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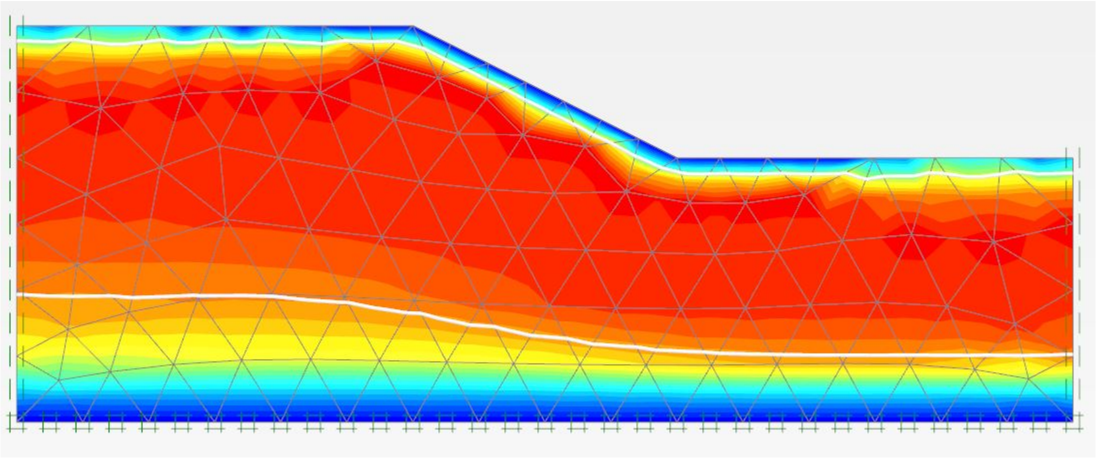

On the Feasibility of Slope Stability Analysis during Freezing and Thawing

Master's thesis in Master Program Infrastructure and Environmental Engineering

Gustav Sjöbeck

Department of Architecture and Civil Engineering
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Master's thesis ACEX30
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Cover: Plot of the heat profile of a freezing soil sample.

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Abstract

The topic for this thesis is to investigate slope stability in relation to climate driven condition changes. Focus was directed on freeze and thaw process of soil and how it affects the stability of slopes. This is then linked to a case study close to Bispgården in Sweden. The Bispgården case had strong indications of frost related damages. The thesis further present freeze and thaw related movement and behaviors of the soil. Mainly focusing on phase change, displacements, water and ice saturation and heat distribution within in the soil body. The *frozen and unfrozen soil model* in PLAXIS was used to model the behavior of a freezing and thawing soil. Resulting in a analyze that indicated a reduction of the slope stability in a semi frozen stage. However, was the use of this model numerically challenging and very sensitive to parameter changes. The conclusion could be drawn that the feasibility of accurately analyzing freeze and thaw related stability problems are limited, due to the high prerequisite. Very specific data- and skill-sets are needed to utilize the potential. This could be problematic with the potential effects of the ongoing climate change in mind.

Keywords: Slope stability, freezing soil, thawing soil, phase change, frozen and unfrozen soil model.

Om genomförbarheten av släntstabilitesanalys under frysning och töning

Masteruppsats inom masterprogrammet Infrastruktur och miljöteknik

GUSTAV SJÖBECK

Institutionen för Arkitektur och samhällsbyggnadsteknik
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Sammanfattning

Ämnet för den här mastersuppsatsen är att undersöka släntstabilitet i relation till klimatdrivna förhållande förändringar. Uppsatsen fokuserade på frys- och tiningsprocesser i jorden och hur de påverkar släntstabiliteten. Detta kopplades till ett projekt nära Bispgården i Sverige. Projektet i Bispgården visade starka indikationer på frysrelaterade skador. Uppsatsen presenterar hur frysning och tining påverkar rörelser och betende i jord, framförallt fasbyte, förflyttningar, vatten- och ismättnad och värmedistrubition i jordmassa. Den *frozen and unfrozen soil model*-modellen användes i PLAXIS för att modellera den frusna och tinande jordbetendet. Det resulterade i en analys som indikera en reduktion i stabiliteten i en halvfrusen slänt. Dock, var modellen svår att hantera numerskt och känslig för förändrade parametrar. Uppsatsen visar att det finns begränsningar för hur användbar analysmetoden är, särklilt på grund av de höga förkunskapskraven. Väldigt specifik data och kunskap krävs för att kunna använda modelen till sin fulla potential. Detta kan vara problematiskt med effekterna av den pågående klimatkrisen i tanken.

