the creep parameter μ^* is not used. Two additional soil layers have been added to the 2D model, as Clay 3 and Clay 4, with their parameters shown in Table 3.7 and Table 3.8.

Table 3.7: Clay 3, Soft Soil model.

Parameter	**Value**	**Unit**
γ_{sat}	16	kN/m^3
γ_{unsat}	16	kN/m^3
k	$5.2 \cdot 10^{-5}$	m/day
λ^*	0.2410	-
κ^*	0.0334	-
c'_{ref}	5.5	kN/m^2
ϕ'	30	$^\circ$
ψ	0	$^\circ$
ν'_{ur}	0.15	-
K_0^{nc}	0.5	-
M	1.62	-
OCR	1.15	-
e_{init}	1.15	-

Table 3.8: Clay 4, Soft Soil model.

Parameter	**Value**	**Unit**
γ_{sat}	16	kN/m^3
γ_{unsat}	16	kN/m^3
k	$5.2 \cdot 10^{-5}$	m/day
λ^*	0.1112	-
κ^*	0.0478	-
c'_{ref}	7.5	kN/m^2
ϕ'	30	°
ψ	0	°
ν'_{ur}	0.15	-
K_0^{nc}	0.5	-
M	1.46	-
OCR	1.02	-
e_{init}	1.15	-

Two different pressure levels were assigned for the upper and lower aquifers, respectively, using data of the stratigraphy provided by the Swedish Transport Administration. With the stratigraphy data it was possible to create varying pressure levels. Hence, when performing a pressure decrease of the lower aquifer, the pressure level is equally decreased throughout the whole profile. As for the 1D cases, a background creep phase of 30 years has been added. For the 2D case, only a scenario of 20 kPa pressure decrease have been performed. A complete presentation of the construction stages is demonstrated in Table 3.9. The boundary conditions of groundwater flow were set the same way as in the 1D cases, with closed in x direction and open in y direction. This because the boundaries would not have an impact on the investigated points. The investigated points were selected at depths where the clay had a thickness of 10 and 15 m, to make it comparable with two of the 1D cases. The 1D case of 5 meters is not evaluated in the 2D model, because the upper zone that is not affected by a pressure drop is set to 5 meters. Hence, no change in pore pressure can be achieved. The coordinates for the chosen points are shown in Table 3.10.

Table 3.9: Calculation phases for 2D analysis in Plaxis.

Analysis type	**Phase**	**Duration [days]**	**Starts from phase**
Gravity loading	Initial phase	-	-
Consolidation	Background creep	10950	Initial Phase
Consolidation	2 m drawdown	20	Initial phase
Consolidation	Following consolidation	10950	2 m drawdown

Table 3.10: Coordinates for the two chosen clay depths.

Clay layer [m]	$\boldsymbol{x}$ **[m]**	$\boldsymbol{y}$ **[m]**
10	385.10	5.28
15	375.30	5.03

3.2.3 GS model

In GS, the models were set up as described earlier in Section 3.2. The models are shown in Figure 3.8 and the pressure level was set at the top of the clay layer for both the upper and lower aquifer. The input values of each parameter in the clay layers are presented in Table 3.11 and 3.12. The soil model for the clay was chosen to Chalmers with creep and for the fill and friction Chalmers without creep.

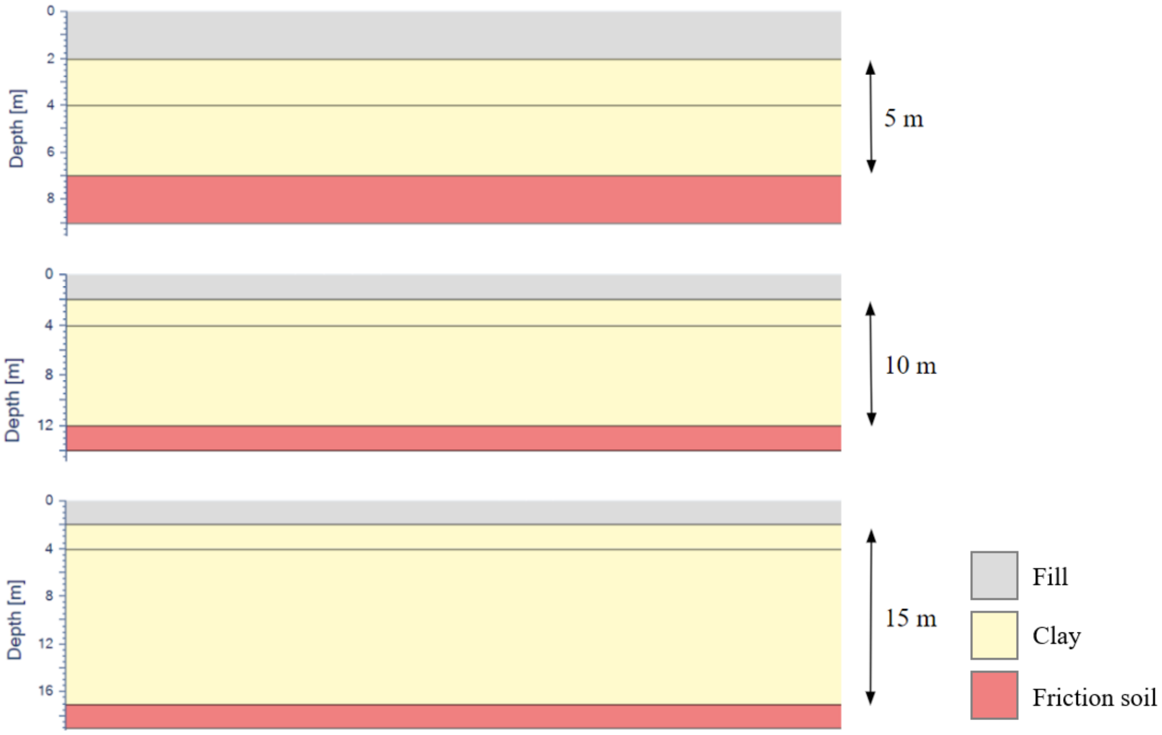


Figure 3.8: GS Settlement models.

Table 3.11: Clay layer 1, Chalmers with creep.

Parameter	Value	Unit
Soil weight	16	kN/m^2
M_0	7000	kN/m^2
M_L	800	kN/m^2
m'	12	-
a_0	0.8	-
a_1	1.0	-
σ'_c	50 - 65	kN/m^2
σ'_L	130	kN/m^2
t_{ref}	1	day
b_0	0.7	-
b_1	1.1	-
r_0	8000	-
r_1	175	-

Table 3.12: Clay layer 2, Chalmers with creep.

Parameter	Value	Unit
Soil weight	16	kN/m^2
M_0	8000	kN/m^2
M_L	800	kN/m^2
m'	12	-
a_0	0.8	-
a_1	1.0	-
σ'_c	65 - 158	kN/m^2
σ'_L	220	kN/m^2
t_{ref}	1	day
b_0	0.8	-
b_1	1.1	-
r_0	3000	-
r_1	175	-

The input parameters of the fill- and friction layers were selected in order to avoid any type of compression. Hence, the modules as well as preconsolidation pressure and limit stress were assigned with heavily exaggerated values.

Once the soil profile was set up with all the parameters needed, the pressure decrease was modelled. The decrease was achieved by inserting a new time step which varied in length depending on the size of the decrease and the ground water level was kept at the same level. In the following modelling step, the pressure profile was adjusted manually by changing the value of the pore pressure at the bottom of the clay layer to the desired value. A linear interpolation was done up to the unaffected zone. Following pressure changes were performed with corresponding time intervals of the drawdown, with the assumptions supported by geotechnicians in the industry. The length of the time step corresponds to the time during which pressure decrease takes place, after which the soil is left to consolidate during 30 years.

- 5 kPa pressure decrease with duration of 7 days
- 20 kPa pressure decrease with duration of 20 days
- 50 kPa pressure decrease with duration of 2 months (60 days)

Lastly, in order to make the application converge properly, a tolerance level of 0.0003 was set. The 'Max iteration' option was set to 9999.

Simplifications to an elastic model was made possible by using Chalmers without creep instead of Chalmers with creep and increasing the preconsolidation pressure. Furthermore, the soil response without creep was analysed by simply changing soil model from Chalmers with creep to Chalmers without creep.

3.3 Multi-criteria analysis

In this section the different steps of the MCA are described.

I. Defining the context

In broad terms, the objective of this MCA was to contribute with a comprehensive evaluation of alternatives available for modelling the soil response during drawdown in the lower aquifer. The purpose of the MCA was not to propose the best modelling alternative and dismiss the remaining, but to identify and rank them according to their appropriateness in several scenarios.

II. Finding alternatives

There are an adequate amount of geotechnical and hydrogeological modelling alternatives, but in order to make the comparison relevant for the context, three alternatives were selected. The stochastic settlement model has high applicability on Swedish standards and empiricism, GS is widely used among industry professionals and finally and Plaxis is one of the most used finite element softwares for geotechnical problems.

III. Finding criteria for evaluation

The following criteria have been established, shown in Table 3.13. All the criteria and sub-criteria are explained more in depth below.

Table 3.13: All criteria and their associated sub-criteria.

Criterion	**Sub-criteria**
1. User experience	1.1 Addressing problem in manual 1.2 Level of visuality 1.3 Expenditure of time 1.4 Required knowledge
2. Costs	2.1 Need for parameters 2.2 Need for investigation methods 2.3 License costs
3. Hydro-geotechnical modelling capabilities	*Ability to:* 3.1 distinguish between aquifers 3.2 estimate the pore pressure profile 3.3 model time dependent drawdown
4. Spatial variability	*Ability to:* 4.1 model varying stratigraphy 4.2 model varying pressure levels 4.3 model a change over large areas 4.4 address uncertainties

Criterion 1. User experience

This criterion was chosen to be able to determine the quality of the user interface of the different computational alternatives. The quality of each alternative depends on how well the modelling problem is communicated and described in manuals, the visuality when modelling, the time needed to accomplish a sufficiently accurate computation as well as how clear the mathematical theory is. Some alternatives might be simplified and hence very straight forward while others require the user to be familiar with the finite element code to achieve the same result. In order to evaluate the quality of the user interface of the three modelling alternatives, scoring of the following subcategories were made.

- *Sub-criterion 1.1 Addressing of modelling problem in manual*
  The scoring of this sub-criterion was simply based on the existence of a clear description of how to perform an analysis of a drawdown in a groundwater aquifer. The alternatives were assigned with a high score if such description in the manual existed and if not, a low score was assigned to the alternative.

- *Sub-criterion 1.2 Level of visuality*
  The user interface must be designed to make it simple, efficient and user-friendly to operate the specific computational alternative in order to produce the result that was sought for. The least possible input is preferable to obtain the desired result, while minimising unwanted outputs for the user.

- *Sub-criterion 1.3 Expenditure of time*
  This sub-criterion treats the expenditure of time for modelling. A high expenditure of time will give a low score.

- *Sub-criterion 1.4 Required knowledge in software and mathematical theory*
  To be able to set up a model in the software, some mathematical knowledge may be necessary. This sub-criterion is based on whether a lot of prior knowledge is needed or if the mathematical theory is straight forward. High knowledge needed corresponds to low scores.

Criterion 2. Costs

The amount of data available often varies depending on the extent of the construction project. If the project is of high importance and associated with high economic costs and risk, it is most likely to be supported by extensive investigations and hence a complex model could be feasible. On the other hand, in case of a less economically significant project less data and therefore a less sophisticated model could be the best option.

- *Sub-criterion 2.1 Need for parameters*
  This sub-criterion evaluates whether the parameters can be obtained from literature or if they have to be developed from investigations in field or laboratory. Need for a lot of parameters from field tests or laboratory tests corre-

sponds to a low score. If the parameters can be estimated from literature, it is scored as high.

