CHALMERS

Ground Settling Due To Groundwater Drawdown

Integrated probabilistic model for soil, groundwater and settlement

Master of Science Thesis in the Master's Programme Geo and Water Engineering

ELYAS HASHEMI

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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Improvement of infrastructures in urban area generally involves underground construction. When constructing in cities founded on soft clay, it is important to consider land subsidence resulting from ground water drawdown. The potential cost of excessive settlement in these projects is immense. In order to handle such problems in projects, there is need to estimate the magnitude of subsidence caused by ground water lowering of ground water table and predict the potential risk for settlement.

In this thesis, a previously planned pedestrian tunnel in Motala was chosen as case study and to perform a predicting model which is integrated by geological, hydrogeological and geotechnical parts. During construction and running phase of the tunnel, groundwater drawdown in a frictional material overlaid by settlement sensitive clay was planned. Deterministic calculation of settlement was performed by Excel and GS Settlement programs. In addition, Probabilistic calculation for obtaining uncertainty of the outcome and sensitivity of included parameters performed for integrated model by using Crystal Ball program.by integrated model, the potential risk of settlement due to the tunnel construction on surrounding residential areas estimated. Furthermore, better ways of visualizing the results were performed by using Surfer program.

The outcome of analysis shows the buildings which are in risk zone of settlement and areas which can be affected by ground water lowering caused by tunnel construction .In addition, by having an uncertainty and sensitivity analysis of parameters, essentiality of investigation which needed for reducing the risk of settlement, clarified. Further investigation can be suggested if the risk become unacceptable.

Key words: Ground water Drawdown, settlement, uncertainty analysis, Probabilistic analysis, Sensitivity analysis.

Contents

Preface

The work Presented in this master thesis was conducted at the Department of Civil and Environmental Engineering at Chalmers University of Technology and at NCC Teknik office in Göteborg. The study was carried out from January 2012 to June 2012.

This master thesis was performed with Anders Bergström form NCC Teknik as supervisor and Professor Claes Alén from Chalmers University of Technology as Examiner.

I wish to thank my supervisor Anders Bergström for his great interest and guidance during this project. I also wish to thanks Professor Claes Alén for his support and interesting discussion during the project.

Special thanks to Jonas Sundell from COWI for initiating this project and for his great support and guidance throughout the project. I would also like to thanks Victoria Tisell for KTH and Minyi Pan from Lund University for invaluable helps for providing geological and hydrogeological data. In addition, the hospitality showed by NCC Teknik has been crucial for my work during spring 2012.

Finally, I would like to wish all my classmates in Geo and Water Program good luck in future.

Göteborg June 2013

Elyas Hashemi

Notations

Roman letters

k Hydraulic conductivity

$M_{\circ}$ Constant constrained modulus below the effective vertical preconsolidation pressure, Swedish method

M_L Constant constrained modulus between $\sigma'_{\circ}$ and σ'_L, Swedish method

u Pore pressure

z Depth

Greek letters

γ Unit weight of soil

γ_{ω} Unit weight of water

$\sigma'_{\circ}$ Effective vertical in-situ stress

σ'_C Preconsolidation pressure

σ'_L Effective stress where the modulus starts to increase with increasing effective stress

$\Delta\sigma$ Excess pressure

δ Settlement

μ Mean value

σ Standard deviation

1 Introduction

1.1 Background

Groundwater depression is one of the frequent consequences of infrastructure projects. The magnitude of depression is relying on drainage depth under groundwater level and the geology of area, which control the permeability. Drained groundwater in areas which have soils sensitive to settlement, such as clay, can cause ground settling and possible consequence can be damaged buildings and constructions.

High construction costs and possible consequence of settlement in soil make it unavoidable to have an investigation about ground settlement and affecting parameters of that.

1.2 Objective and Aim of study

The amount of the settling in soft soils like clay is reliant to extent of the ground water depression, thickness of clay, its compression and consolidation properties and also pore pressure behavior in different soil layers. By modeling it is possible to map a prediction of the ground settlement due to ground water depression. The consultant companies COWI and NCC Teknik have performed this type of modeling in Motala with the Swedish Transport Administration as the client. The aim of this master thesis is to develop the used modeling method.

This kind of model consists of a variety of parameters with a different magnitude of uncertainties, such as the soils permeability and thickness of clay layers, and the consolidation properties of the clay. The uncertainties partly derive from interpolations in the model but also from sampling. Through quantification with the Monte Carlo simulation it is possible to verify the models reliability and to control which parameters are most important for the uncertainties in one part of the model. By doing this simulation, additional field investigations can be prioritized in order to improve the reliability of the model.

By performing this study, it is possible to identify the probable risk situation and obtaining an overview about risk of settlement on nearby buildings due to the underground construction.

Specific aims are to:

-Develop a methodology to express groundwater drawdown and possible subsidence with a conceptual model.

-Develop a methodology to show how uncertainties in input parameters should be described.

-Develop a methodology to implement probabilistic calculation for groundwater drainage and subsidence model based on integrated model which involve geological, hydrogeological and geotechnical data together.

2 Literature Review

This Chapter contains the review of literatures related to the subject of this thesis .In the first part, general description about settlement and consolidation theory will be presented and then it will be followed by description about uncertainty in geotechnical engineering and common methods to deal with uncertainty.

2.1 General description about settlement

2.1.1 Settlement in soil and causes

One of the most important concepts in soil mechanics is effective stress which calculated by having the total stress and pore water pressure in soil. Effective stress can cause a compression in soil skeleton and present the settlement. This compression can occur under various conditions and variety of causes such as construction process, vibration and groundwater lowering(Terzaghi, 1923).In fact,increased effective stress create a compression by make a deformation in soil elements and also by rearrangement of soil particles to each other or with discharging the water or air from the soil voids(Terzaghi, 1923).

In geotechnical engineering projects knowing about total settlement (volume change) and time which is necessary for settlement of compressible layer is significant. Total settlement involves three different parts which describe below (Dinesh, 2006).

1-Immidiate settlement: an elastic deformation in soil that occurs right away after application of load, in general due to high permeability in clay, pore pressure support entire load and no immediate settlement occurs.

2-Primary consolidation: a process which an increasing in effective stress occurs at the same time with drop in pore pressure and volume in soil(Claesson, 2003).

Figure 2.1 shows the settlement behavior versus time in primary consolidation.

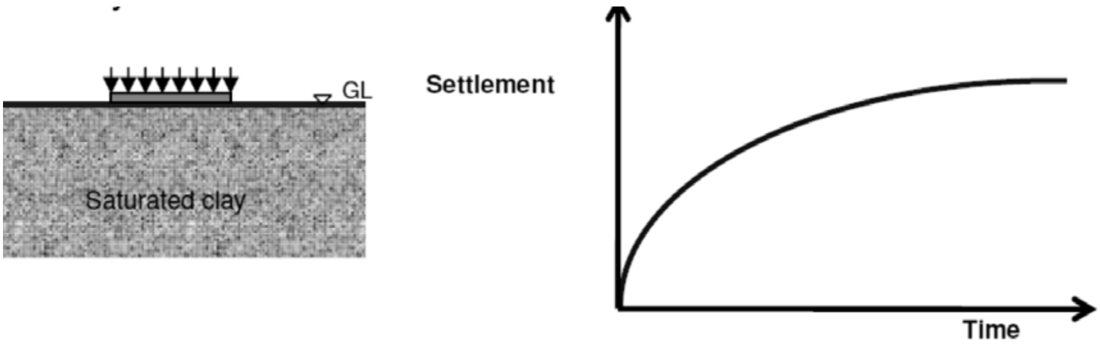


Figure 2.1 Settlement versus time in primary consolidation settlement (*Dinesh, 2006*).

3-Secondry consolidation (Creep): Is a process which is defined as reduce in volume under steady effective stress (Claesson, 2003).Actually one dimensional compression goes on after dissipation of all excess pore pressure. In general, creep consider as a result of change in soil structures (Atkinson, 2007). Figure 2.2 shows the relationship between effective stress and time in primary and secondary consolidation.

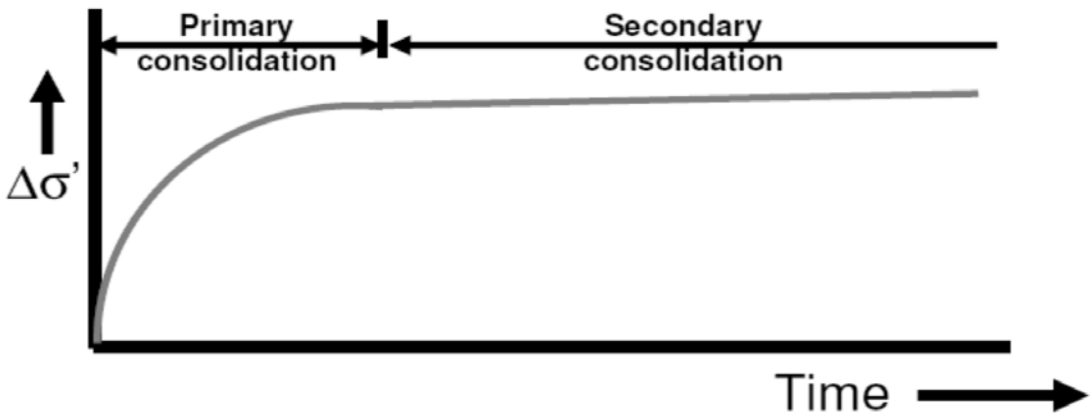


Figure 2.2 Effective stress versus time in primary and secondary consolidation (Dinesh, 2006).

In this thesis, all calculation and investigation performed based on primary consolidation and creep effect does not consider for calculation.

2.1.2 Consolidation

When a saturated clay layer loaded, pore water pressure in the layer start to increase. Under different site condition this excessive pore pressure should leave the soil.As a result of low hydraulic conductivity in clay, this process takes some times which contribute to consolidation settlement in soil (M.Das, 2007).Consolidation is a time dependent process and the rate of consolidation decrease with time.

2.1.3 The classical theory of consolidation

The classical theory of consolidation was developed by Terzaghi. This theory still is base for one-dimensional consolidation theory. Consolidation theory is based on the assumption that effective stress and strain are relative to each other independent of time.

As described before consolidation is a result of steady dispersion of surplus pore pressure from clay layer. This process increases the effective stress which causes settlement. In geotechnical engineering, soil materials with low hydraulic conductivity demonstrate hydrodynamicaly delay in settlement. This kind of settlement occurs during a long period of time (Alén, 2011). To assess the degree of consolidation in the clay layer in some time *t* after load application, it is necessary to know about rate of dispersion of excess pore pressure.