Nyckelord: Slänt stabilitet, jord som fryser, jord som töar, fasförändring, frusen och ofrusen jordmodell

Acknowledgements

There is a large probability that this thesis is my last educational task. I do want to take the opportunity to thank and show my gratitude to those whom deserve.

A large thank you to every one at the division of Geology and Geotechnincs here at Chalmers University of Technology. Especially Jelke Dijkstra and Ayman Abed, you did not only teach, but also sparked a genuine interest in geotechnics.

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At last, thanks to all my friends, family and others that have inspired, helped and cared for me throughout the work with this thesis and my education.

Gustav Sjöbeck, Gothenburg, June 2023

List of Acronyms

Below is the list of acronyms used throughout the thesis, listed in alphabetical order:

BC	Boundary Conditions
CPT	Cone Penetration Test
FTC	Freeze-Thaw Cycle
F-U	Frozen and Unfrozen soil model
NBS	Natural Based Solution
SGI	Swedish Geotechnical Institute
SGU	Geological Survey of Sweden
SF	Safety Factor
THM	Thermo-Hydro-Mechanical

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1

Introduction

Climate change is and will be a future challenge for geotechnical engineers (Vardon, 2015). One example of climate change is the changing weather patterns including longer droughts, more intense rainfall and changed seasonal shifts (Vahedifard et al., 2018). These are all factors that in the end will impact ground conditions and thereby also the stability of natural and artificial slopes (Lollino et al., 2014). Natural and constructed slopes are common all over the world. Failing slopes could cause damages to structures, infrastructures and property. Historically has landslides had fatal outcomes not only in Sweden but globally (Kirschbaum et al., 2012; Viberg, 1989).Therefore is it important to understand and be able to analyze the failure mechanisms of slopes, during changing conditions due to environmental changes.

The original idea for this master thesis was to model and evaluate the feasibility to increase the stability of a partially saturated silty slope under increased precipitation with nature based solutions (NBS). The thought behind this was to understand and model the effects of climate driven changes to slope stability. Moreover study the potentially mitigating effects from vegetation, as a NBS, both mechanically and hydraulically.

During 2002 the Swedish Geotechnical Institute (SGI) started a set demonstration trails of different types of NBS in Bispgården, region of Jämtland, Sweden, see Figure 1.1.

Figure 1.1: Location of Bispgården (Lantmäteriet, n.d.)

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The trails were summarized in the rapport *Växter som skydd mot erosion och ytliga ras i branta jordslänter Demonstrationsförsök i Bispgården och Bydalen* by Lundström and Andersson (2008), and were chosen as a reference project for this thesis. The trails where separated into two different main locations. Several smaller types of NBS where tested along roadsides in the area of Bydalen, west of Östersund. These test had very limited geotechnical data. More extensive research was conducted at the other test site close to the village of Bispgården, east of Östersund. The Bispgården test site consisted of a cut slope of approximately 30° in silty soil, where different types of NBS were tested in sections alongside a traditional slope stabilisation method. Unfortunately, the two test sections of the slope failed in the spring of 2006, prematurely ending the project. Interestingly was not the spring of 2006 the first time the slope sections experienced structural problems. The prior spring did the slope experience frost- and thaw processes force-full enough to break roots and branches that where parts of NBS and did fill installed drainage pipes with soil. See Figure 1.2 and Figure 1.3 to compare the slope before and after the first winter.