- *Sub-criterion 2.2 Need for investigation methods*
  Geotechnical site investigation and laboratory analysis should be well motivated and further investigations that are not strictly needed should be avoided from an economical perspective. The scoring of this subcategory is therefore made according to what level of site investigation is needed, e.g. IL oedometer tests or triaxial tests.

- *Sub-criterion 2.3 License costs*
  The pricing of the softwares can be varying depending on the user. Some softwares may have different costs for students or professionals. The higher the cost, the lower the scoring points.

Criterion 3. Hydro-geotechnical modelling capabilities

Criterion 3 treats the level of complexity when modelling. The main purpose with this criterion was to evaluate how well the problem could be evaluated from a coupled geotechnical and hydrogeological point of view.

- *Sub-criterion 3.1 Ability to distinguish between groundwater aquifers*
  This sub-criterion is about whether the modelling alternative is capable of defining one pressure level for the unconfined groundwater aquifer and one for the confined, or a common one for both.

- *Sub-criterion 3.2 Ability to estimate of pore pressure profile*
  Is the pore pressure profile changed manually or by the software? The scoring treats the possibility of monitoring the pore pressure profile.

- *Sub-criterion 3.3 Ability to model time dependent drawdown*
  This sub-criterion is about whether it is possible to assign a duration until full drawdown is achieved or if the drawdown takes place instantaneous.

Criterion 4. Spatial variability

Groundwater pressure decrease might affect a large area and therefore the need of spatial settlement prediction can be of importance.

- *Sub-criterion 4.1 Ability to model varying stratigraphy*
  Is it possible for the water in the model to flow in both horizontal and vertical direction? The scoring is based whether or not the modelling alternative takes into account effect of varying stratigraphy, i.e. if 2D analysis can be performed.

- *Sub-criterion 4.2 Ability to model non-horizontal pressure levels*
  Non-horizontal water levels can be of relevance in the case when the drawdown occurs in a smaller area due to low hydraulic conductivity in the clay, which

causes a tilted water level.

- *Sub-criterion 4.3 Ability to model a change over large areas*
  This sub-criterion refers to the ability to effectively perform a spatial analysis, with emphasis made on the effectiveness.

- *Sub-criterion 4.4 Ability to address uncertainties*
  Since analysis performed on large areas rarely have homogenous soil properties, it can be useful to evaluate the capability of the computational alternatives to address uncertainties. The alternatives are thereby scored based on whether the parameters can be assigned with an uncertainty interval or not.

IV. Scoring the alternatives

The three different computational alternatives were assigned different scores according to their appropriateness of the previously presented criteria. The scoring was done according to a global scale, as explained in Section 2.7. The possible scores ranges between 10 and 100. The scoring was made by the authors of this thesis and is based on their subjective opinion.

For criterion 1, the first two sub-criteria (1.1 and 1.2) can be set as low, moderate or high which corresponds to 10, 50 and 100 points respectively. Sub-criteria 1.3 and 1.4 is scored the other way around, where a high expenditure of time and a high required knowledge corresponds to 10 points, and low to 100 points, seen in Table 3.14. Criterion 2 treats cost, where a high need for parameters (sub-criterion 2.1), high need for investigation methods (sub-criterion 2.2) and a high license cost (sub-criterion 2.3) will correspond to 10 points. Low need and cost corresponds to 100 points, as shown in Table 3.15. Both criteria 3 and 4 are scored based on if the statement in the sub-criterion is possible or not, where possible corresponds to 100 points and not possible to 10 points, presented in Table 3.16 and Table 3.17.

Table 3.14: Scoring of criterion 1

Score Sub-criterion	**10**	**50**	**100**
1.1	Low	Moderate	High
1.2	Low	Moderate	High
1.3	High	Moderate	Low
1.4	High	Moderate	Low

Table 3.15: Scoring of criterion 2

Score **Sub-criterion**	**10**	**50**	**100**
2.1	High	Moderate	Low
2.2	High	Moderate	Low
2.3	High	Moderate	Low

Table 3.16: Scoring of criterion 3

Score **Sub-criterion**	**10**	**100**
3.1	Not possible	Possible
3.2	Not possible	Possible
3.3	Not possible	Possible

Table 3.17: Scoring of criterion 4

Score **Sub-criterion**	**10**	**100**
4.1	Not possible	Possible
4.2	Not possible	Possible
4.3	Not possible	Possible
4.4	Not possible	Possible

V. Weighting the criteria

The weighting was individually performed by a group of specialists wihtin the fields of geotechnics and hydrogeology. Each subset of sub-criteria was given 100 points respectively which were to be distributed according to their importance with every group. The most important sub-criteria were given the highest points while the less important were given the lowest. Points between 0 and 100 was allowed and the sum of all points in each subset of sub-criteria had to be equal to 100. The same procedure was carried out for the principal criteria as well. The form for weighting of criteria and sub-criteria that the specialists used, as well as their filled forms are presented in Appendix B. Once the points had been distributed, they were normalised to a scale of 0 to 1.

VI. Combining scores and weights

The scores of the different computational approaches and the resulting weights of the main criteria and sub-criteria were multiplied to get the result of combined scores and weights. This was made firstly by multiplying the scores for the sub-criteria with the resulting weights to have a weighted score of each sub-criterion. The weighted score of each sub-criterion was summed up. These sums where then multiplied, one by one, with the weights of the main criteria.

VII. Sensitivity analysis

Since the weighting itself is subjective and might vary depending on the opinions of the specialist group, a sensitivity analysis of the weighting was carried out. This was done by changing the weights of the criteria and analysing how the result varies in three alternative scenarios.

The first alternative scenario took into account the profession of the weighting group. If e.g. consultancy people were to perform the weighting they would probably consider the user experience and cost criteria as highly important. The next scenario was set to evaluate how the alternatives were to perform if no difference were made regarding the importance of the criteria, which would show the impact of the scoring itself. Lastly, the final alternative scenario that was studied considered a highly funded project in an early stage. A scenario of this kind prioritises to model a change over a large area and identify all possible uncertainties.

4

Results

The results in this thesis are presented through modelling results of settlement calculation by the stochastic settlement model, Plaxis and GS as well as an MCA of the three different computational alternatives. The 1D modelling results are presented in Section 4.1 and the 2D results in Section 4.2. Due to an embedded error in the stochastic model, the prediction of creep was made incorrectly. Therefore, the results from the stochastic model are only shown in terms of primary consolidation while the remaining modelling approaches are evaluated taking into consideration creep effects in the 1D analysis. To make a fair comparison, creep effects are not taken into account for the 2D analysis. For the MCA, different criteria are scored and weighted in order to obtain the most preferred alternative. The scoring of the alternatives is presented in Section 4.3 and the weighting in Section 4.4.

4.1 Modelling results of 1D cases

In this section the 1D results are presented, where only vertical flow was allowed.

Analysis of waterflow theoretical framework

For Plaxis and GS, a comparison was made between elastic models and the models that take creep into consideration, which are SSC and Chalmers with creep (abbreviated as CWC in Figure 4.5), as a control of concordance in parameters between the programs. In Figure 4.5 it is shown that elastic parts correspond well to each other, which means that the water flow theoretical frameworks employed in Plaxis and GS are similar. It is also possible to see that creep yields extra excess pore pressure. Hence, both Plaxis and GS takes into consideration the effect of creep on the excess pore pressure.

Presence of excess pore pressure, p_{excess}, in the upper unaffected zone in the Plaxis and GS creep models visible in Figure 4.1(b) and 4.1(c) is only related to creep that yields extra excess pore pressure throughout the profile. Since the stochastic model assumes a change in the whole profile, the upper part is subjected to an increase in excess pore pressure as well. Moreover, the highest value of the pore pressure is of the same magnitude as in the creep models. This indicates a difference between the elastic behaviour of the stochastic model with the Plaxis and GS model.

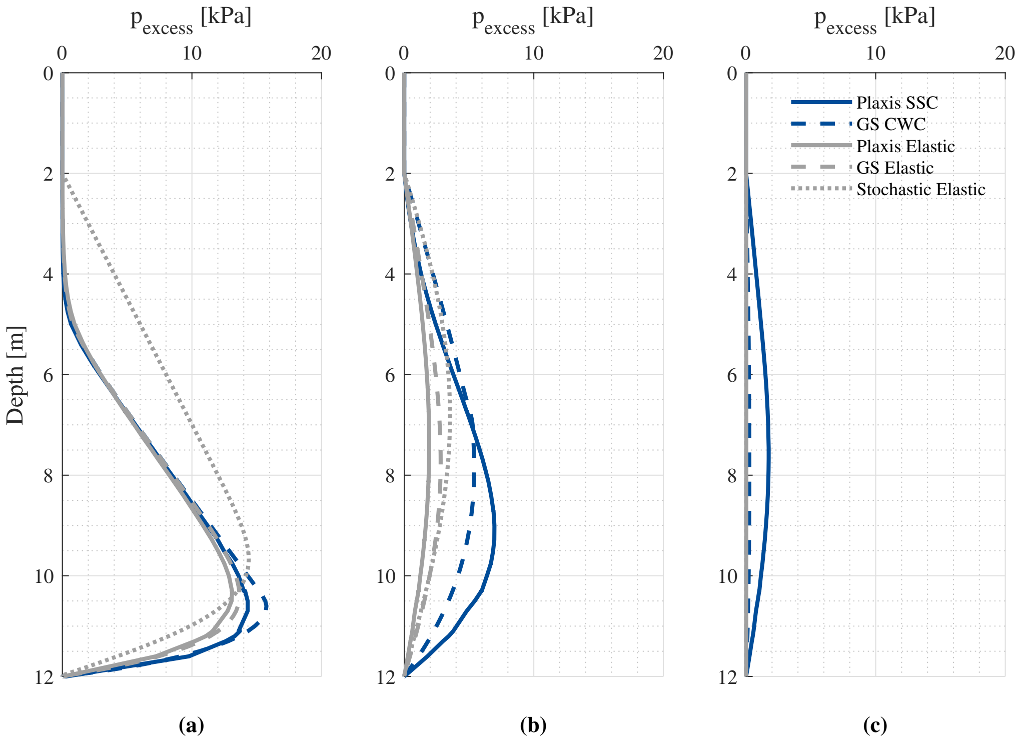


Figure 4.1: Comparison of elastic and creep model in the stochastic model, Plaxis and GS for (a) t = 20 days, (b) t = 1 year, (c) t = 10 years.

A further evaluation of how the pore pressure adapts for the same profile when the three models are given the same time of drawdown (1 day) are shown in Figure A.1 in Appendix A. By then, the three models showed similar generation of excess pore pressure. It can also be seen that the stochastic model generates a slightly higher excess pore pressure than Plaxis and GS.

Analysis of the elasto-plastic behaviour

Figure 4.2 shows the settlement over time when creep is not included. In this case the Soft Soil model in Plaxis and the Chalmers without creep model in GS was investigated. For the stochastic model, the standard deviation of all the parameters was set to zero and the settlement output did not include creep. The investigated model had a clay thickness of 10 meters and was subjected to a drawdown of 20 kPa. When comparing the three graphs it is possible to see that the behaviour during primary consolidation is quite similar for all three models. The difference between the three models has a maximum magnitude of approximately 0.75 cm. Even though the differences are minor, the stochastic model predicts the highest settlement while Plaxis gives the lowest value of settlement.