Terzaghi theories for consolidation describe the settlement with a partial differential equation as below formula (Claesson, 2003):

$$\frac{\partial u}{\partial t} = \frac{M}{\gamma} . \frac{\partial}{\partial z}\left(k . \frac{\partial u}{\partial z}\right) \tag{2.1}$$

Or

$$\frac{\partial u}{\partial t} = Cv\left(\frac{\partial^2 u}{\partial z^2}\right) \tag{2.2}$$

Coefficient of consolidation (Cv) is defined by the formula as below with this assumption that k does not change by depth.

$$Cv = \frac{k.M}{\gamma_{\omega}} \tag{2.3}$$

Where k =permeability [m/s]

M=compression modulus [kPa]

γ_{ω} =unit weight of water [kN/m^3]

Equation (2.2) explains the relationship between excess pore water pressure (u), depth below the top of clay layer (z) and time (t) from immediate application of increasing the total stress.

Terzaghi equation is applicable under the following assumptions (Claesson, 2003):

-Soil consider as completely saturated and homogeneous.

-Solid particles and pore water are incompressible.

-The flow of pore water pressure and compression are one dimensional and in vertical direction.

-Darcy's law is applicable at all hydraulic gradient.

-There is a correlation between pore water pressure and effective stress and change in pore pressure is equal to the change of effective stress.

-The strain is only relying on the effective stress.

The general solution for the partial equation (2.2) is complex and can still explain for homogenous soil and simple and idealized initial pore pressure (Sällfors & Alén, 2011).

In 1936 Terzaghi suggested a model which based on that the degree of consolidation can be calculated (Claesson, 2003).

The degree of consolidation which includes a time factor, Tv, in combination with a graph can be used for calculating the time dependent settlement, See Figure 2.3 and Figure 2.4. The following formula describes the time factor calculation:

$$Tv = \frac{Cv}{H^2}.t \tag{2.4}$$

Where H=longest drainage path which demonstrated in Figure 1.2 [m]

Cv =Coefficient of consolidation [$\frac{\mathrm{m}^2}{\mathrm{s}}$]

t=time[s]

Then average degree of consolidation, U, will be defined by Equation below and will be found from the Figure 2.4(Terzaghi & Fröhlich, 1936).

$$U = \frac{\delta t}{\delta tot} \tag{2.5}$$

Where δt =Settlement at time t

δtot =Total amount of settlement

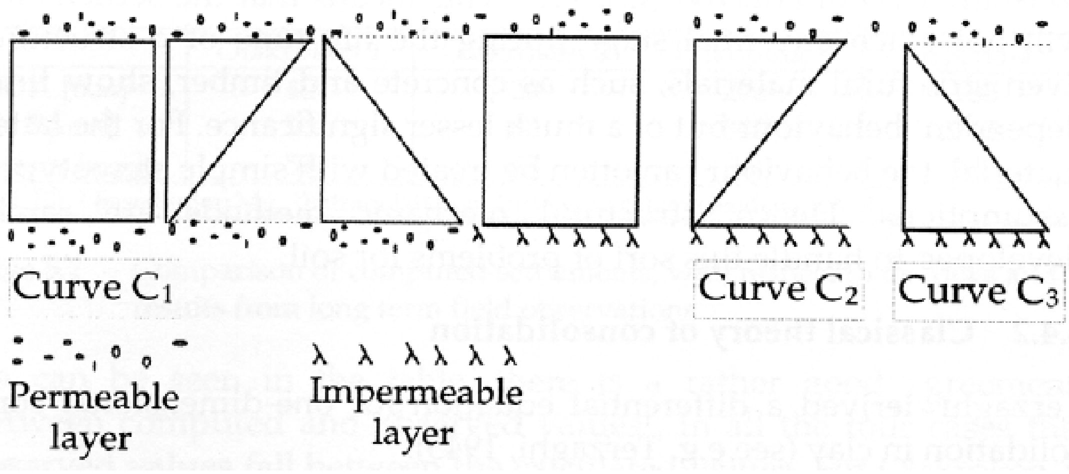


Figure 2.3 Initial variations of excess pore pressure and drainage conditions (Terzaghi & Fröhlich, 1936).

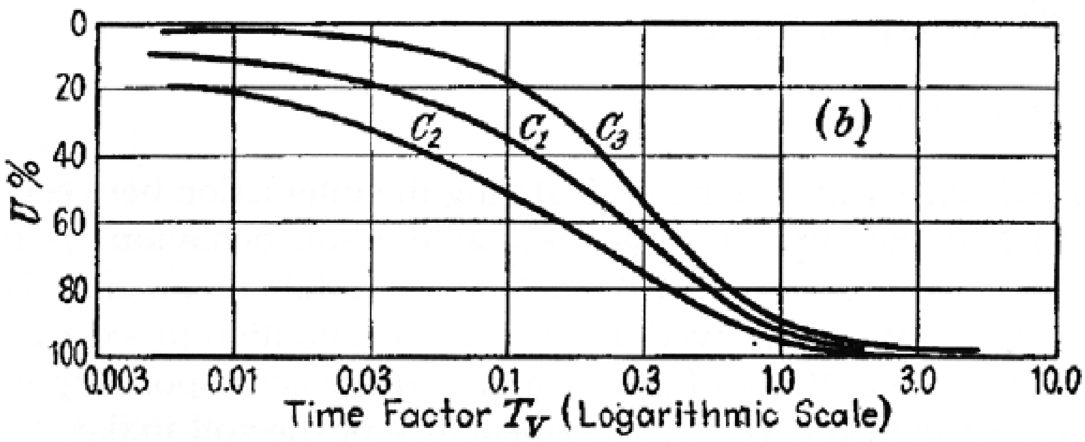


Figure 2.4 Connections between time factor and average degree of consolidation (Terzaghi & Fröhlich, 1936). The time factor plotted in a logarithmic scale. The three curves C1 to C3 match up to three different types of excess pore pressure behaviour and drainage condition (Claesson, 2003).

For a homogenous soil layer which consider as double drainage layer, the following equation give moderately precise results (Sällfors & Alén, 2011).

$$U = 2\sqrt{\frac{Tv}{\pi}} \qquad \text{For } Tv<0.2 \tag{2.6}$$

$$U = 1 - 0.8.e^{-2.5Tv} \qquad \text{For } Tv>0.2 \tag{2.7}$$

2.1.4 Important parameters for calculating the settlement

As described before, consolidation of overlaying clays can occur by reducing the ground water table. According to formula (2.2) and (2.3), the main parameters for consolidation settlement calculation are constrained modulus, coefficient of consolidation, hydraulic conductivity and preconsolidation stress. To obtain good values for mentioned parameters, some field studies and laboratory tests should be performed.By implementing the CRS test (Constant Rate of Stress) and using the Swedish standard practice which describe by Sällfors(1975), modouls and preconsolidation strss and hydaulic conductivity can be evaluated(Persson, 2007).

In a CRS test an undisturbed sample is consolidated in a vertical direction which is under steady rate of deformation and also in a fixed cross section. When test is in process, the vertical force which is necessary for deform the sample, measured continuously. Additionally, the pore pressure is evaluated at the undrained lower surface of sample (Moritz, 1995).

The result from CRS test provide a graph which demonstrate the vertical effective stress corresponding to vertical deformation .From this graph preconsolidation stress ($\sigma'c$) can be determined which graphically corresponds to a vertical effective stress without happening great settlement. Also the constrained modulus (M_L), the limit stress (σ'_L) which corresponds to that modulus starts to increase again, and the relationship between increase in effective stress and simultaneous increasing in modulus or modulus number (M') can be evaluated. Figure 2.5 shows example of results from CRS test for evaluating the parameters. In addition, CRS test can provide the values for permeability by plotting a logarithmic graph for permeability and deformation. From corresponding measured pore pressure and deformation rate, permeability can be measured (Moritz, 1995).

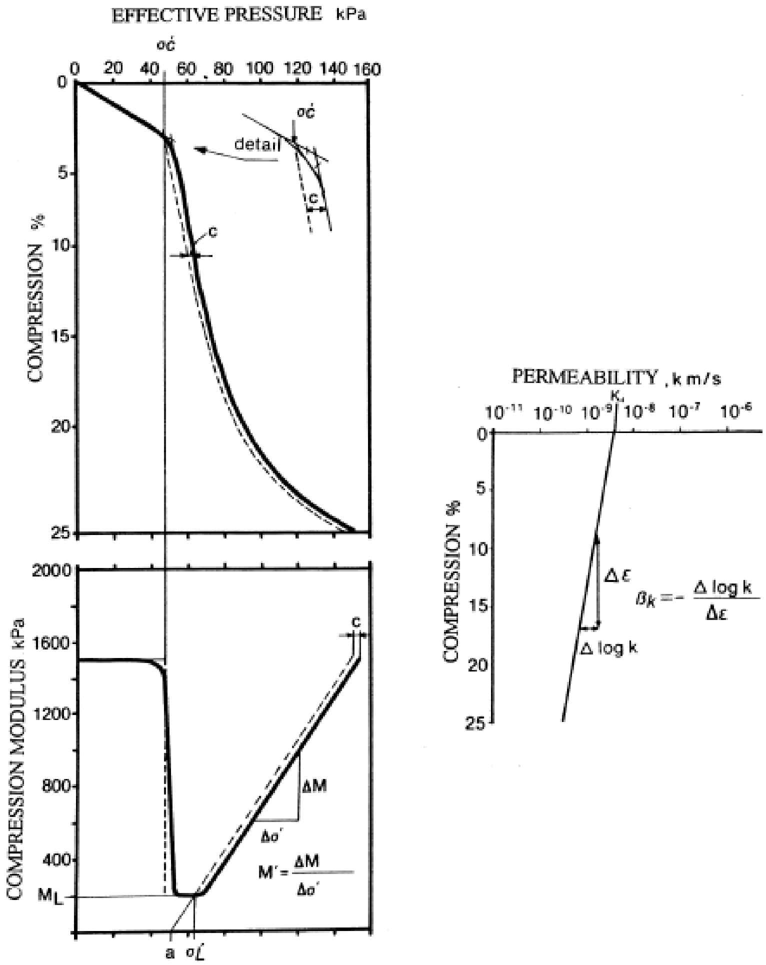


Figure 2.5 Examples of results from CRS test for evaluating the essential parameters for calculation of consolidation settlement (Larsson, 1982).

2.2 Probabilistic approach in geotechnical engineering

2.2.1 Uncertainty in geotechnics

Uncertainty is an important concept in geotechnical engineering and majority of parameters in geotechnics and especially in soil mechanic deal with that. Due to significance of uncertainty analysis and effect of that, knowing more about this concept is an essential task in geotechnical engineering. By increasing uncertainty, more investigation about effect of that into the results is unavoidable. It is common that geotechnical engineers utilize reasonable conservative parameters to deal with uncertainty, but it is obvious this method is not able to deal with uncertainty and solve the probabilistic aspects in geotechnics(Nadim, 2007).