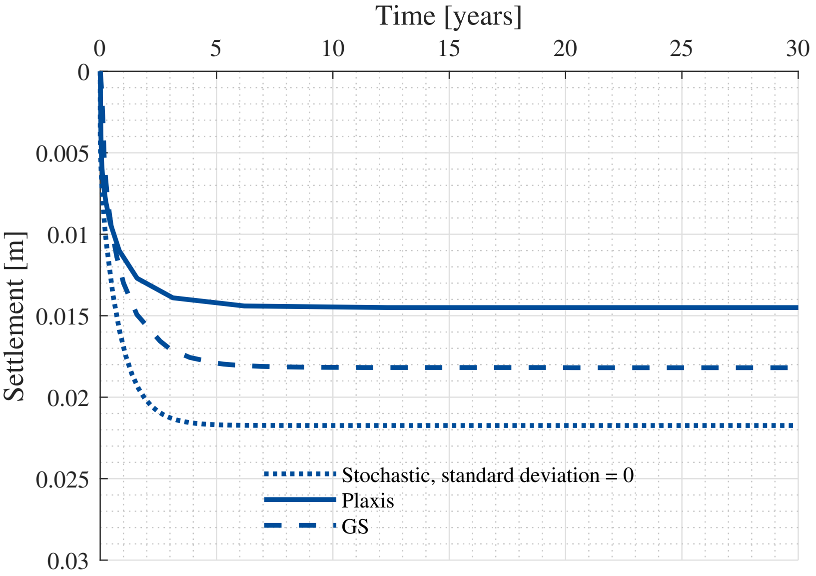


Figure 4.2: Settlement for 10 m clay and 20 kPa drawdown, without creep.

Dissipation of excess pore pressure over time

The excess pore pressure for 10 meters of clay thickness and 20 kPa drawdown in Plaxis and GS are shown in Figure 4.3. It is clear that almost all the excess pore water has dissipated after 1 year for the GS Settlement model, whereas in Plaxis the dissipation is slower and creep is still occurring after 10 years.

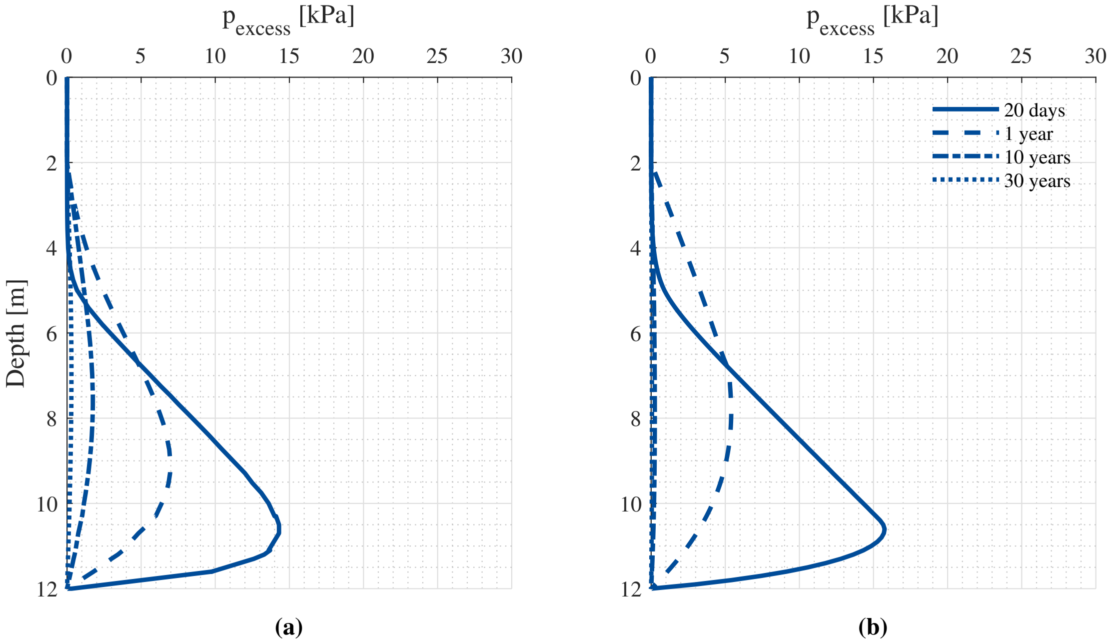
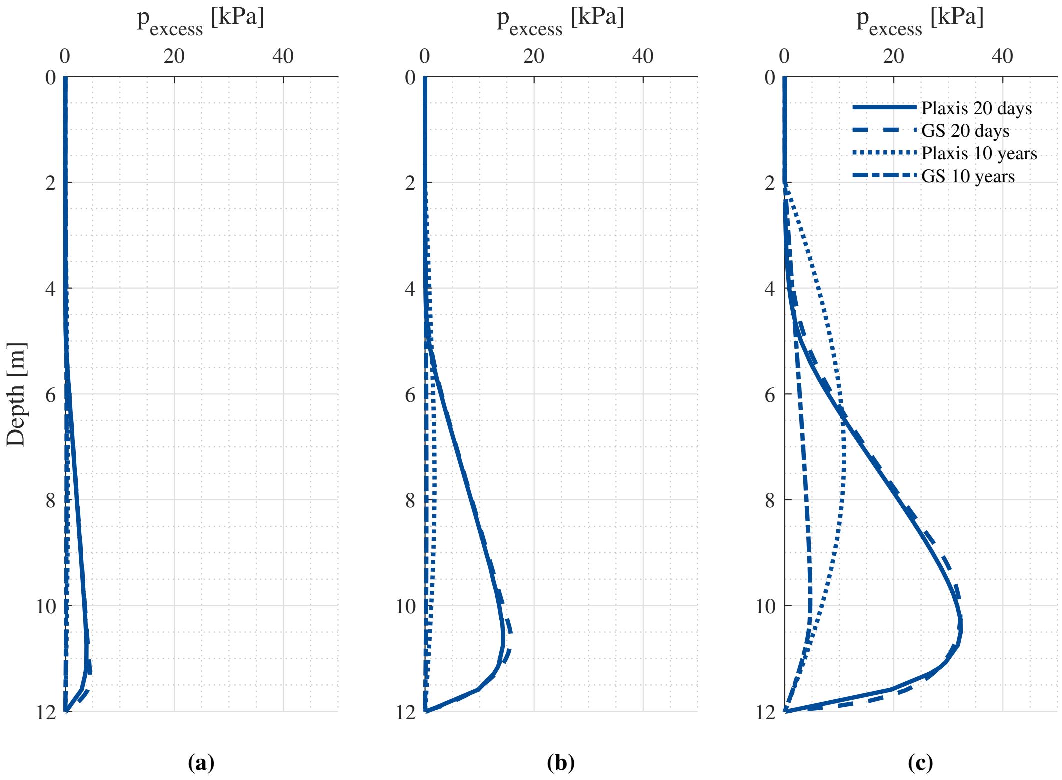


Figure 4.3: Excess pore pressure for 10 m clay and 20 kPa pressure decrease for (a) Plaxis and (b) GS.

Generation and dissipation of excess pore pressure with varying drawdowns

The excess pore pressures with varying drawdowns in Plaxis and GS are presented in Figure 4.4. In general the response is similar for drawdowns of 5 and 20 kPa. For a drawdown of 50 kPa, the excess pore pressure takes longer time to dissipate in Plaxis than for GS. Also, more creep occurs in the upper zone in Plaxis than in GS.



(a)

(b)

(c)

Figure 4.4: Excess pore pressure for (a) -5 kPa, (b) -20 kPa and (c) -50 kPa, for 10 m clay.

Ground settlements with varying drawdowns

The effect of varying pressure decrease on settlement for the stochastic model is presented without creep, shown in Figure 4.5(a). This is since the creep could not be taken into consideration in the stochastic model. Plaxis and GS is presented both with and without creep effects, in Figure 4.5(b) and Figure 4.5(c) below. For both 5 kPa and 20 kPa pressure decrease, the primary consolidation behaviour was similar among the three approaches. The primary consolidation curves for a 50 kPa pressure change for both Plaxis 2D and GS Settlement flattened out while for the stochastic model, it was still consolidating after 30 years. In terms of creep behaviour, Plaxis predicted the highest settlements for a 20 kPa pressure change, while GS predicted the highest settlements in the case of a 50 kPa pressure change, as seen in Figure 4.5. Since the case of 20 kPa cause yielding, as previously shown in Figure 3.4, the models seem to behave differently around the limit stress state that distinguishes between different compression behaviour.

In Figure 4.6, the 5^{th} and 95^{th} percentiles in the stochastic model are plotted together with Plaxis and GS Settlement for 5 kPa, 20 kPa and 50 kPa drawdown. It should be noticed that the scales are different in (a), (b) and (c) in Figure 4.6. The percentiles are plotted to see the stochastic distribution of the settlement and check whether the stochastic model captures the uncertainties or not. It is clear that both the Plaxis and GS models are in the uncertainty range of the 5^{th} and 95^{th} percentiles in the stochastic model for both 20 and 50 kPa drawdown. However, for a drawdown of 5 kPa the stochastic model does not capture the uncertainties.

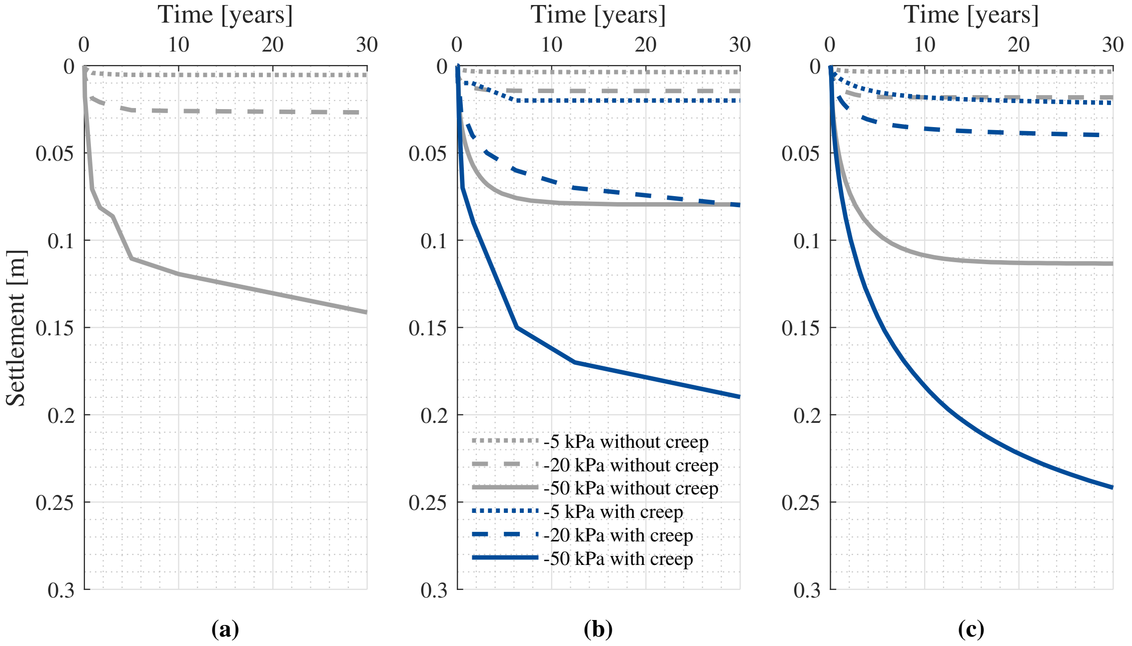


Figure 4.5: Varying pressure decrease for (a) the stochastic model (50^{th} percentile), (b) Plaxis and (c) GS.

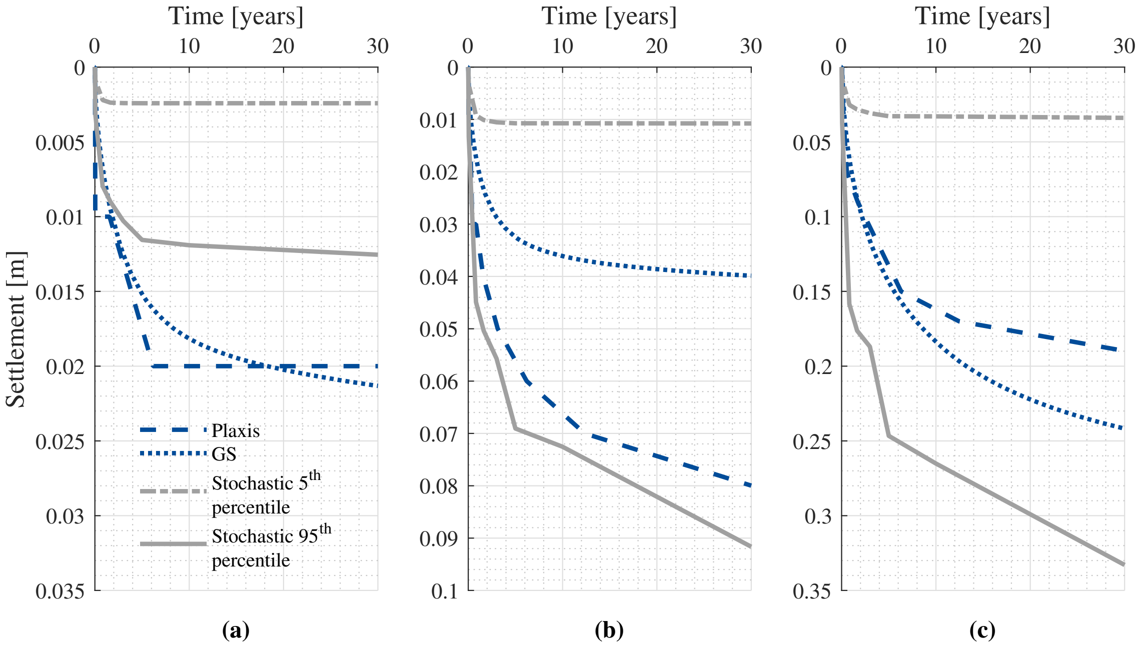
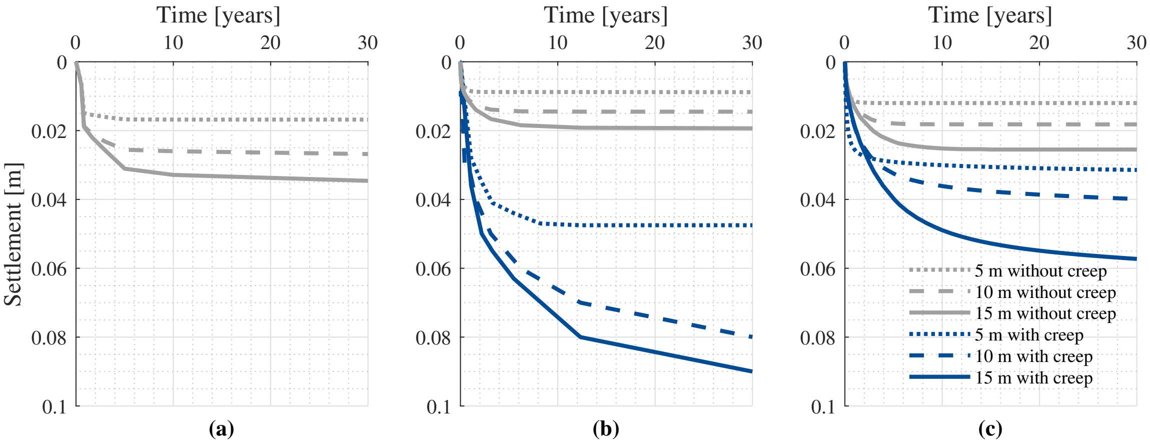


Figure 4.6: Comparison of 5^{th} and 95^{th} percentile in the stochastic model without creep with predicted settlement in Plaxis and GS with creep for (a) -5 kPa (b) -20 kPa and (c) -50 kPa.

Ground settlements with varying clay layer thickness

Figure 4.7 shows the result for 20 kPa pressure decrease performed on sections with thickness of 5, 10 and 15 meters respectively. Both primary consolidation and creep behaviour is evalualted for Plaxis and GS, since creep effects in the stochastic model could not be investigated as already mentioned. This allowed for comparison of the primary consolidation behaviour among the three alternatives. From the graphs it it possible to see that the primary consolidation behaviour is quite similar for all three approaches. However, the predicted creep for the 10 meter and 15 meter model has a greater inclination and is therefore much higher for Plaxis than GS. Also, the 5 meter model is higher for Plaxis than GS.

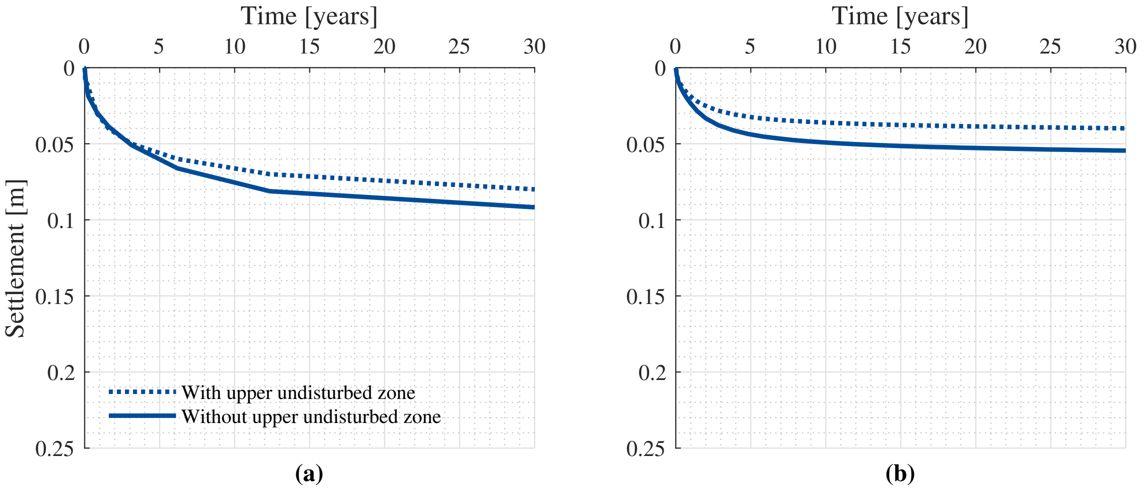


(a) (b) (c)

Figure 4.7: Effect of clay layer thickness for (a) stochastic model (50^{th} percentile) (b) Plaxis and (c) GS models subjected to 20 kPa pressure decrease.

Influence of upper undisturbed zone

As explained in Section 2.4 and Section 3.2, it is assumed that the pore pressure profile in Plaxis and GS has an upper unaffected zone. A 10 meter clay with 20 kPa drawdown is presented in Figure 4.8 and a 5 meter clay with a 50 kPa drawdown is shown in Figure 4.9. From the figures it can be clarified that when the upper zone is not taken into account, higher settlements will occur. For the 10 meter clay layer and 20 kPa drawdown, the additional settlement due to neglection of the upper undisturbed zone is ranging between 1 to 2 centimeter both for Plaxis and GS. The exaggerated scenario, presented in Figure 4.9, when a thin layer (5 m) is subjected to a large drawdown (50 kPa), the assumption of whether the clay will be fully drained or not has a higher significance. In that case, the neglection of an upper undisturbed zone predicts an additional settlement of 5 centimeters in Plaxis and 7 centimeters in GS.



(a) (b)

Figure 4.8: 10 m clay 20 kPa drawdown, with and without upper undisturbed zone for (a) Plaxis and (b) GS.

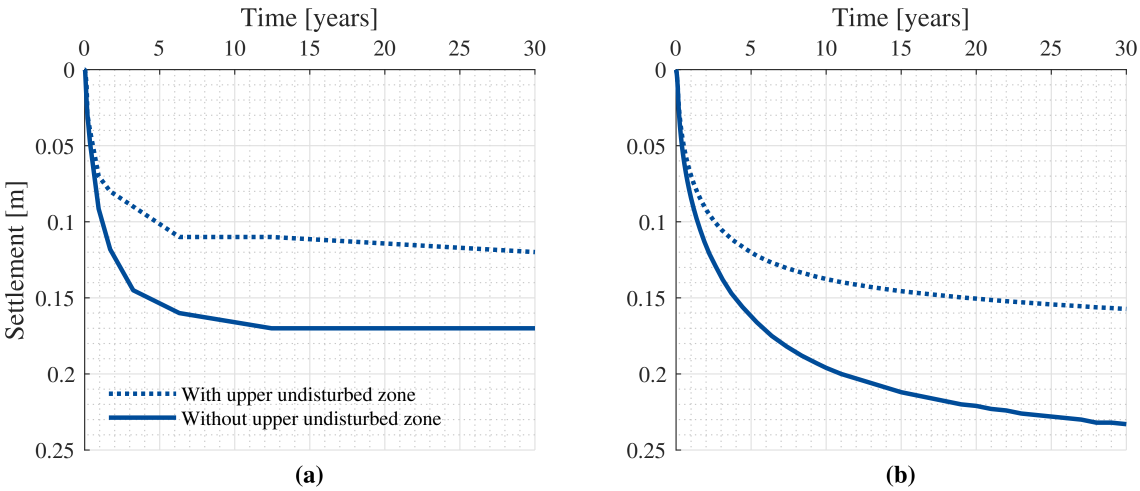


Figure 4.9: 5 m clay 50 kPa drawdown, with and without upper undisturbed zone for (a) Plaxis and (b) GS.

4.2 Modelling results of 2D cases

In this section the 2D results are presented. The stratigraphy used are shown in Figure 3.6 and Figure 3.7, presented in Section 3.2.2

Ground settlement prediction

Figure 4.10 shows a comparison between the predictions of settlement in terms of primary consolidation for the stochastic model (50^{th} percentile) and Plaxis. In addition it also shows the 5^{th} and 95^{th} percentile of the stochastic model, to check whether it could capture the uncertainties of additional settlements due to two dimensional primary consolidation.

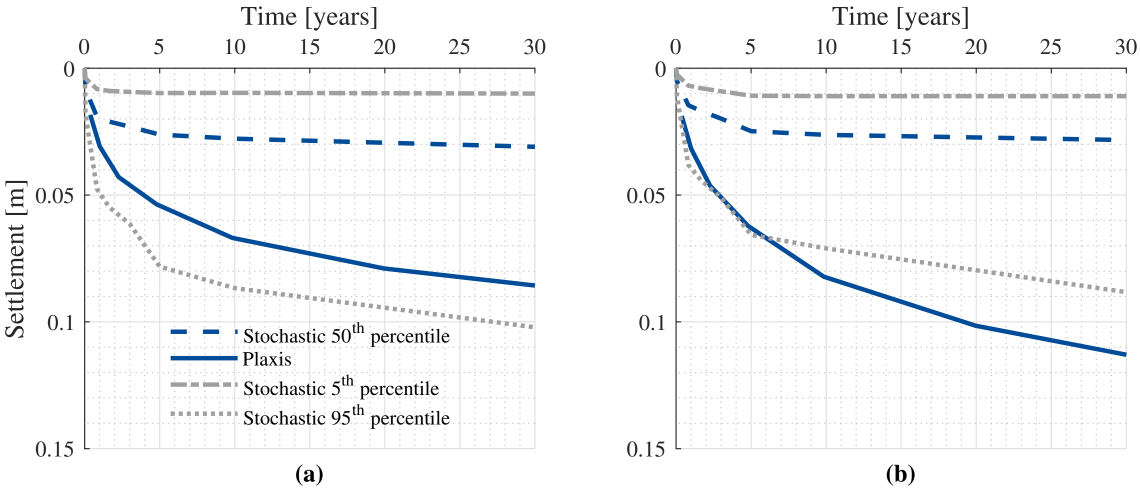


Figure 4.10: Comparison of the settlements in the stochastic model (50^{th} percentile) and Plaxis for 20 kPa drawdown and (a) 10 m clay and (b) 15 m clay.

Generation and dissipation of excess pore pressure

A comparison of the predicted generation of excess pore pressure in the stochastic model and Plaxis was performed for 10 meter and 15 meter clay, with 20 kPa drawdown. Figure 4.11 shows that directly after drawdown (20 days) the stochastic model predicts a higher excess pore pressure for the 10 meter clay. For 15 meters, the stochastic model and Plaxis predicts almost the same peak value. The stochastic model has a faster dissipation of the excess pore pressure, both for 10 and 15 meter clay.