Uncertainty in soil parameters can be divided into two types. First,random one which is related to natural haphazardness of soil characteristics and depend on spatial variability of the soil and not entitled to any reduction. Second type of uncertainty called subjective uncertainty which belongs to lack of information.

Uncertainty in soil parameters can be defined by their mean value and standard deviation of them and using a suitable probabilistic distribution. In fact, it is not a wise choice to define a deterministic value for soil characteristics. On the other hand, it is better to have best characterizing value as expected one based on available recourses and data. Figure 2.6 shows deterministic value in comparison to probabilistic value for soil property.

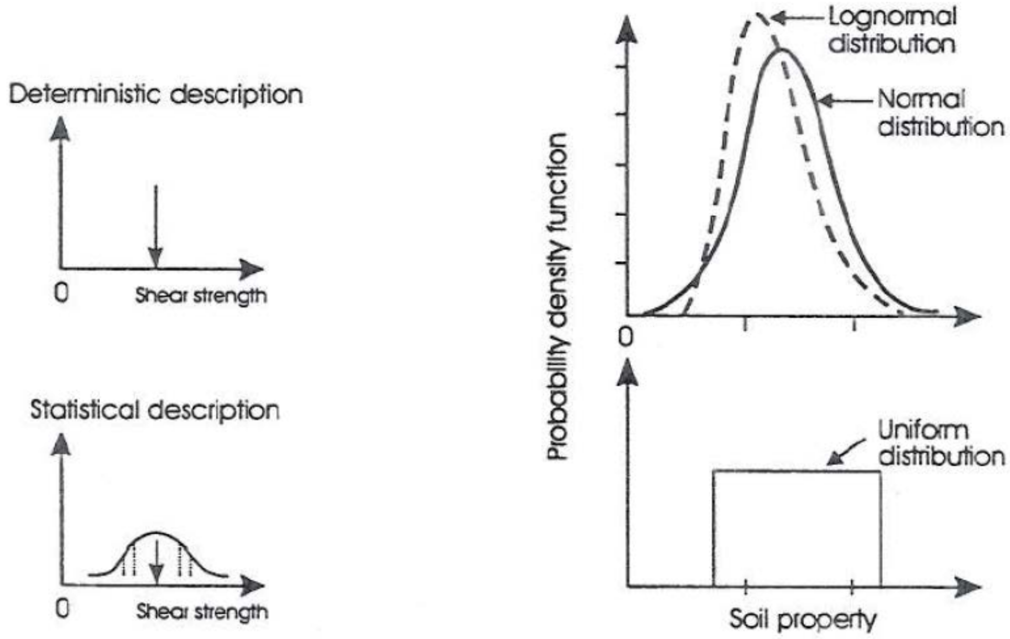


Figure 2.6 Deterministic and probabilistic description for soil property (Nadim, 2007).

To deal with uncertainty and probabilistic analysis, suitable probabilistic distribution for parameters should be defined .Different types of probabilistic distributions will be described briefly later on. Generally, it is a good way to establish a data bank for different parameters for their probabilistic behaviour which is useful in uncertainty and reliability analysis. Lacasse and Nadim(1996) provided a table for coefficient of variation and suitable type of distribution based on test results which was from Norwegian Geotechnical Institute. Table 2.1 displays the variability and probability distribution function for soil properties.

Table 2.1 Common distribution types and coefficient of variation for soil properties (Lacasse & Nadim, 1996).

Soil property	Soil type	Prob. distr. function	CoV
Cone resistance	Sand Clay	LN N/LN	Varies greatly from site to site
Undrained shear strength, s_u^*	Clay (triax) Clay (index s_u) Clayey silt	LN LN N	5 - 20% 10 - 35% 10 - 30%
Ratio s_u/σ'_{vo}	Clay	N/LN	5 - 15%
Plastic limit	Clay	N	3 - 20%
Liquid limit	Clay	N	3 - 20%
Submerged unit weight	All soils	N	0 - 10%
Friction angle	Sand	N	2 - 5%
Void ratio, porosity, initial void ratio	All soils	N	7 - 30%
Overconsolidation ratio	Clay	N/LN	10 - 35%

LN: Lognormal distribution N: Normal distribution

2.2.2 Different distribution types for geotechnical parameters

In statistics, probability distribution assigns probability to an interval of numbers. There are varieties of probabilistic distribution which can be used for handling the geotechnical problems. Finding the most appropriate type depends on some factors such as character of parameters and also the problem in hand (Alén, 1998). A brief description about most common types of distribution which used in geotechnical engineering describe as follow.

-Normal distribution

Probably the most well-known type of distribution is normal distribution. It is used most of the time due to its ease and accessibility (Alén, 1998). All normal distribution have some features such as being symmetric and having bell-shaped form. By having mean value (μ) which happen in the peak of probability density function, and also standard deviation (σ) which describe the spread of the probability density function, normal distribution can be established. A specific type of normal distribution called standard normal distribution which has mean value equal to zero and standard deviation equal to unity. All normal distribution can be transformed to standard one by using below formula:

$$y = \frac{x-\mu}{\sigma} \qquad (2.8)$$

This is general method for transformation in statistics which called location-scale transformation (Alén, 1998).

-Lognormal distribution

If logarithmic value of a random variable is normally distributed, then the variable consider as log normally distributed. Only positive values are possible for variables and the distribution is skewed to the left(Limpert, Stahel, & Abbt, 2001).It should be mentioned that the non-negatives parameters can also be accomplished by using another type of distribution, for instance the permeability of a soil can be modelled by an exponential distribution(Alén, 1998).

By utilizing the logarithm of variable, calculation of a lognormal variable can be transformed into the normal one which is easier to use (Alén, 1998). There are three different conditions underlying in this type of distribution (Gentry, 2008).

- The unknown variable can rise without limit, but is confined to a finite value at the lower limit.
- The unknown variable shows a distribution with positive skew.
- The natural logarithm of the unknown variable produces a normal curve.

-β Distribution

Another type of probabilistic distributions which defined by four parameters is β Distribution. These parameters are mean value, standard deviation and maximum and minimum values (Alén, 1998).

This distribution is very flexible distribution for probabilistic modelling based on Bayesian statistics. An unknown variable in β Distribution is a random value which located between minimum and maximum and shape of distribution can be recognised by two positive values.

There are many distributions which can be used in probabilistic approach such as Triangular, Exponential and Uniform distribution. Choosing the most suitable type of distribution for different parameters is one of the important tasks in probabilistic approach. In this thesis Crystal ball program which is a spreadsheet-based application was chosen for performing probabilistic study. In Crystal Ball it is possible to define different types of probabilistic distribution for parameters. Table 2.2 shows a brief description about most common used distributions in this program.

Table 2.2 Common available distribution types in Crystal ball modelling (Oracle, 2008).

Distribution	Conditions	Applications
 Normal	• Mean value is most likely. • It is symmetrical about the mean. • More likely to be close to the mean than far away.	Natural phenomena.
 Triangular	• Minimum and maximum are fixed. • It has a most likely value in this range, which forms a triangle with the minimum and maximum.	When you know the minimum, maximum, and most-likely values, *useful with limited data.*
 Lognormal	• Upper and lower limits are unlimited. • Distribution is positively skewed, with most values near lower limit. • Natural logarithm of the distribution is a normal distribution.	Situations where values are positively skewed.
 Uniform  Discrete Uniform	• Minimum is fixed. • Maximum is fixed. • All values in range are equally likely to occur. • Discrete Uniform is the discrete equivalent of the Uniform distribution.	When you know the range and all possible values are equally likely.

2.2.3 Monte Carlo Simulation

Different techniques are used to assess the consequence of variability in parameters. Many fields in Engineering utilize simulation method based on Randomized input, which called as Monte Carlo methods (Baecher & Christian, 2003).

In Monte Carlo Simulation several calculation are implemented for the parameters randomly determined from the given probability distribution function. This technique helps to have a resulting probability distribution and a stable solution which conclude from enough calculations. However, Monte Carlo simulation needs to define probability distribution for each of parameters (Persson, 2007).

In this thesis, simulation of model is performed by Crystal Ball which also uses Monte Carlo simulation to study the effect of variability.

3 Methodology

One of the main scopes of this thesis is to develop a methodology to implement probabilistic calculation for groundwater drainage and relative subsidence based on an integrated model. Probabilistic approach considers the effect of variability for different parameters involved in settlement calculation model.

Established model in this thesis deals with a ground water reduction and relative risk of settlement for a real project data. Main cause for ground water reduction is constructing a tunnel for pedestrian in a traffic junction. Due to the existence of residential area around the place which consider for constructing the tunnel, knowing about behaviour of settlement and effect of that on mentioned residential area was inevitable since permanent drainage is a side effect of underground construction and should be consider for possible ground subsidence in the area with sensitive soils to settlement.

3.1 Real case data

For conducting the study in this thesis, using information related to one project in Sweden took into account. The study was applied to Road 50 in Motala, which clay is a dominant soil type in most of the parts and based on that, a study about ground water drawdown and possible consequences related to settlement was applicable.

A previously planned pedestrian tunnel under multilevel traffic junction in Motala was chosen to perform a predicting model. Regarding that, extensive excavation for tunnel construction which located under existing ground water table was unavoidable. During construction and running phase of the tunnel, groundwater drawdown in a frictional material overlaid by settlement sensitive clay was planned .Figure 3.1 And 3.2 Show the location of the tunnel which investigated and a conceptual soil profile of the area which used for further estimation about ground water level and possible subsidence in ground. Based on location of tunnel, surrounding residential buildings have potential risk for settlement. Soil condition under the road was complex with two clay layers and a frictional material layer between and till at the bottom of the profile which demonstrates in Figure 3.2. Soil parameters, such as permeability and compression and consolidation properties vary both between and in the soil layers. Conditions of soil were very unclear in the early stage of the project. A few samples however existed which based on that first estimation was performed. Later on by using geostatistics method and utilizing interpolation techniques conceptual model was established.

After using geostatictics for geology of the area, hydrological and geotechnical model can be calculated using numerical modelling. It is noticeable that the study implemented based on real project, the assumptions and estimation were however fictive.

Figure 3.1 Road50 in Motala and surrounding residential building with risk of settlement after construction the tunnel.Selected tunnel for study marked by red ellipse.

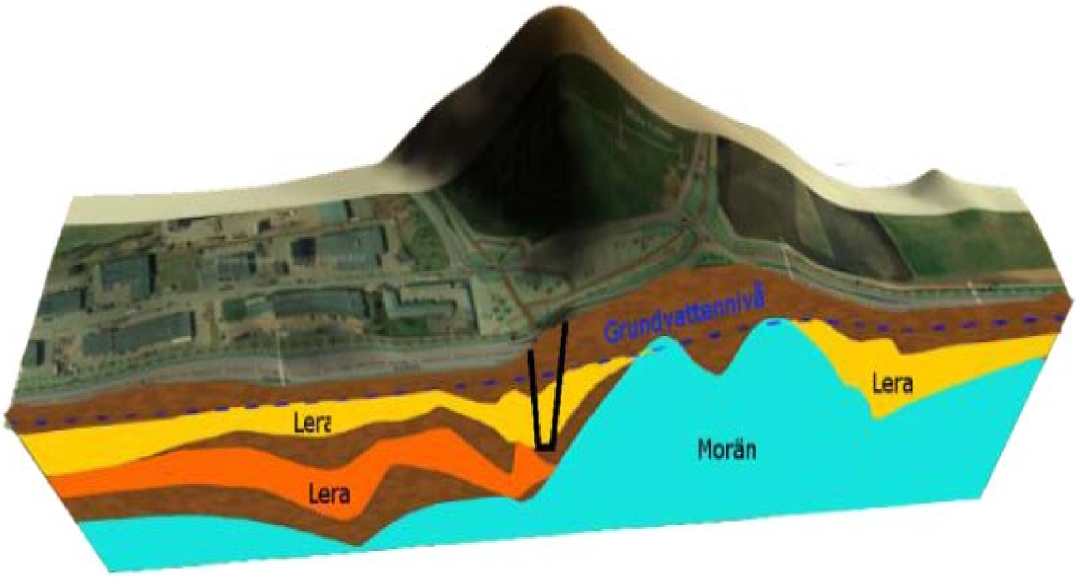


Figure 3.2 Conceptual model for soil layers in the area. Location for planned tunnel seen by black line (Lera=Clay, Grundvattennivå=Ground water level, Morän=Till).The layers in between, above and below the clay are frictional material.

3.2 Deterministic integrated Model

As it mentioned in Chapter 2, Crystal Ball program was chosen for probabilistic study. Crystal ball is a spreadsheet-based application for prognostic modelling, forecasting, simulation and optimization (Gentry, 2008).Using such spreadsheet-application, made it necessary to establish a deterministic model in excel which be able to calculate the settlement due to the groundwater lowering. Subsequently, deterministic model extends to probabilistic one and simulation will be executed in Crystal Ball. Deterministic model also helps to identify the main parameters and to perform a sensitivity analysis.

For establish a deterministic model three different parts merged together. First step was using the geographic data which used to identify the soil strata. Second part of the model was related to hydrogeological part which calculates the groundwater drawdown due to the tunnel construction, and finally, geotechnical part which used results from other parts to calculate the settlement in ground due to the related ground water drawdown. A brief description of soil and ground water models which come from parallel studies will be presented here.

3.2.1 Soil profile model

For a construction project, it is necessary to check the subsurface soil stratification in order to address the settlement sensitive soil. The soil strata information is obtained by drilling boreholes up to certain depths and then soil parameters such as soil composition and soil layer elevations are interpreted. Traditionally, the soil strata of the whole area are based on interpolation and extrapolation from individual boreholes by experiences of geotechnical engineers. Soil model employs GIS approach for interpolating soil strata and presenting results. GIS has been proved to enhance the quality of soil mapping in geotechnical engineering and geotechnician’s decisions for preventing foundation problems (Aguib, 2005).Here, a soil strata model was created from sample boreholes data by using a geostatistical method called kriging. This method also provides a probabilistic distribution for estimated soil elevation value. The risk and sensitivity of the model was then analysed by using Monte Carlo methods together with the probabilistic distribution of soil elevation obtained from kriging.

Generally, Soil model mainly produces two kinds of results; Elevation data and uncertainty data of the elevation data. These results are important inputs for the groundwater and settlement model. For example, groundwater model uses the elevation data to decide the geology of the area and geotechnical model uses the elevation data to decide the thickness of the clay.

It should be mentioned that study area in soil model has a dimension about 580m (W-E) and 680m (N-W) and surface soil type included clay, sand, till and glaciofluvial deposit. 120 samples were used for interpolation of soil strata for constructing the soil model. Furthermore, ground surface elevation obtained in 20*20m regular space grid from National Land Survey of Sweden and map projection used in the study was SWEREF 99_15_00. Figure 3.3 shows the sample points location and surface soil type around the tunnel. If the readers are interested to know more about geological model and its results, please refer to Pan(2012).

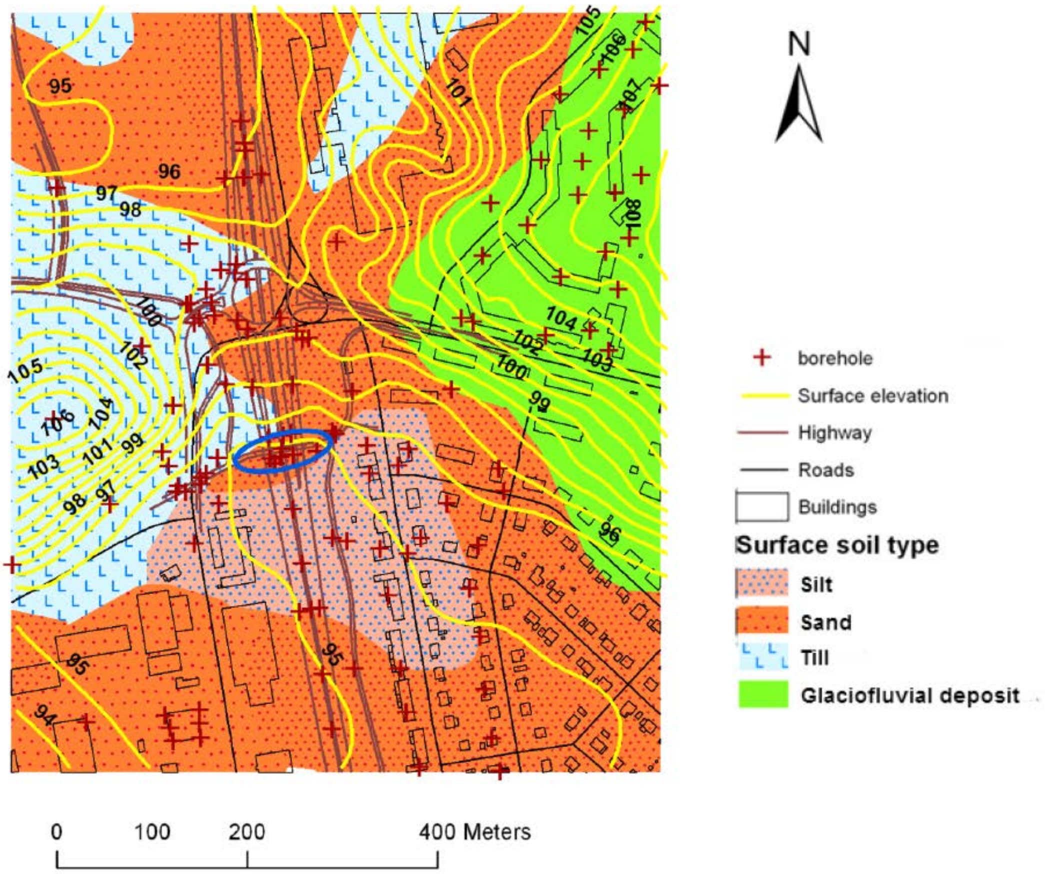


Figure 3.3 Sample points location and surface soil type around the tunnel which shown by blue ellipse (Pan, 2012).

3.2.2 Hydrogeological model

The model calculates the groundwater drawdown depending on the geology. Three soil types from the soil model are set to three different hydraulic conductivities. These hydraulic conductivities together with annual net precipitation are used as parameters in the groundwater model. When adding groundwater recharge, the geology of the soil profile decides the amount of available water. The transmissivity of each soil layer comes from the soil layer thickness times the hydraulic conductivity of the soil type. The model is based on an iterative method where the drawdown is calculated from a number of cells with set drainage depth, representing the tunnel. The boundary conditions of the model are set to zero, simulating a constant groundwater level at the boarders. This creates a cone of depression.

The output of the model is the new groundwater level over the study area, or the drawdown. Figure 3.4 shows one results from hydrogeological model. More information about hydrogeological model is available at parallel master thesis by Tisell (2012).

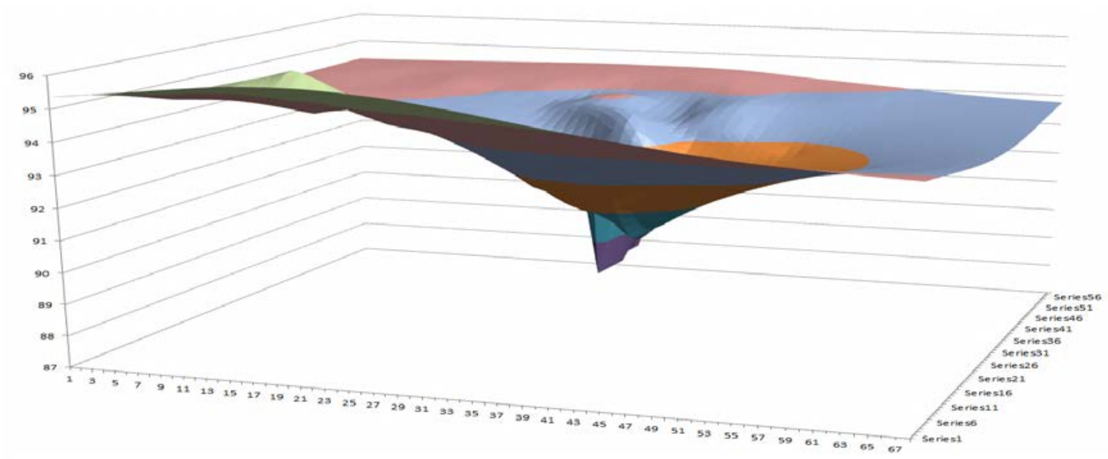


Figure 3.4 A Result from groundwater excel based model. Final ground water table in assumed area (Tisell,2012).

3.2.3 Geotechnical model

By having the data for soil layers and also ground water behaviour, values for layer thickness and also pore pressure and excess pore pressure can be defined in the geotechnical model. Different processes considered in this model to estimate the amount of settlement in different points.

The model calculates the total settlement based on Swedish method and creep effect did not consider in this calculations .Main parameters in deterministic model are effective stress, preconsolidation stress, soil modulus and excess pore pressure .As this model tried to cover a large area and due to the lack of data and investigations, some assumptions and simplification for establishing the model was unavoidable.

3.2.4 Different steps to reach a deterministic model

Conceptual model which consider for integrated model includes four soil layers. After establishing the geographical model, two clay layers with a sand layer between them and an underlying layer of till consider for the area.