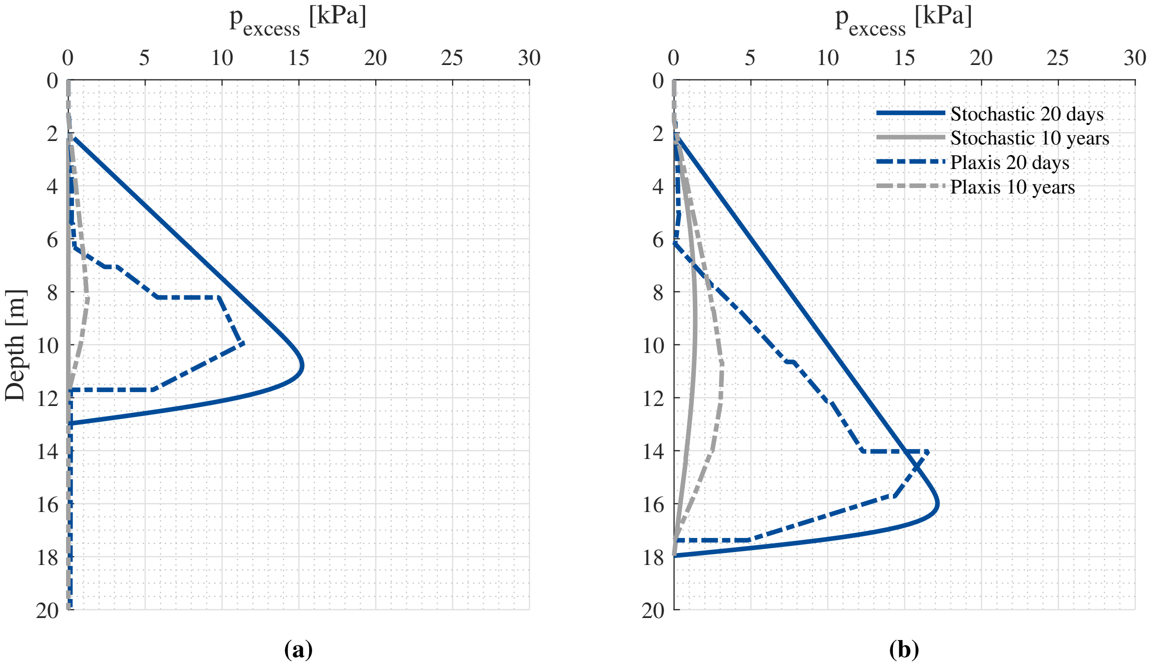


Figure 4.11: Comparison of the excess pore pressure profile for the Statistial model and Plaxis for 20 kPa drawdown of a (a) 10 m clay and (b) 15 m clay.

4.3 Scoring of alternatives

Criterion 1. User experience

The scores for criterion 1 for the three different alternatives are described below and presented in Table 4.1.

Stochastic settlement model

Lack of manual and no graphic visuality presented when modelling makes its performance deficient. Due to large data demand and long calculation times, the time expenditure could be considered as high. Additionally, high knowledge is required of the software and mathematical theory.

Plaxis

For Plaxis there are tutorials of modelling problems assigned in the manuals. However, there is no direct explanation of the scenario regarding groundwater drawdown for two different aquifers. The level of visuality is high because the soil profile and its layers can be shown in different colors, construction stages are easily made and it is possible to perform soil tests to check the appropriateness of input parameters.

Moreover, it is possible to see the deformed mesh when calculating and generation of graphs are accessible in the output window. The expenditure of time can be considered as moderate since relatively large amounts of parameters needs to be evaluated. The required knowledge is moderate since there are a high amount of features beyond the basic settings and many options that possibly can be changed. Also, meshing and the amount of nodes have to be selected which could require some knowledge in FEM. Furthermore, the boundary conditions have to be changed.

GS Settlement

When it comes to the criteria regarding addressing modelling problem in manual, it can be stated that there is no clear explanation of how to address two different groundwater aquifers. Pore pressure profile is a compiled result that does not make any distinction about the different water levels. Information about how new pressure levels arise exists, but there is no theoretical background of how a drawdown in lower aquifer is simulated. Therefore the scoring of sub-criterion 1.1 is moderate. The level of visuality is also moderate since the soil profile, stress chart and flow chart is shown while modelling, but it is not possible to e.g. see the deformed mesh. The expenditure of time depends on experience, but the relatively simple user interface together with a sparse amount of parameters rates it as low. The required knowledge in software and mathematical theory would be moderate. This is because only 1D calculation is possible with no visible mesh that needs to be generated and no selection of nodes or Gauss points. However, a proper tolerance level needs to be assigned.

Table 4.1: Scoring of criterion 1

	Stochastic			Plaxis			GS		
Score Sub-criterion	**10**	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**
1.1	X				X			X	
1.2	X					X		X	
1.3	X				X				X
1.4	X				X			X	

Criterion 2. Costs

The scoring for criterion 2 for the three different alternatives is described below and presented in Table 4.2.

Stochastic settlement model

The parameters used in stochastic model are evaluated from investigation methods and not from literature. They are dependent on large amount of data evaluated at many points, and therefore the accuracy relies strongly on a large data interval. A small data interval would lower its accuracy. It can be assumed that both the amount of parameters needed are high, as well as the fact that they have to be obtained from field and laboratory tests. The cost can be assumed as low since the code is based on available soil deformation theory and is not embedded in any type of software. The cost for Matlab as a computational platform can be neglected since it is only an enabler to run the code.

Plaxis

All the parameters for Soft Soil Creep in Plaxis are presented in Table 3.4 and 3.5. Various parameters can be obtained from literature. However, some of the parameters need to be obtained from investigations and need further calculations. For instance, κ^* and λ^* are developed from M_0 and M_L from CRS-curves, using conversion equations as explained in Section 2.5.1. The oedometer modulus M_0 can also be determined empirically. Besides, the parameters ν_{ur} together with K_0^{nc} and the M^* are estimated automatically by Plaxis itself. What has to be known, however, is the stress history of the soil, i.e. its preconsolidation pressure. Therefore, the sub-criteria of need for parameters and need for investigation methods are scored as moderate. The license cost is USD 3,950 to 6,825 for a 12 month subscription including 3 to 5 keys, which corresponds to 6,621 to 19,062 SEK per person, based on current exchange rate. This license cost is interpreted as moderate.

GS Settlement

The parameters needed in GS are shown in Table 3.11 and Table 3.12. Most parameters can be found in literature and by empiricism, as explained in Section 2.5.2. The stress history is crucial, though, and therefore the need for parameters and investigation methods can be be considered as moderate. An annual subscription of GeoSuite Toolbox package is 30,000 SEK for a name user and 33,000 SEK for a floating license. In terms of license cost it is therefore scored as high.

Table 4.2: Scoring of criterion 2

	Stochastic			Plaxis			GS		
Score Sub-criterion	**10**	**50**	**100**	**10**	**50**	**100**	**10**	**50**	**100**
2.1	X				X			X	
2.2	X				X			X	
2.3			X		X		X		

Criterion 3. Hydro-geotechnical modelling capabilities

The scoring for criterion 3 for the three different alternatives are described below and presented in Table 4.3.

Stochastic settlement model

When setting up the geometry for the stochastic model it is possible to distinguish between two different groundwater aquifers. However, it is not possible to change the pore pressure profile since it is generated automatically. Furthermore, it is not possible to reproduce a time dependent drawdown. Instead, the drawdown takes place immediately.

Plaxis

In Plaxis it is possible to assign and distinguish between two different groundwater aquifers. Also, it is possible to change the pore pressure profile, by adding a new pressure level in a different phase. Regarding the ability of reproduced time dependent drawdown, it is fully possible to assign a duration until full drawdown is achieved.

GS Settlement

It is not possible to distinguish between two groundwater aquifers when modelling in GS. However, the pore pressure profile can manually be changed. Regarding the ability of reproducing time dependent drawdown, a time limit can be set during which drawdown occurs.

Table 4.3: Scoring of criterion 3

	Stochastic		Plaxis		GS	
Score **Sub-criterion**	**10**	**100**	**10**	**100**	**10**	**100**
3.1		X		X	X	
3.2	X			X		X
3.3	X			X		X

Criterion 4. Spatial variability

The scoring for criterion 4 for the three different alternatives are described below and presented in Table 4.4.

Stochastic settlement model

The first sub-criterion is the ability of modelling varying stratigraphy which is possible. It should, however, be mentioned that only one dimensional calculations can be performed and therefore the effect of varying stratigraphy cannot be evaluated. It is possible to model varying pressure levels since the water levels can be reproduced in all spatial points. To model a change over large areas is possible and it can be achieved effectively. The ability of the alternative to address uncertainty can be considered high since it has an embedded Monte Carlo analysis.

Plaxis

For the ability of modelling varying stratigraphy it is possible since the ground profile can be fully reproduced. Modelling of varying pressure levels is possible, by drawing the pressure level as preferred. Modelling a change over a large area is possible, since the pressure level easily can be adjusted. When it comes to addressing of uncertainties, the parameters are given fixed values and cannot be assigned an uncertainty interval.

GS Settlement

It is not possible to model varying stratigraphy in GS. If it is desired to analyse different stratigraphies, a new file has to be made. However, it is possible to model varying pressure levels. A spatial analysis cannot be made due to the inability of modelling varying stratigraphy. For the uncertainty interval the parameters are given rigid values.

Table 4.4: Scoring of criterion 4

	Stochastic		Plaxis		GS	
Score Sub-criterion	**10**	**100**	**10**	**100**	**10**	**100**
4.1		X		X	X	
4.2		X		X		X
4.3		X		X	X	
4.4		X	X		X	

4.4 Weighting of criteria

The compiled direct weights of all the specialists and the resulting weights after normalisation are presented in Figure 4.12 below. In Appendix C the results are also available as Table C.1.

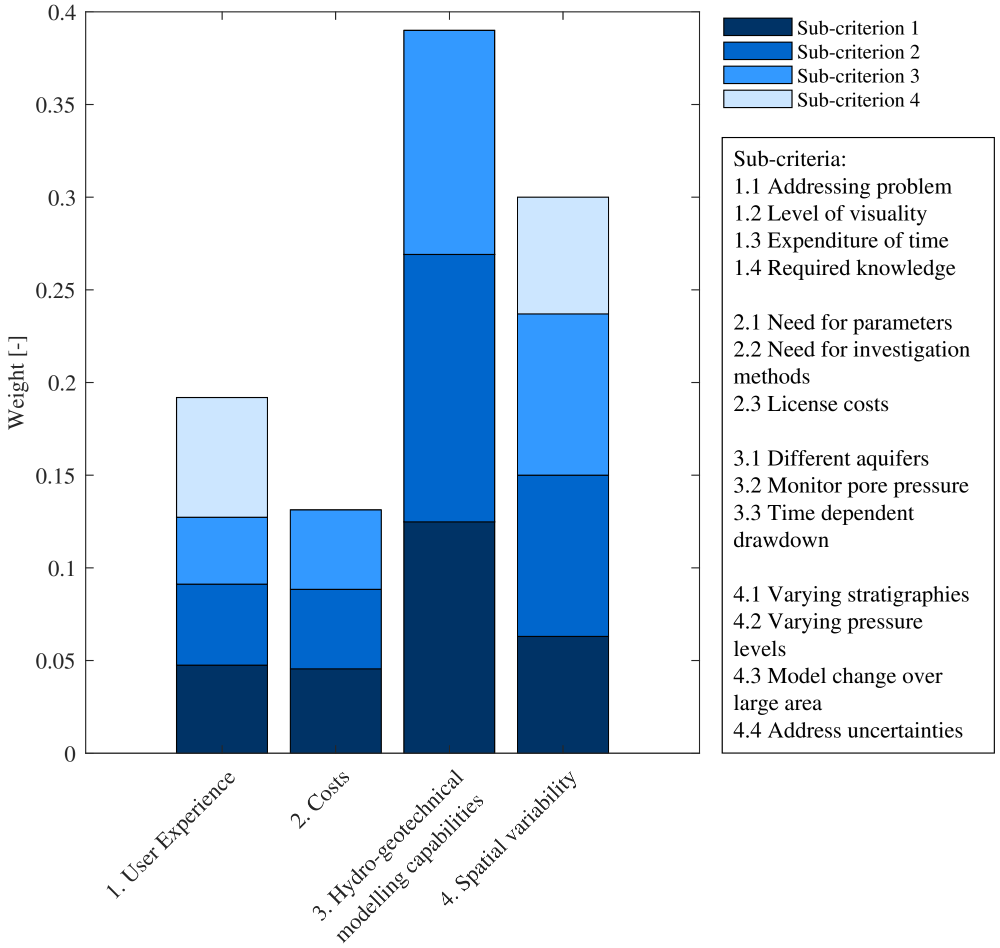


Figure 4.12: Weights for the different criteria and sub-criteria.