As the integrated model is a spreadsheet based model and it should shows the groundwater drawdown and corresponding subsidence, considered area divided to the cells which each cell covers an area equal to 30*30 meters and the coordination was performed for different cells .Initial and final ground water table data and thickness of clay inputted to the model.

First step is to calculate the total stress based on soil data and unit weight of the each layer .In addition, initial and final pore pressure which govern the excess pore pressure, as a factor for settlement, come from elevation of water in each cell and also layer elevation. Later on effective stress which plays an important role in settlement can be calculated based on total stress and pore pressure.

For preconsolidation stress, effective stress data and also OCR data are useful .Based on data provided from a pre investigation, OCR for first clay layer considered as 1.5 and for second one as 1.25. Based on this information, preconsolidation pressure was estimated in the model for each clay layer.

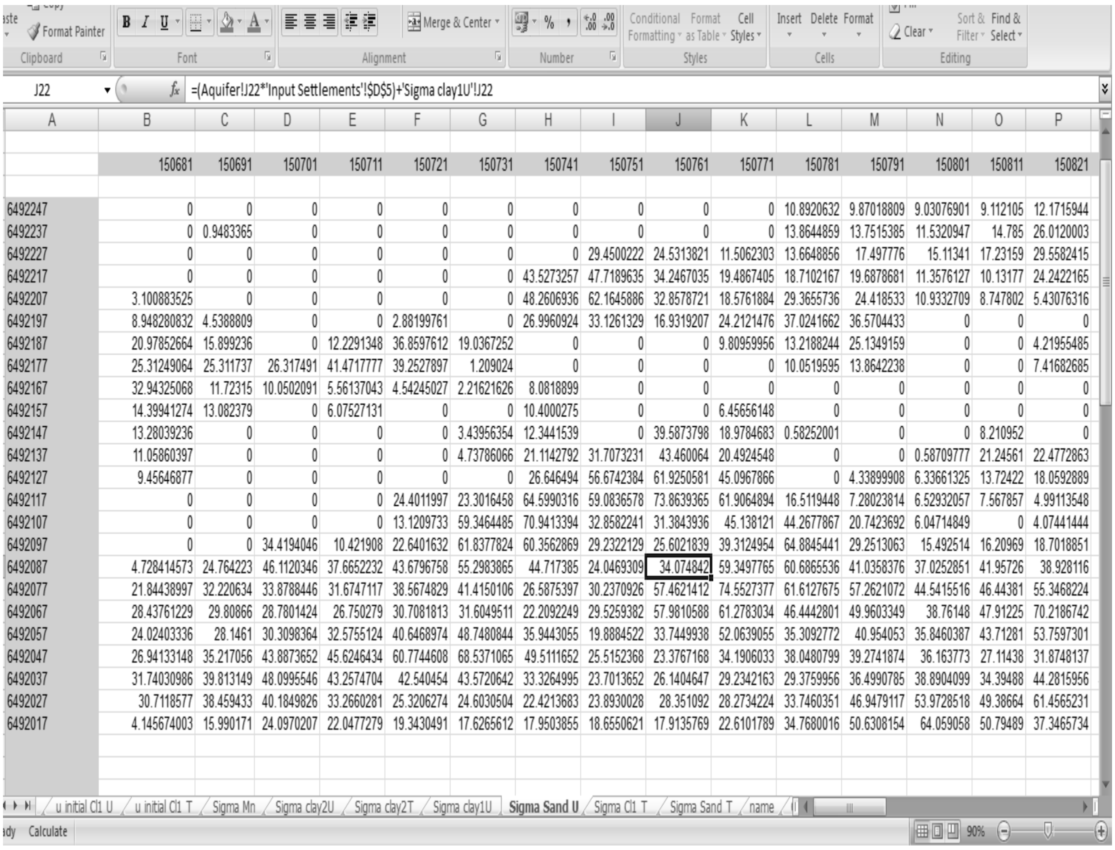
Another step is to define excess pore pressure which comes from initial and final pore pressure in each elevation .Middle point of layers was chosen to calculate the settlement, so the data for those points was calculated and then settlement estimated for them. Formula which used for total settlement calculation in integrated model describe here,

$$\delta = [\frac{(\sigma'c-\sigma'.)}{M.} + \frac{(\sigma'.+\Delta\sigma-\sigma'c)}{ML}] * h \quad (3.1)$$

Where

δ =Settlement (m)
$\sigma'.$=Effective stress (kPa)
$\Delta\sigma$ =Excess pore pressure (kPa)
$\sigma'c$ =Preconsolidationpressure (kPa)
$M.$ & ML=Soil modulus
h=Thickness of clay (m)

Figure 3.5 shows excel based model which used for calculations.


J22 =(Aquifer!J22*'Input Settlements'!D5)+'Sigma clay1U'!J22

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	150681	150691	150701	150711	150721	150731	150741	150751	150761	150771	150781	150791	150801	150811	150821
6492247	0	0	0	0	0	0	0	0	0	0	10.8920632	9.87018809	9.03076901	9.112105	12.1715944
6492237	0	0.9483365	0	0	0	0	0	0	0	0	13.8644859	13.7515385	11.5320947	14.785	26.0120003
6492227	0	0	0	0	0	0	0	29.4500222	24.5313821	11.5062303	13.6648856	17.497776	15.11341	17.23159	29.5582415
6492217	0	0	0	0	0	0	43.5273257	47.7189635	34.2467035	19.4867405	18.7102167	19.6878681	11.3576127	10.13177	24.2422165
6492207	3.100883525	0	0	0	0	0	48.2606936	62.1645886	32.8578721	18.5761884	29.3655736	24.418533	10.9332709	8.747802	5.43076316
6492197	8.948280832	4.5388809	0	0	2.88199761	0	26.9960924	33.1261329	16.9319207	24.2121476	37.0241662	36.5704433	0	0	0
6492187	20.97852664	15.899236	0	12.2291348	36.8597612	19.0367252	0	0	0	9.80959956	13.2188244	25.1349159	0	0	4.21955485
6492177	25.31249064	25.311737	26.317491	41.4717777	39.2527897	1.209024	0	0	0	0	10.0519595	13.8642238	0	0	7.41682685
6492167	32.94325068	11.72315	10.0502091	5.56137043	4.54245027	2.21621626	8.0818899	0	0	0	0	0	0	0	0
6492157	14.39941274	13.082379	0	6.07527131	0	0	10.4000275	0	0	6.45656148	0	0	0	0	0
6492147	13.28039236	0	0	0	0	3.43956354	12.3441539	0	39.5873798	18.9784683	0.58252001	0	0	8.210952	0
6492137	11.05860397	0	0	0	0	4.73786066	21.1142792	31.7073231	43.460064	20.4924548	0	0	0.58709777	21.24561	22.4772863
6492127	9.45646877	0	0	0	0	0	26.646494	56.6742384	61.9250581	45.0967866	0	4.33899908	6.33661325	13.72422	18.0592889
6492117	0	0	0	0	24.4011997	23.3016458	64.5990316	59.0836578	73.8639365	61.9064894	16.5119448	7.28023814	6.52932057	7.567857	4.99113548
6492107	0	0	0	0	13.1209733	59.3464485	70.9413394	32.8582241	31.3843936	45.138121	44.2677867	20.7423692	6.04714849	0	4.07441444
6492097	0	0	34.4194046	10.421908	22.6401632	61.8377824	60.3562869	29.2322129	25.6021839	39.3124954	64.8845441	29.2513063	15.492514	16.20969	18.7018851
6492087	4.728414573	24.764223	46.1120346	37.6652232	43.6796758	55.2983865	44.717385	24.0469309	34.074842	59.3497765	60.6865536	41.0358376	37.0252851	41.95726	38.928116
6492077	21.84438997	32.220634	33.8788446	31.6747117	38.5674829	41.4150106	26.5875397	30.2370926	57.4621412	74.5527377	61.6127675	57.2621072	44.5415516	46.44381	55.3468224
6492067	28.43761229	29.80866	28.7801424	26.750279	30.7081813	31.6049511	22.2092249	29.5259382	57.9810588	61.2783034	46.4442801	49.9603349	38.76148	47.91225	70.2186742
6492057	24.02403336	28.1461	30.3098364	32.5755124	40.6468974	48.7480844	35.9443055	19.8884522	33.7449938	52.0639055	35.3092772	40.954053	35.8460387	43.71281	53.7597301
6492047	26.94133148	35.217056	43.8873652	45.6246434	60.7744608	68.5371065	49.5111652	25.5152368	23.3767168	34.1906033	38.0480799	39.2741874	36.163773	27.11438	31.8748137
6492037	31.74030986	39.813149	48.0995546	43.2574704	42.540454	43.5720642	33.3264995	23.7013652	26.1404647	29.2342163	29.3759956	36.4990785	38.8904099	34.39488	44.2815956
6492027	30.7118577	38.459433	40.1849826	33.2660281	25.3206274	24.6030504	22.4213683	23.8930028	28.351092	28.2734224	33.7460351	46.9479117	53.9728518	49.38664	61.4565231
6492017	4.145674003	15.990171	24.0970207	22.0477279	19.3430491	17.6265612	17.9503855	18.6550621	17.9135769	22.6101789	34.7680016	50.6308154	64.059058	50.79489	37.3465734

Figure 3.5 Excel based model for calculating the total settlement.

To check the accuracy of deterministic integrated model,validation of results performed by using GS Settlement program. GS Settlement is one of the several programs in Geosuite toolbox which calculates the settlement in single points. Purpose of this program is to calculate the time-dependent settlement under loads and boundary condition, which can change as a function of time (Olsson, 2010).After establishing the deterministic model and calculating the settlement for different points, some points which were more sensitive to settlement chose to validation of results.

3.3 Probabilistic model

In the model, there are some parameters which have uncertainty, such as permeability and consolidation properties in soil layers. The uncertainty comes from conceptualization, i.e. that the model doesn't correctly describe the system, in addition it derives from parameters uncertainty in input data.

By quantifying uncertainty with geostatistics and Monte Carlo simulation, it is possible to evaluate the reliability of the model and also knowing that which parameters are significant in a certain part of the model.

Probabilistic model follows the rules for deterministic model but with some differences. In fact, for variable parameters, mean values and standard deviations should be considered and then assumptions and forecast should be defined in Crystal Ball. Later on, simulation of final model in the program should be performed. This procedure makes it possible to perform uncertainty analysis for different parameters and also implement a sensitivity analysis for parameters. Mean values and standard deviation for geological part gained from GIS program which used for establishing the geological model and for hydrogeological and geotechnical parts, by using some references data which provided by related researches, see Table 2.1.

Probabilistic model run in Crystal Ball for different number of trials. In this thesis 500 and 2500 trials were performed to see the effect of trials number on the final results. After this step, it seen that different trials give a small difference for final results.