4.5 Combining scores and weights

The weighted scores of the different computational approaches are calculated as presented in Section 3.3. The results of the combined scores and weights are presented in 4.13 and can also be found in Table D.1 in Appendix D.

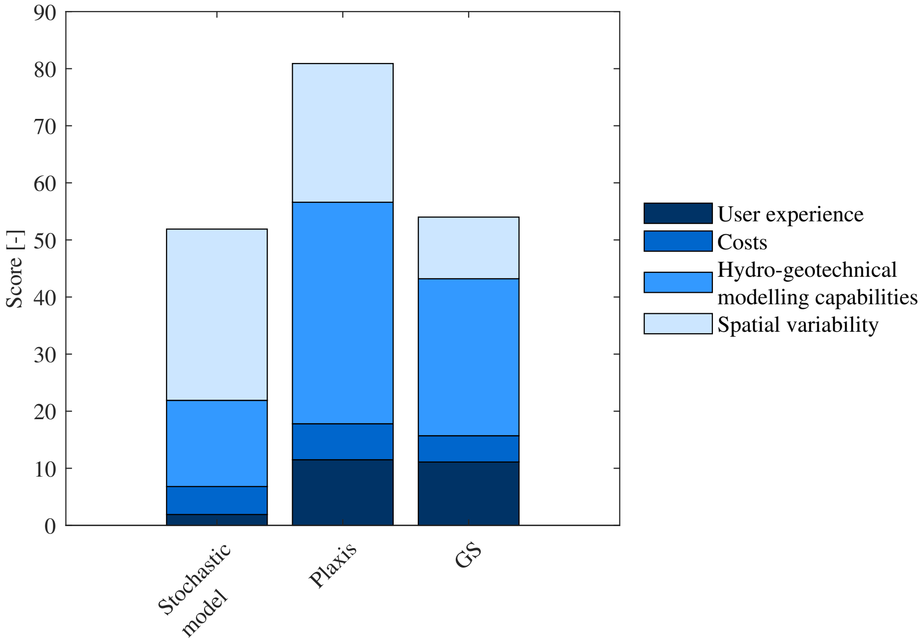


Figure 4.13: Combination of scores and weights.

4.6 Sensitivity analysis of weighting

Three alternative weighting scenarios were carried out and are presented in detail in Appendix E. The first alternative scenario (see Table E.1) refers to when the normalised weights were increased for user experience (criterion 1) and costs (criterion 2), and decreased for hydro-geotechnical modelling capabilities (criterion 3) and spatial variability (criterion 4). The weight were then changed to 0.4 for criteria 1 and 2 and to 0.1 for criteria 3 and 4. In that case, the best alternative is still Plaxis and the least preferred is still the stochastic model. In the alternative weighting scenario 2 (see Table E.2), all of the criteria were to be weighted equally. In this case the ranking also remained unchanged. The third scenario (see Table E.3) evaluates when another alternative has the possibility of being the most preferred option. In order for another alternative to outrank Plaxis, the weight of criteria 1-3 have to be set to 0.1 while criteria 4 has a weight of 0.7. In this case, the stochastic model is considered as the most preferred option.

5

Discussion

This chapter discusses the modelling results, sources of error, results of the MCA and sensitivity analysis of weighting.

5.1 Modelling results

The comparison of the different computational tools shows that the elastic behaviour of the models as well as the prediction of the primary consolidation settlement is quite similar among the three computational tools. It can further be confirmed that both Plaxis and GS assumes that creep yields extra excess pore pressure. Hence, it serves as a verification for Plaxis against a well established program such as GS which specialises in 1D settlement predictions.

Regarding the dissipation of excess pore pressure for the 1D modelling, it can be stated that Plaxis has slower dissipation than GS since creep is still occuring after 10 years (see Figure 4.3). This implies that the settlement process is faster in GS and that the predicted settlements will be generated in a higher pace. Consequently, it might predict a higher risk of damage on surrounding constructions within a shorter matter of time.

The effects of drawdown magnitude were evaluated and it is prominent that the primary consolidation prediction was similar for all three alternatives in the case of 5 and 20 kPa. However, for 50 kPa drawdown (when the preconsolidation pressure is exceeded), Plaxis predicts the stiffest response, i.e. lower settlements and the stochastic model predicts the softest response, i.e. higher settlements. Moreover, the stochastic model seems to still be consolidating after 30 years. With respect to the creep effects, for 5 kPa drawdown, the creep prediction is matching very well for Plaxis and GS, while for 20 kPa the creep increases to a greater extent in Plaxis than in GS. This might be explained by the fact that the stress state is approaching the preconsolidation pressure which highlights the difference in the interpretation of the creep parameters. Since the creep prediction of a 20 kPa drawdown results in a wide distribution of possible settlements for the three computational tools, it is difficult to draw any conclusions on the impact of soil thickness. With regards to the stress charts provided in Figure 3.4, there is reason to predict a stress state which is closer to 80 percent of the preconsolidation pressure in the 10 meter clay layer than for the 15 meter clay. This would potentially imply that a higher level of creep can be expected in the 10 meter section compared to the 15 meter section. However, this cannot be interpreted from the figures.

Although the creep is not properly implemented in the stochastic model, its uncertainty interval related to parameter variability enables it to capture the additional deformation related to creep for drawdowns of 20 and 50 kPa well. It can be questioned why a comparison is made between a model that does consider creep with a model that does not. But for such comparison however, the stochastic model can be considered a sufficiently good tool, since it captures the additional settlements from creep. For the 5 kPa case, however, the stochastical model predicts an uncertainty interval that is much smaller. Therefore it cannot capture the effects of creep by only taking into account primary consolidation. Anyhow, if it manages to capture the effects of creep, as in the cases of 20 and 50 kPa, it can be considered as very conservative and robust, which emphasise the downsides with this comparison. In early stages of a project when the aim is to capture all of the possible uncertainties, it might be advantageous. However, for later stages, this might be unfavourable and costly. By taking too many precautions for instance using sealing measures, higher quantities of non-environmental friendly materials such as cement and steel will be used. More accurate predictions are therefore preferable.

The method for modelling a groundwater drawdown varies among the alternatives. Apart from settlement calculations with application of the load on top of the soil, the load distribution in case of a drawdown in the lower aquifer originates from the bottom of the clay layer with an upward decrease of load distribution. This requires assumptions for how this drawdown process should be modelled. However, it also brings an uncertainty with regards to how the new pore pressure profile adapts, the time course of the event and how the softwares models it. One of the assumptions that had to be made was at which height the pressure change spread. The assumption of not having a 5 meter upper undisturbed zone gave an additional settlement of approximately 1 to 2 centimeters. For a thin layer of 5 meter, a 50 kPa drawdown could, if no upper undisturbed zone was assumed, mean full drainage of the layer and resulted in an increase of settlements by 5 centimeters in Plaxis and almost 7 centimeters in GS. It is therefore of importance to be aware of that the assumption of an undisturbed zone might provide a less severe worst case scenario. In the case of 5 meter clay it can although be discussed whether the profile should be modelled with the upper zone or not. When the clay is this thin, it means that it is probably close to an area with outcropping bedrock and a pressure decrease of the lower aquifer may actually also drain the upper aquifer.

When the water instead was allowed to drain in two dimensions (the 2D case), it was shown that the *primary* consolidation behaviour differed with about 5.5 centimeters between the stochastic model (50^{th} percentile) and Plaxis for the 10 meter clay layer and approximately 8 centimeters for the 15 meter clay layer. Starting off as relatively similar when analysing 1D behaviour, they now predict a noticeable difference in the magnitude of settlements. This difference is anyhow captured by the uncertainty interval in the stochastic model for the 10 meter scenario with a 20 kPa drawdown, while for a 15 meter clay thickness it is not captured. Therefore it would be reasonable to discuss whether the stochastic model should be further developed in order to capture the uncertainties related to two dimensional primary consolidation. It can be established that for the 2D case, the 10 meter clay layer is predicted to generate higher settlements than the 15 meter layer in the stochastic model. Presumably, this is related to the calculation time. For a short time span, the thinner layer might show more settlements while for a longer perspective the outcome would probably be the reverse.

5.2 Sources of error

Since real case scenarios are too complex to reproduce, simplifications are necessary when performing analysis of soil behaviour and these are potential sources of error. The first source of error in the modelling process could be the interpretation of the site characteristics such as horizontal layering and constant parameter values within the layers. Since the stochastic model relies on a large data interval and is suitable in that context, the remaining models have to comply with its data interpretation. This leads to relatively robust assumptions in the Plaxis and GS models in order to allow for them to be comparable. The large data interval also lets the stochastic model consider all of the possible uncertainties, while the remaining models are given a fixed value. However, if the data range were to be scaled down it might be at the expense of the stochastic model instead. Hence, it becomes difficult to perform the comparison between the computational tools when the stochastic model allows for a high level of uncertainty and also a dependency among the parameters.

Another source of error parameter-wise is the implementation of the creep indices. A value of $\mu^* = 0.00571$ and $r_1 = 175$ could be considered as relatively high and a conservative value. This may also be the reason to why the stochastic model does not succeed in capturing the creep effects in its uncertainty range. Furthermore, GS uses the factors b_0 and b_1 with the time resistance parameters r_0 and r_1. A high value of r_0 as well as misconception of b_0 could make the soil less prone to creep in the overconsolidated range, which might be an explanation to why the GS model predicts less creep around the preconsolidation pressure in the 20 kPa drawdown scenario. This further highlights the difference in implementation of creep where GS requires 5 parameters to define creep behaviour and Plaxis only requires one parameter. It is not possible to state whether GS brings a more accurate result in terms of creep, but it might be seen as less conservative in its prediction compared to Plaxis.

Moreover, there is reason to suspect a source of error related to the interpretation of stress history of the clay. The trends towards depth have been considered the same for all sections. Depending on the location, the geology might vary and also the stress history. Therefore, the stress history should have been interpreted differently depending on the clay layer thickness.

In terms of simulating the drawdown process there are differences in how the pressure change was achieved. For the stochastic model and the Plaxis software, the pressure head was given an elevation expressed in meters. For GS, the pressure head was expressed in kPa. In addition, the drawdown in the stochastic model took place instantly while Plaxis and GS allowed the confined aquifer pressure to decrease during a given time period depending on the size of drawdown. Concerning how the new pressure adjusts, the stochastic model assumed the whole profile to be affected by the drawdown, while Plaxis and GS allowed the soil profile to be unaffected in the upper 5 meters of the soil. This in turn generated different distribution of the excess pore pressure load, where the soil got subjected to a higher load in the stochastic model than in the remaining models and hence maybe a more conservative settlement prediction.

Lastly, another likely error is the lack of validation against a real life scenario. Since there is no possibility to use any measured values for final settlements as a benchmark, the result cannot be confirmed fully.

5.3 MCA results

The MCA was added to this thesis in order to make a broader comparison between the computational tools. The final result of the MCA shows that Plaxis is the best performing computational tool. From the expert judgments of the specialist group, the criteria 3 and 4 got a normalised weighting of 0.39 and 0.3, respectively, whereas criteria 1 and 2 only got 0.19 and 0.13, respectively. In criterion 3, Plaxis got the highest possible score for all sub-criteria and for criterion 4, all sub-criteria except one was assigned the highest score. Hence, the reason why Plaxis got the best results should be that it got higher scores for the criteria and sub-criteria that was highly weighted from the research group. The stochastic model performed best for criterion 4, but it was not enough due to poor results in the other criteria. GS performed better than the stochastic model in general, and showed mediocre scores for all criteria.

For the first criterion, regarding user interface, the stochastic model got the lowest score for each sub-criteria. The reason is that this criterion was highly based on the easiness of how to navigate when modelling and for the stochastic model, it was considered complicated. Hence, it can be discussed whether another sub-criterion should have been added to the user interface criterion, for example the flexibility of an open code. An open source code can always be modified and in a programming tool such as Matlab, anything can be changed. This would have given the stochastic model a high score and perhaps a more fair result. Another sub-criterion that could have been added to the user interface criterion is the effort it takes when modelling. For both the stochastic model and Plaxis the effort could be considered as quite high, while for GS the modelling process is more straightforward. For criterion 2, regarding costs, the parameters of the stochastic model was evaluated from investigation methods, while for Plaxis and GS some of the parameters could be found in literature, which was seen as more practical. On the other hand it could be disadvantageous since they are not site specific. However, the license cost was interpreted as low for the stochastic model, since the code that was used can be adapted to any other type of numeric programming language. This interpretation could instead have been done in the same way as for Plaxis and GS, where the license cost was presented as the price when buying the software. The hydro-geotechnical modelling capabilities (criterion 3) showed a varying result between the different computational tools. Plaxis got the highest score for all three sub-criteria and can therefore be seen as the most appropriate tool in the case of modelling a groundwater drawdown in lower aquifer. The fourth criterion, which is about spatial variability, is advantageous for the stochastic model, since the code is programmed to be used over a large area and to address uncertainties.

Regarding the scoring, it is possible to question whether the use of a global scale is preferable over a local scale. In particular, a global scale can cause confusion in the definition of what a good performance means as well as how a moderate performance should be valued in relation to the best performance score. When using a local scale it is not predefined what a high or low score implies. Instead, the investigated alternatives are simply ranked based on which performs best and worse for the different criteria, which could be seen as a more straightforward way of scoring. The weakness with a local scale is that when normalising the scale against the alternative that performs the best or worst, small and perhaps quite insignificant effects can have a very large impact on the final result.

When taking into account the weights of the researach group, the MCA results show that Plaxis will be the most preferable computational tool. In order to properly assess the weighting of each criterion it could have been valuable to set up likely scenarios of at which time stage of a project the risk of decreasing pressure in the confined aquifer would be evaluated. One example could be to consider two different scenarios, where the first could be denoted as an early stage in the project, a so-called "feasibility planning". Here the aim is generally to select proper location together with preliminary design and identify possible risks. Characteristical for this time stage of a project is desk studies and use of already existing data together with a need for a lot of assumptions based on empiricism. The second scenario considered could be later on in the process, during the design stage. This stage is characterised by a better understanding of the problem and the data available is much higher than before. It is important to highlight the diversity of infrastructure projects and depending on their nature, the different criteria are of varying significance.

5.4 Sensitivity analysis of weighting

It is of importance to stress that the results of the MCA can be dependent on how the weighting was performed. The research group in this study weighted hydro-geotechnical modelling capabilities and spatial variability (criterion 3 and 4) as the highest. Yet, for other people that is going to choose between the three computational tools, the user experience or the cost could be more important. The result of combined scores and weights show that even for a scenario where the weights of criteria 1 and 2 were increased and criteria 3 and 4 decreased, Plaxis still got the highest and the stochastic model got the lowest result (see Table E.1). Also, when changing the normalised weighting to equal for all the criteria, the order of the most preferable computational tools remained unchanged, as shown in Table E.2. In order for an alternative to outrank Plaxis, the weight of the forth criteria had to be heavily amplified to a weight of 0.7. This could potentially be a case when investigating a large area with high parameter uncertainty in an early stage of a project as discussed in Section 5.1.

6

Conclusions and future work

The following chapter presents the conclusions of this thesis and suggestions of future studies.

6.1 Conclusion

This thesis examines three computational tools in their ability to predict settlement caused by drawdown in a confined aquifer. To obtain a holistic perspective, a MCAs was made in parallel with a 1D and 2D analysis of characteristic soil sections.

The results shows that the elastic behaviour of the models and the elasto-plastic settlement is rather similar for the three computational tools. What mainly differs is the creep estimation, which can be explained by different model formulation. The inability for the stochastic settlement model to predict creep is for 1D modelling captured well by the uncertainty interval related to parameter variability. GS seems to predict a less conservative response in terms of creep compared to Plaxis for stress states around the preconsolidation pressure. On the other hand, when the preconsolidation pressure is exceeded heavily, GS predicts higher settlements than Plaxis. This demonstrates that the softwares might predict settlements differently, although the input parameters are similar. In terms of 2D primary consolidation, the comparison between the stochastic model and Plaxis demonstrates relatively large difference in settlement prediction. The question of whether the stochastic settlement model can capture the effects of 2D primary consolidation by the parameter uncertainty interval or not needs to be further assessed. To conclude, this thesis highlights the differences in the computational tools and does not aim to determine which alternative is outperforming the other. All of the studied computational tools have their advantages and drawbacks. The stochastic settlement model emerges with its good capability of handling spatial uncertainties. Being an open code allows for flexibility, but can also be disadvantageous due to the low level of intuition. Plaxis is rather straight-forward in its way of simulating a drawdown at the same time as its ability to reproduce reality is advantageous. On the other hand, the calculation effort becomes quite intensive for Plaxis. GS possesses the benefits of being more intuitive and requires a lower calculation effort, but lacks the ability of performing more calculations with complex geometries. Because of the varying nature of the computational tools it can be confirmed that there are challenges in comparing them. The result from an MCA of this kind should be considered as subjective, both in terms of scoring and in weighting, since it always needs to be based on expert judgement. However, the MCA can serve as a support for future projects, to accomplish a versatile analysis in a structured way.

6.2 Future studies

This thesis can be further developed in many ways. To finalise the analysis, the creep error in the stochastic settlement model should be solved. Moreover, a sensitivity analysis in modelling can be performed by changing input parameters, in order to evaluate how differences in soil properties affects the result. The study can be further elaborated by investigating temporary drawdowns. This can serve as a support to evaluate how the different tools assesses the risk of settlements for a non-permanent drawdown, indicating when damage appears. Another recommendation could be to compare the analysis with a real scenario. This would enable judgement about which tool is the most accurate. Lastly, to be up to date within current research, 3D calculations would be of interest to consider.

References

Alén, C. (1998). *On probability in geotechnics* [Doctoral dissertation, Chalmers University of Technology]. Retrieved from https://publications.lib.chalmers.se/records/fulltext/927/927.pdf

Amavasai, A., & Karstunen, M. (2017). *BEST SOIL: Soft soil modelling and parameter determination* (Tech. Rep. No. November). Department of Architecture and Civil Engineering Chalmers University of Technology.

Berntson, J. A. (1983). *Portrycksvariationer i leror i Göteborgsregionen* (Tech. Rep.). Linköping: Swedish Geotechnical Institute.

Blomén, H. (2017). *Pore pressure response in the uppermost part of a clay soil slope* [Licentiate dissertation, Chalmers University of Technology]. Chalmers Research. Retrieved from https://research.chalmers.se/publication/250093

Broms, B. B., Fredriksson, A., & Carlsson, L. (1976). Land subsidence in Sweden due to water-leakage into deep-lying tunnels and its effect on pile supported structures. In *Anaheim symposium* (Vol. 121, pp. 375–388). International Association of Hydrological Sciences.

Carlsson, L., & Gustafsson, G. (1984). *Provpumpning som geohydrologisk undersökningsmetodik* (Tech. Rep.). Stockholm: Statens råd för byggnadsforskning.

Cashman, P. M., Preene, M., & Rosser, M. (2012). *Groundwater Lowering in Construction : A Practical Guide to Dewatering* (2nd ed., Vol. 6). Taylor & Francis Group.

Claesson, P. (2003). *Long term settlements in soft clays* [Doctoral dissertation, Chalmers University of Technology]. Chalmers Research. Retrieved from https://research.chalmers.se/publication/409

Dodgson, J. S., Spackman, M., Pearman, A., & Phillips, L. D. (2009). *Multi-criteria analysis : a manual* (Vol. 11) (No. 1-3). Retrieved from http://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf doi: 10.1002/mcda.399

Fetter, C. (2014). *Applied hydrogeology* (4th ed.). Pearson Education.

Google. (2021). [Google Earth, map over area of Haga, Gothenburg]. Retrieved from https://earth.google.com/web/@57.6988235,11.96240305,1568.59843419a,0d,35y,-0.0001h,1.4875t,0r?utm_source=earth7&utm_campaign=vine&hl=en (Accessed 23 May 2021)

Hammersley, J., & Handscomb, D. (1964). *Monte Carlo Methods* (1st ed. ed.). Springer, Dordrecht.

Havel, F. (2004). *Creep in soft soils* [Doctoral dissertation, Norwegian University of Science and Technology]. Fakultet for ingeniørvitenskap og teknologi.

Retrieved from https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/231200

Högsta, U., & Sanell, K. (2014). *Västlänken och Olskroken planskildhet* (Tech. Rep.). Swedish Transport Administration.

Knappett, J., & Craig, R. F. (2012). *Craig's soil mechanics.* (8th ed. ed.). Spon Press.

Larsson, R. (1986). *Consolidation of soft soils* (Tech. Rep. No. 29). Statens Geotekniska Institut.

Larsson, R. (2008). Jords egenskaper. *Statens geotekniska institut (SGI)*(5), 62.

Larsson, R., Bengtsson, P.-E., & Eriksson, L. (1997). Prediction of settlements of embankments on soft, fine-grained soils. *Swedish Geotechnical Institute*, 56.

Larsson, R., & Sällfors, G. (1986). Automatic Continuous Consolidation Testing in Sweden. *Consolidation of Soils: Testing and Evaluation*, Philadelphia.

Leroueil, S. (2006). The isotache approach. Where are we 50 years after its development by Professor Šuklje? (2006 Prof. Šuklje's Memorial Lecture). *Proceedings of the 13th Danube-European Conference on Geotechnical Engineering; Ljubljana, Vol. 1,*(September), 55–88.

Merisalu, J., Sundell, J., & Rosén, L. (2020). Kostnads-nyttoanalys av skyddsåtgärder för hantering av hydrogeologiska risker vid undermarksbyggande.

Novapoint. (2021a). *GS Settlement Help Calculation Data.*

Novapoint. (2021b). *GS Settlement Help Soil Models.*

Olsson, M. (2010). *Calculating long-term settlement in soft clays* (Tech. Rep.). Linköping: Swedish Geotechnical Institute.

Plaxis. (2019). *Material Models Manual.* doi: 10.1007/978-981-10-2507-5{_}2

Plaxis. (2020). *Reference Manual* (Tech. Rep.).

Runesson, K. (2006). Constitutive Modeling of Engineering Materials - Theory and Computation. *The Primer*. doi: 10.1016/c2017-0-01163-1

Sällfors, G. (2013). *Geoteknik : jordmateriallära, jordmekanik* (5th ed. ed.). Gothenburg: Cremona Förlag.