After finishing the simulation for probabilistic model, main part is extracting the data from model and then arranges them for exporting to the Surfer program which used to demonstration the final results. Surfer helps to visualize the results better by using different kind of maps.

Extracting the data makes it possible to have important information about different locations. In fact, it provides tables for statistics such as mean values and standard deviation and different percentiles for each location and sensitivity analysis data of assumptions. Table 3.1 shows the different information which Crystal Ball provided after extracting the final results.

Table 3.1 Different types of results which contributed from extracting the data.

Statistics	Percentiles
Trials	5%
Base Case	10%
Mean	50%
Median	90%
Mode	95%
Standard Deviation	

3.4 Assumptions and simplifications

Deterministic model deals with a single value for settlement in each cell. As this model considered a large area and also because of varieties of parameters which affect the final results, making some assumption and simplifications became necessary to cope with parameters variability and region size. A brief description of some of the main assumptions and simplifications illustrates here.

In conceptual modelling, soil strata involve four layers for whole area. Soil layering consist of two clay layer with a sand layer between them and a layer of till which placed beneath of them. This stratum considered for whole area for simplifying the model. In addition, after defining and calculating the different parameters, settlement in each cell calculated based on two clay layers and total settlement comes from settlement in these two layers.

Furthermore, soil modulus and hydraulic conductivity considered as constant in each layer, moreover OCR numbers which used to estimate preconsolidation stress in cooperation with effective stresses chose as constant in each layer.

Finally, Settlement calculated in the middle of each clay layer to have average value in the layer. By having more data provided by in situ and laboratory tests, some of the stated assumptions can be fixed in the model and accuracy of the results can be increased.

4 Result and Discussion

In this chapter results from integrated model will be presented. Final model which established in excel shows the results of settlement in different area based on corresponding level of ground water drawdown.

4.1 Excel Based Model

As it describe in chapter 2, due to the aim of this project which was risk analysis of ground water drawdown in settlement sensitive areas, an Excel based model chosen for calculating the settlement based on coordination of each point. This model can run in Crystal Ball program and results for different trials of simulation can be interpreted for probabilistic approach.

As described in chapter3, groundwater model which depends on soil model and conductivity of soil material, used for calculating the pore water pressure and excess pore pressure in settlement model. According to soil model total stress (σ), pore pressure (u) and effective stress (σ') for different elevations calculated in excel model. Excess pore pressure which resulted from difference between initial and final ground water levels also calculated in same elevations. As mentioned in Chapter 3 for soil modulus (M_L) data from pre study used and due to the simplification in model same values considered in each layer. In addition for preconsolidation stress values for OCR and effective stress in each layer utilized and amount of preconsolidation in different location estimated.

The amount of settlement in each cell calculated based on formula (3.1) and maximum amount of settlement which is near the tunnel construction place identified. Results from Excel model checked with GS Settlement to see how accurate is the calculations which will describe in next part.

After accomplishing the deterministic model and as it has uncertainty, both due to the lack of data in certain areas and also investigation methods, stochastic variables and probabilistic model should be used. By doing this, it is possible to estimate the uncertainty of the model and deciding which parameters affect the results. Probabilistic model established by defining the distribution for different parameters. Following that, model ran in Crystal Ball to gain necessary information for uncertainty and sensitivity analysis of data. Since, parameters in the model are given stochastic variables, a Monte Carlo simulation can be performed.

A significant part in probabilistic model is to define a probabilistic distribution function to related parameters which affect the results. For this reason, coefficient of variation can be useful. The mean values and standard deviations as two main concepts for normal and lognormal distribution provided from literature study and pre research which implemented about uncertainty of parameters ,see Chapter 2 and in particular Table 2.1.

Important parameters in Geotechnical parts which investigated are unit weight of soil, OCR number and Soil modulus. Also soil thickness and hydraulic conductivity of clay layers considered in geological and hydrological models which provided from two parallel researches. A small standard deviation equal to 5% considered for unit weight of soil (V[γ] =5%).This uncertainty can comes from type of clay, e.g silty clay or normal one. For soil modulus and in both clay layers coefficient of variation equal to 25% was chosen. For OCR which affect the preconsolidation in the model, coefficient of variation equal to 20% selected and used in defining the probabilistic distributions.

For geotechnical parameters normal distribution chosen and for hydraulic conductivity lognormal distribution was chosen. Figure 4.1 shows how the mean value and standard deviation utilized in crystal ball to define distribution for soil modulus in top clay layer.

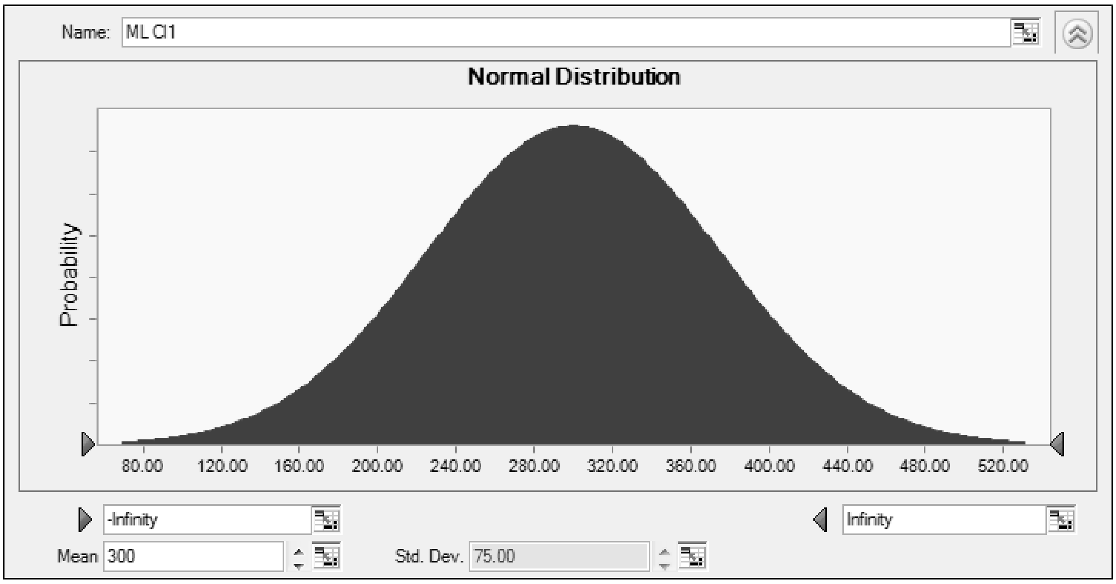


Figure 4.1 Defining distributions for soil modulus in crystal ball software.

4.2 Comparison between Excel and GS Settlement

For validation of results which contributed form calculation in deterministic model, a comparison of final settlement values between GS Settlement and Excel were performed. For this reason, two different points were chosen. First point considered as a point near the tunnel location which has one of the highest settlement values due to the high groundwater drawdown. Second point chosen 120m far from tunnel location which less affected by groundwater reduction. Figure 4.2 displays the amount of settlement in subjected points which calculated by Excel model. Tables 4.1and 4.2 show the input values for both points.

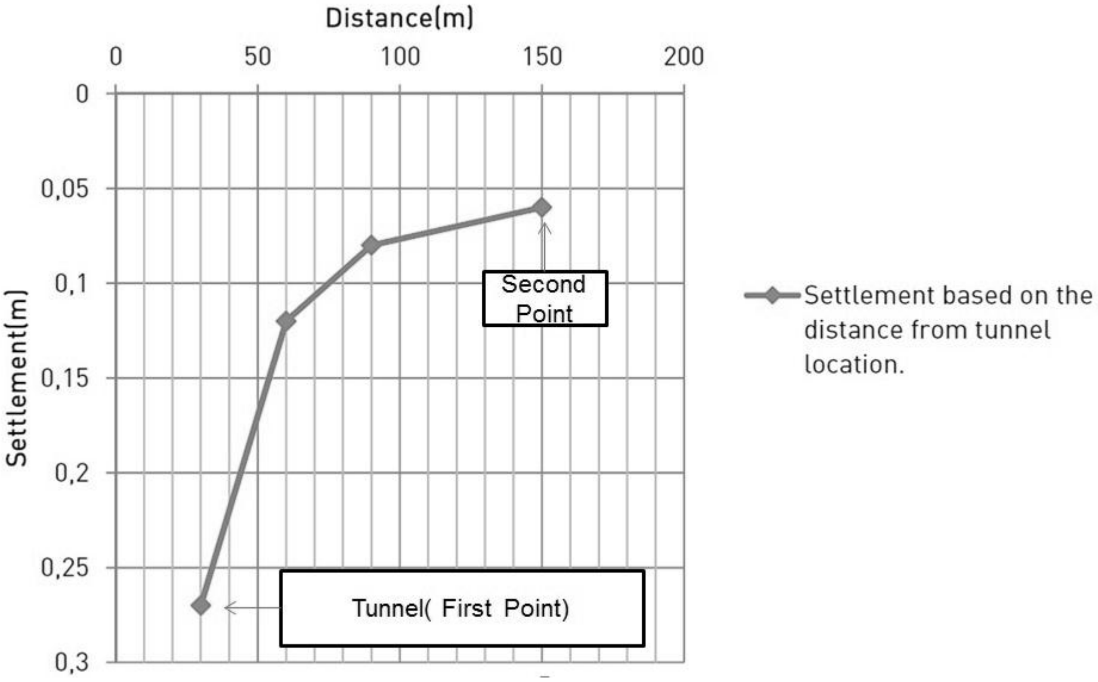


Figure 4.2 Calculated settlements in two subjected points. Near the tunnel location and 120 meter far from it.

Input parameters for using in GS settlement are presented below. In GS settlement different model are available for calculating the settlement. Here Chalmers model without creep used for estimating the displacement.

Table 4.1 Input parameters for GS settlement.

Depth(m)	Unit Weight(kN/m^3)	M0(kPa)	ML(kPa)	M'(-)	Sigma' C(kPa)	Sigma' L(kPa)	Kinit(m/s)
0	18	5000	200	1	7.5	8.5	0.032
1.8	18	5000	400	1	7.5	8.5	0.032
1.8	16	15000	15000	1	100	150	32
3.4	16	15000	15000	1	100	150	32
3.4	17	5000	700	1	47	53	0.032
8.3	17	5000	700	1	47	53	0.032
8.3	19	30000	30000	1	150	200	0.32
10.5	19	30000	30000	1	150	200	0.32

Table 4 .2 Input parameters of GS settlement for point with 120 meter distance from tunnel.