SGU. (2019). *Hydrogeologisk bakgrund* . Retrieved from https://www.sgu.se/anvandarstod-for-geologiska-fragor/bedomning-av-influensomrade-avseende-grundvatten/hydrogeologisk-bakgrund-forutsattningar/ (Accessed 29 January 2021)

SGU. (2021). *Soil type map* . Retrieved from https://apps.sgu.se/kartvisare/kartvisare-jordarter-25-100.html (Accessed 23 May 2021)

Sundell, J. (2018). *Risk Assessment of Groundwater Drawdown in Subsidence Sensitive Areas* [Doctoral dissertation, Chalmers University of Technology]. Chalmers Research. Retrieved from https://research.chalmers.se/en/publication/505182

Sundell, J., Haaf, E., Tornborg, J., & Rosén, L. (2019a). Comprehensive risk assessment of groundwater drawdown induced subsidence. *Stochastic Environmental Research and Risk Assessment*, *33*(2), 427–449. doi: 10.1007/s00477-018-01647-x

Sundell, J., Rosén, L., Norberg, T., Haaf, E., Alén, C., & Karlsson, M. (2019b). Risk Mapping of Groundwater-Drawdown-Induced Land Subsidence in Heterogeneous Soils on Large Areas. *Risk Analysis*, *39*(1), 105–124.

Sundell, J., Rosén, L., Norberg, T., Wladis, D., & Alén, C. (2015). A Framework for Risk Assessment of Groundwater Drawdown Induced Subsidence. In *Geotechnical safety and risk v* (pp. 256–262). Retrieved from https://research.chalmers.se/publication/238898

Swedish Transport Administration. (2018). *Om Västlänken* . Retrieved from https://www.trafikverket.se/nara-dig/Vastra-gotaland/vi-bygger-och-forbattrar/Vastlanken---smidigare-pendling-och-effektivare-trafik/Om-Vastlanken/ (Accessed 24 March 2021)

Terzaghi, K. (1923). Die Berechnung der Durchlassigkeitsziffer des Tones aus Dem Verlauf der Hidrodynamichen Span-nungserscheinungen Akademie der Wissenschaften in Wien. *Mathematish-Naturwissen-Schaftiliche Klasse*, *123*, 55–88.

Thiem, G. (1906). *Hydrologische methoden* . [Dissertation, TH Stuttgart]. Leipzig : Gebhardt.

Waterman, D., & Broere, W. (2004). Practical application of the soft soil creep model. *Plaxis Bulletin*(15), 14–15.

Wikby, P., & Andersson, R. (2020). *Stochastic Settlement Model Including Creep Effects Simulation of Groundwater Induced Subsidence* [Master's thesis, KTH Royal Institute of Technology]. DiVA. Retrieved from http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1460537&dswid=-3339

Winter, T. C., Harvey, J. W., Lehn, O., William, F., & Alley, M. (1999). *Ground Water and Surface Water A Single Resource U.S. Geological Survey Circular 1139* (Tech. Rep.).

Xie, K. H., Tao, L. W., Wang, Y. L., & Li, C. X. (2012). One-dimensional consolidation solution and analysis for aquitard in leakage system. *Shenyang Gongye Daxue Xuebao/Journal of Shenyang University of Technology*, *34*(5), 581–585. Retrieved from https://www.researchgate.net/publication/287464092_One-dimensional_consolidation_solution_and_analysis_for_aquitard_in_leakage_system

A

Modelling results

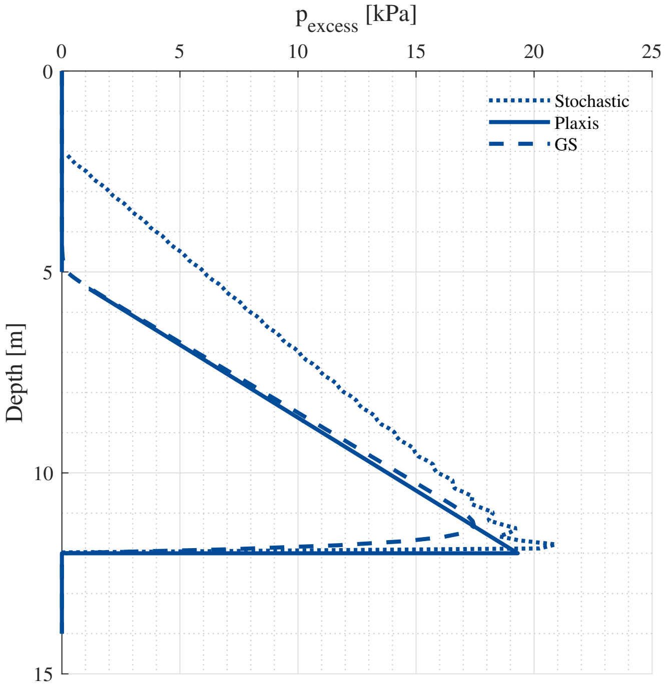


Figure A.1: Excess pore pressure for a 10 m section and 20 kPa pressure decrease after 1 day.

B

Weighting results

Table B.1: Form for weighting of criteria and sub-criteria.

Criterion or sub-criterion	**Weight of criterion or sub-criterion**
1	
1.1	
1.2	
1.3	
1.4	
2	
2.1	
2.2	
2.3	
3	
3.1	
3.2	
3.3	
4	
4.1	
4.2	
4.3	
4.4	

Table B.2: Weighting by specialist A.

Criterion or sub-criterion	**Weight of criterion- or sub-criterion**
1	**10**
1.1	20
1.2	20
1.3	40
1.4	20
2	**10**
2.1	20
2.2	20
2.3	60
3	**40**
3.1	33
3.2	33
3.3	34
4	**40**
4.1	20
4.2	20
4.3	30
4.4	30

Table B.3: Weighting by specialist B.

Criterion or sub-criterion	**Weight of criterion- or sub-criterion**
1	**30**
1.1	30
1.2	10
1.3	10
1.4	50
2	**10**
2.1	40
2.2	40
2.3	20
3	**35**
3.1	30
3.2	50
3.3	20
4	**25**
4.1	10
4.2	50
4.3	30
4.4	10

Table B.4: Weighting by specialist C.

Criterion or sub-criterion	**Weight of criterion or sub-criterion**
1	**15**
1.1	20
1.2	40
1.3	15
1.4	25
2	**20**
2.1	40
2.2	30
2.3	30
3	**40**
3.1	33
3.2	33
3.3	34
4	**25**
4.1	30
4.2	20
4.3	30
4.4	20

Table B.5: Weighting by specialist D.

Criterion or sub-criterion	**Weight of criterion or sub-criterion**
1	**20**
1.1	30
1.2	20
1.3	10
1.4	40
2	**10**
2.1	40
2.2	40
2.3	20
3	**40**
3.1	33
3.2	33
3.3	34
4	**30**
4.1	25
4.2	25
4.3	25
4.4	25

C

Normalisation of weights

Table C.1: Normalisation of weights for criteria and sub-criteria.

Criterion or sub-criterion	Direct weight	Result weight
1	19	0.19
1.1	25	0.25
1.2	23	0.23
1.3	19	0.19
1.4	34	0.34
2	13	0.13
2.1	35	0.35
2.2	33	0.33
2.3	33	0.33
3	39	0.39
3.1	32	0.32
3.2	37	0.37
3.3	31	0.31
4	30	0.3
4.1	21	0.21
4.2	29	0.29
4.3	29	0.29
4.4	21	0.21

D

Combining scores and weights

Table D.1: Combination of scores and weights.

Criterion or sub-criterion	**Weighted score Stochastic**	**Weighted score Plaxis**	**Weighted score GS**
1.1	2.5	12.5	12.5
1.2	2.3	22.5	11.3
1.3	1.9	9.4	18.8
1.4	3.4	16.9	16.9
Sum 1	10	61.3	59.4
Weighted sum 1	1.9	11.5	11.1
2.1	3.5	17.5	17.5
2.2	3.3	16.3	16.3
2.3	32.5	16.3	3.3
Sum 2	39.3	50	37.1
Weighted sum 2	4.9	6.3	4.6
3.1	32.3	32.3	3.2
3.2	3.7	37.3	37.3
3.3	3.1	30.5	30.5
Sum 3	39	100	71
Weighted sum 3	15.1	38.8	27.5
4.1	21.3	21.3	2.1
4.2	28.8	28.8	28.8
4.3	28.8	28.8	2.9
4.4	21.3	2.1	2.1
Sum 4	100	80.9	35.9
Weighted sum 4	30	24.3	10.8
Final result	51.9	80.7	53.6

E

Alternative weighting scenarios

Table E.1: Combination of scores and weights for alternative scenario 1.

Criterion or sub-criterion	**Weighted score Stochastic**	**Weighted score Plaxis**	**Weighted score GS**
1.1	2.5	12.5	12.5
1.2	2.3	22.5	11.3
1.3	1.9	9.4	18.8
1.4	3.4	16.9	16.9
Sum 1	10	61.3	59.4
Weighted sum 1	4	24.5	23.8
2.1	3.5	17.5	17.5
2.2	3.3	16.3	16.3
2.3	32.5	16.3	3.3
Sum 2	39.3	50	37.1
Weighted sum 2	15.7	20	14.8
3.1	32.3	32.3	3.2
3.2	3.7	37.3	37.3
3.3	3.1	30.5	30.5
Sum 3	39	100	71
Weighted sum 3	3.9	10	7.1
4.1	21.3	21.3	2.1
4.2	28.8	28.8	28.8
4.3	28.8	28.8	2.9
4.4	21.3	2.1	2.1
Sum 4	100	80.9	35.9
Weighted sum 4	10	8.1	3.6
Final result	33.6	62.6	49.2

Table E.2: Combination of scores and weights for alternative scenario 2.

Criterion or sub-criterion	**Weighted score Stochastic**	**Weighted score Plaxis**	**Weighted score GS**
1.1	2.5	12.5	12.5
1.2	2.3	22.5	11.3
1.3	1.9	9.4	18.8
1.4	3.4	16.9	16.9
Sum 1	10	61.3	59.4
Weighted sum 1	2.5	15.3	14.8
2.1	3.5	17.5	17.5
2.2	3.3	16.3	16.3
2.3	32.5	16.3	3.3
Sum 2	39.3	50	37.1
Weighted sum 2	9.8	12.5	9.3
3.1	32.3	32.3	3.2
3.2	3.7	37.3	37.3
3.3	3.1	30.5	30.5
Sum 3	39	100	71
Weighted sum 3	9.8	25	17.7
4.1	21.3	21.3	2.1
4.2	28.8	28.8	28.8
4.3	28.8	28.8	2.9
4.4	21.3	2.1	2.1
Sum 4	100	80.9	35.9
Weighted sum 4	25	20.2	9.0
Final result	47.1	73	50.8

Table E.3: Combination of scores and weights for alternative scenario 3.

Criterion or sub-criterion	**Weighted score Stochastic**	**Weighted score Plaxis**	**Weighted score GS**
1.1	2.5	12.5	12.5
1.2	2.3	22.5	11.3
1.3	1.9	9.4	18.8
1.4	3.4	16.9	16.9
Sum 1	10	61.3	59.4
Weighted sum 1	1	6.1	5.9
2.1	3.5	17.5	17.5
2.2	3.3	16.3	16.3
2.3	32.5	16.3	3.3
Sum 2	39.3	50	37.1
Weighted sum 2	3.9	5.0	3.7
3.1	32.3	32.3	3.2
3.2	3.7	37.3	37.3
3.3	3.1	30.5	30.5
Sum 3	39	100	71
Weighted sum 3	3.9	10	7.1
4.1	21.3	21.3	2.1
4.2	28.8	28.8	28.8
4.3	28.8	28.8	2.9
4.4	21.3	2.1	2.1
Sum 4	100	80.9	35.9
Weighted sum 4	70	56.6	25.1
Final result	78.8	77.7	41.8

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se