Depth(m)	Unit Weight(kN/m^3)	M0(kPa)	ML(kPa)	M'(-)	Sigma' C(kPa)	Sigma' L(kPa)	Kinit(m/s)
0	17	5000	200	1	2.5	4	0.032
0.8	17	5000	400	1	2.5	4	0.032
0.8	18	15000	15000	1	100	150	32
1.2	18	15000	15000	1	100	150	32
1.2	17	5000	700	1	21	30	0.032
3.85	17	5000	700	1	21	30	0.032
3.85	19	30000	30000	1	150	200	0.32
8.5	19	30000	30000	1	150	200	0.32

Figure 4.3 shows the amount of total settlement for the point near tunnel location.

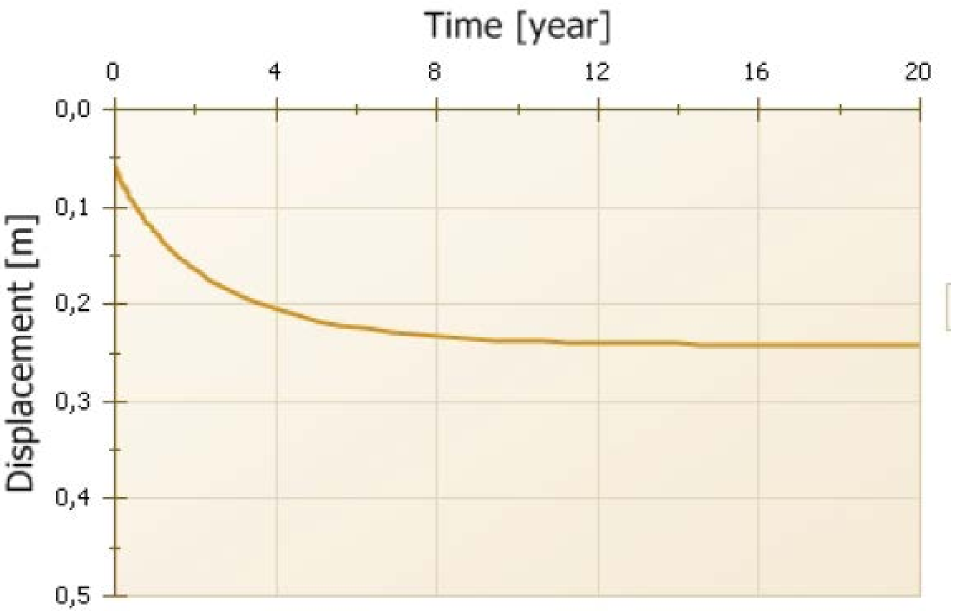


Figure 4.3 Result from settlement calculated with GS settlement for point near the tunnel.

For second point which located 120 meter far from tunnel, input data according to Table 4.2 were chosen for GS Settlement. Result for total settlement for this point shows in figure 4.4.

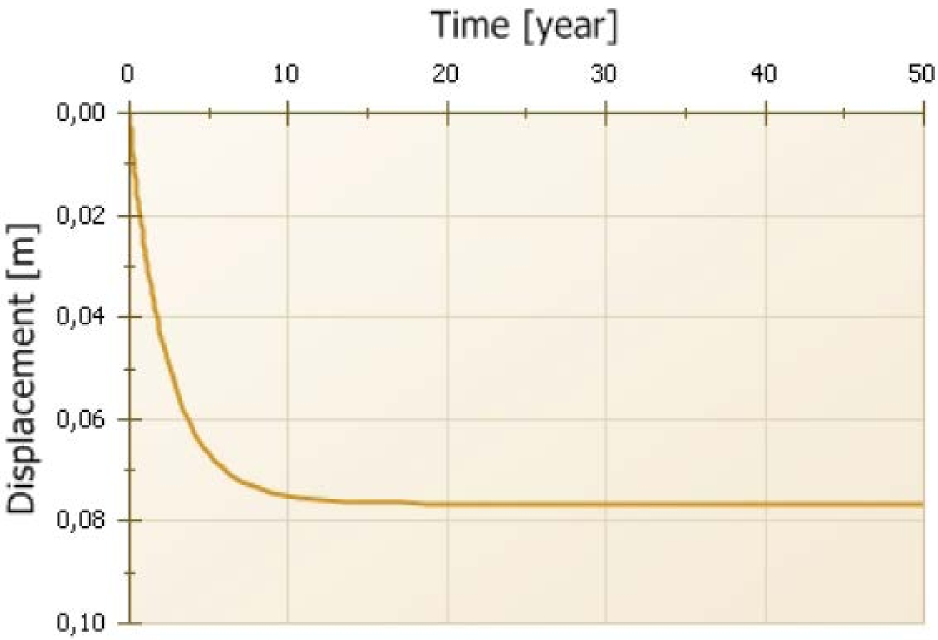


Figure 4.4 Settlement for point with 120 meter distance from tunnel.

According to results from GS settlement for different points and also results from Excel for corresponded points, it can be seen that Excel model demonstrates approximately accurate result based on input parameters. It should be mentioned that having accurate results for settlement calculation need accurate values for soil parameters which contributed from in situ and laboratory tests such as CRS test and also more advance programs which are available for calculating the settlement. But as it mentioned before, this model established in Excel to have the possibility of using Crystal Ball program and also probability analysis of results.

4.3 Visualizing the results

Visualizing of groundwater levels, subsidence and uncertainty and sensitivity analysis on a map, creates direct information for decision makers and others involved in the project.

Program called Surfer used here for demonstrate the output and results of model. As it described in Chapter 3, extracted data from Crystal Ball simulation were used in Surfer. By doing this, different alternatives for visualizing the results are possible. By visualizing the output from model, it is achievable to compare different statistics, for example for 90th and 95thpercentiles. Many maps were available from the model, but here some of the main results which fulfilled the aim of this study will be presented.

By considering a critical value for settlement, it is possible to determine the areas which have settlement values below the critical one or bigger than that.Here critical amount of settlement chose as 50 mm. Figure 4.5 shows a contour map where 50 mm settlement is marked with a black line. The left figure is the 90th percentile and the right is the 95th percentile for settlement. It can be seen that the 95th percentile of 50 mm has a larger area than the 90th percentile of 50mm settlement. It should be mentioned that choosing higher percentiles means higher safety and in this project means more safety for not having the damaged buildings.

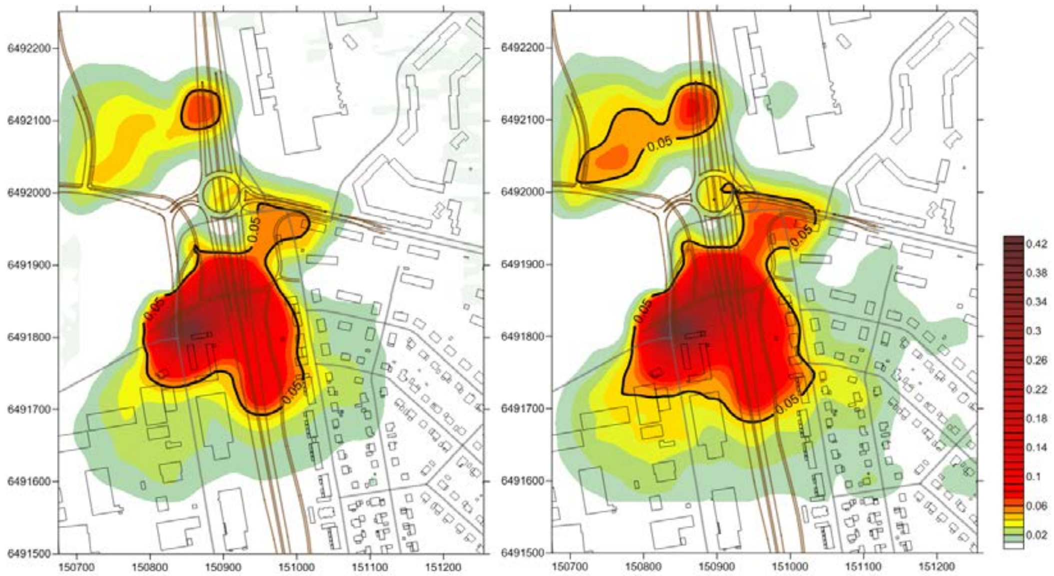


Figure 4.5 Left picture is 90th percentile and the right one is the 95th percentile for 50 mm settlement as critical value.50mm settlement marked with black line.

Standard deviation is a factor which considered as a boundary for the results. Actually, standard deviation explains the uncertainties of the results. In fact, a large standard deviation means the uncertainty is greater. Figure 4.6 displays standard deviation of 20 mm for settlement and also 95th percentile for 50 mm settlement. Combination of these two figures also can be useful. By combining these two factors, it is possible to get this figure where the red line represents the 95th percentile of 50 mm and the black line the standard deviation of 20 mm. As it described in Chapter 3, residential building around the tunnel construction are in risk for settlement. Figure 4.7 shows the buildings within the area of not acceptable risk which coloured in blue.

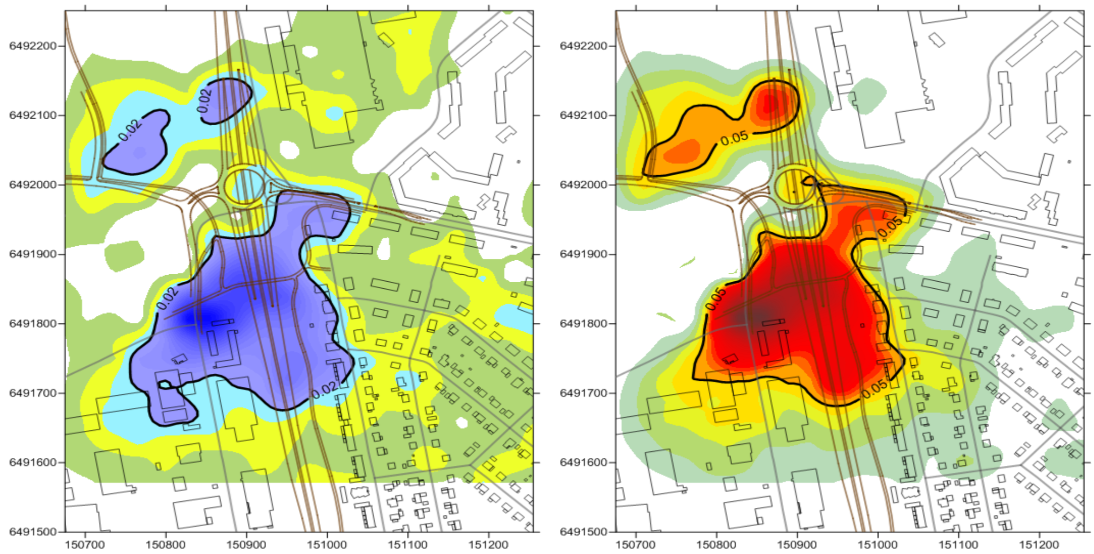


Figure 4.6 Standard deviation of 20 mm for settlement (left) and also95th percentile for 50 mm settlement (right).

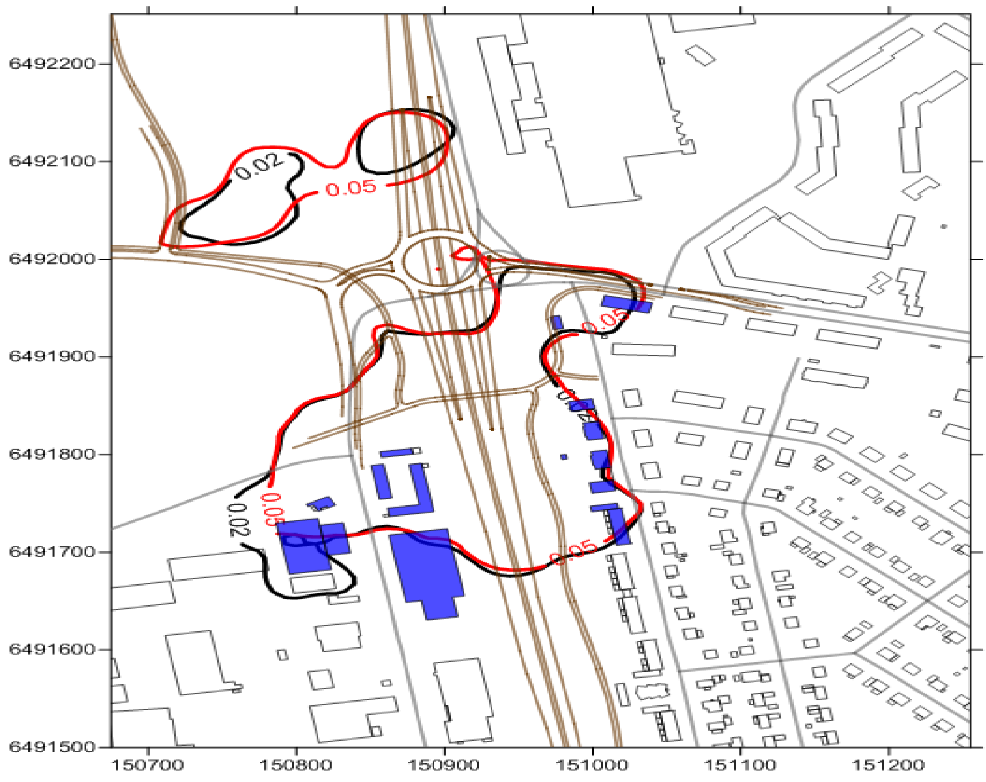


Figure4.7 Red line represents the 95th percentile of 50 mm and the black line the standard deviation of 20 mm. The buildings within the area of not acceptable risk are colored in blue.

4.4 Sensitivity analysis

An important task in the modelling of this project is sensitivity analysis of the model. In other words, it is necessary to know which parameters have most effect on the calculation results and in special inside the risk areas, in order to prioritize the measures and further needed investigations.

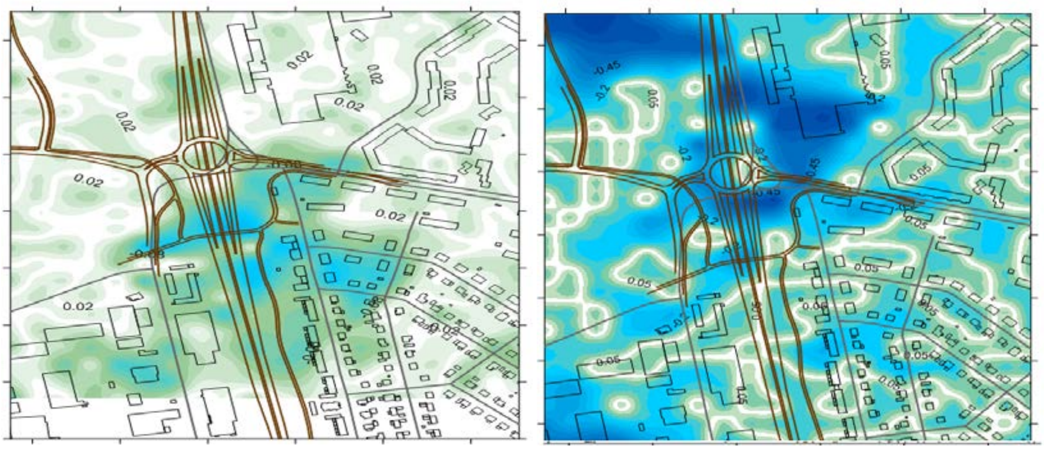
As Crystal Ball used for probabilistic study, different alternatives for sensitivity analysis were available. Crystal Ball calculates the sensitivity by computing the rank correlation coefficient between every assumption and every forecast when model simulation is running. Correlation coefficient helps to identify which assumption and forecast change together. When coefficient of correlation is high between an assumption and forecast, it means that the assumption has great impact on forecast. When coefficient is positive, it shows that an increase in assumption is connected with an increase in forecast. Negative coefficient displays a reverse behaviour (Gentry, 2008).

The program has different type of sensitivity charts on view menu which can use for demonstrate the results. One of the common ways which is a default view in the program is Contribution to Variance. This method helps to interpret the rank correlation. This option displays the direction of each item's contribution to the target forecast's variance.(Gentry, 2008).In this type, items with positive contribution has bars on the right of zero line and describe the direct relationship between the assumption and target forecast. In addition, items with negative contribution show the inverse relationship between item and target forecast and display on the left side of zero line. Also percentages of this contribution appear in this kind of charts.

The method is an approximation method and is not precisely variance decomposition. Program calculates the contribution to variance by squaring the rank correlation coefficients and normalizing them to 100 % (Gentry, 2008).

In this thesis, method called Sensitivity data used which actually shows the contribution to variance for each assumption in numeric form (Crystal Ball help, 2012).

After extracting the data, the output also contains sensitivity data which utilized for sensitivity analysis here. Selectivity analysis by Sensitivity data method from Crystal Ball can be used for each parameter or all parameters together. Figure 4.8 shows effect of some parameters in the model. Dark blue is the area with most influence and white represents the least influence.



(a) *(b)*

Figure4.8 Sensitivity analysis for parameters in model.(a)Conductivity in clay (b) OCR in clay layer one. Dark blue is the area with most influence and white represents the least influence.

The parameters in the model have different magnitude of influence. By comparing the parameters, sensitivity map can be produced where parameters with the most influenced can be presented. This kind of map can be connected to such a map in Figure4.7. Consequently, it is possible to see what parameters need to make further investigation about. Figure 4.9 displays the resulted sensitivity map for different parameters in the whole area. As Figure shows, OCR in second clay layer has largest uncertainty in the model. Inside the risk area, thickness of clay gives the biggest uncertainty.

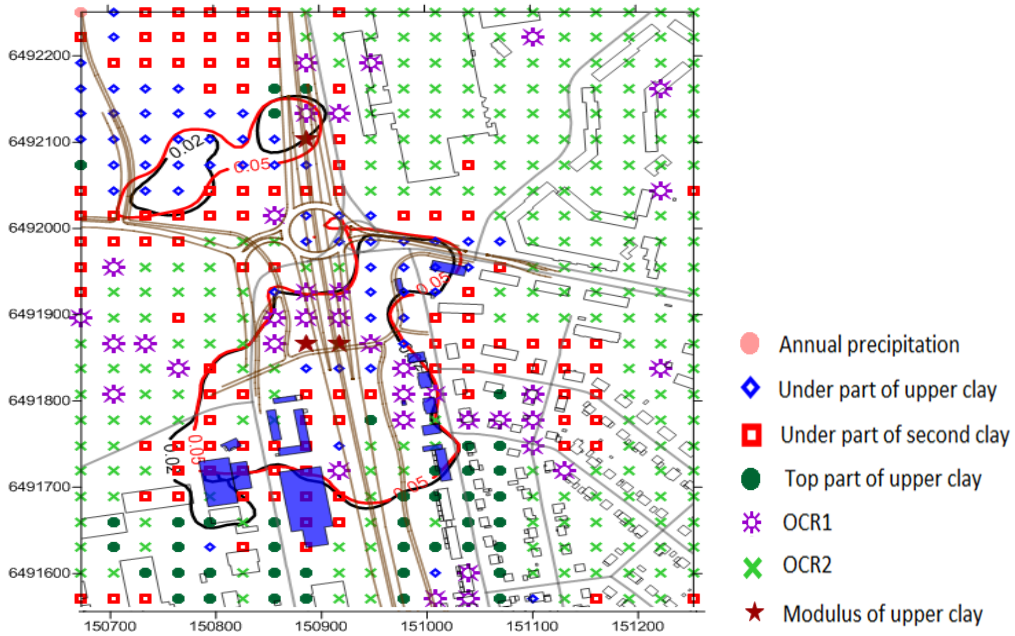


Figure4.9 Sensitivity map for influence of parameters in combination with risk analysis map. It is possible to see what parameter to make further investigations about.

5 Conclusion and further research

5.1 Conclusion

As overall conclusion it can be seen that by using the described model, risk of settlement due to ground water reduction can be presented in a better way. By this kind of visualize maps, it is possible to have a better discussion with responsible persons in similar projects and better decision can be taken by using such a model. In other word, by using this kind of model to accurate risk prediction, making decision become more efficient. Moreover, cost of risk reduction measures will be reduced and communication about the risks between stake holders, authorities and contractors will be improved.

The model makes it possible to compare the importance of parameters. In addition, uncertainty can be quantified in such a model. The model consist of different parameters in geological, hydrogeological and geotechnical fields that can be used as an integrated model which will be more precise by using obtained data from related in-situ and laboratory tests.

Many suggested techniques in this thesis, such as ground water and subsidence modelling, assessing the parameters variability with probability density function and geostatictics, are developed in separated programs but not fully integrated. Described integrated model in this thesis can provides a basis for more efficient prioritization of measures, decrease the risks of harmful subsidence and reduce unexpected project risks.

Results of model demonstrate that OCR in second clay layer has largest uncertainty in the model and thickness of clay also gives the uncertainties in risk area where residential building can be affected by settlement. Due to these uncertainties, it is suggested that further investigation should be performed for the area where 95th percentile of 50 mm settlement and 20 mm standard deviation overlap.

5.2 Further research

The following points have been identified for further research work

-Study the dependencies between parameters and see how it can affect the results.

-Considering secondary consolidation for establishing the deterministic and probabilistic models.

-Develop the soil model by considering the heterogeneity and sampling error.

-Develop a methodology which takes costs of additional data or alternative measure in to the account and then compare the costs with the benefits of reduced risks for incorrect decisions.

-Development of such a model for describing ground water drainage and possible subsidence where conceptual model further developed into numerical modelling such as finite differences and finite elements methods.

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