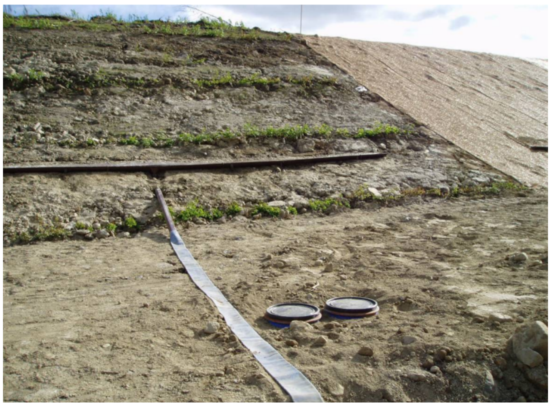


Figure 1.2: The slope in the summer of 2004 (Lundström & Andersson, 2008).

Figure 1.3: The slope in the spring of 2005 (Lundström & Andersson, 2008).

This lead to the suspicion that frost- and thawing cycles could be the biggest threat to stability of this slope and moreover slopes in general with similar conditions. Research connecting frozen soil with slope stability is very limited (J. Dijkstra, personal communication, Feburary 23, 2023). Therefore did the focus of the thesis change from modeling the potentially slope stabilizing effects of the NBS, to modeling the potentially destabilising effects of the freeze-thaw cycle (FTC). Still within the overall theme of the thesis: slope stability and climate driven condition change. Especially considering rapid weather changes from cold weather, well below freezing, to warmer weather with summer temperatures just within a short period of time. These rapid weather changes seems to be more common in northern part of Sweden the future (Nylén et al., 2015).

1.1 Aim

The task to find out exactly how the slope in Bispgården failed is next to impossible; the geotechnical data available is too in-comprehensive and it would risk leading to a game of educated guesses. Instead will the aim of this thesis be to try identify, explain and model the potential failure of a silty slope in a sub-arctic climate, exposed to seasonal FTC. An idealisation of the original slope will still be used as the basis for the model. The thesis will focus on the phase changes in the soil during freezing- and thawing processes and will try to evaluate the slope stability at critical points in the analysis.

1.2 Research Questions

To reach the aim of thesis the following research questions need to be answered:

- Can freezing and thawing behaviors implemented into a finite element soil model?
- How is the freezing- and thawing processes incorporated in the stability analysis for a marginally stable silty slope?
- Does the freezing- and thawing process have the potential to make the slope in Bispgården fail?

1.3 Methodology

The first research question will be answered by a literature study and thereby set the basis for the modelling, that will be used to answer the following two research questions. To answer research question two and three modelling and analyses will be done on a test sample and a marginally stable silty slope located in Bispgården with finite elements using *the Frozen and Unfrozen Soil Model* by Ghoreishian Amiri et al. (2016) in *PLAXIS 2D Ultimate*.

1.4 Limitations

The calculations of this thesis will be limited to one specific slope located in Bispgården, northern Sweden and a test cube. The potential failure mechanism analysed will not be unique to the problem at hand, hence will this not be a complete list of causes of potential failures for all silty slopes exposed to freezing and thawing. Moreover no outside impact on the slope except freezing and thawing and thereby temperature and time will be considered as potential stability threats to the slope. This eliminates perhaps the most probable cause of slides: direct human activity (Sällfors, 2013).

Further this thesis is limited to a two-dimensional representation of the three dimensional problem. It is important to remember that the model is a simplification of the reality and should not be confused with reality itself. This means that results of the analysis in a pure sense will be answer to what happens in the model and not in reality. The hope is that model is an accurate enough representation of reality so that relevant conclusions can be drawn. The freeze-thaw behavior is complicated to model with several different components as: water flow, temperature flow, time and changing soil properties. These components are hard to control, as many of the parameters used to govern these components are uncommon to use in geothechnics. Therefore is also data often missing about the cite specific parameters describing the freezing and thawing of the soil.

2

Theory

Freezing of soil or rather the freezing of water in soil starts to occur when temperatures drop below 0 °C or 273.15 K in atmospheric pressure (Burström, 2007). If water is available then this result in transformation of the affected soil, referred to as a phase change (Williams & Smith, 1989). The soil changes from a granular material to a frozen continuous composite, composed of a polycrystaline ice-body filled with soil particles, unfrozen water and air voids (Ting et al., 1981), as seen in Figure 2.1. Resulting in a new set of properties and behaviors compared to "normal" unfrozen soil.

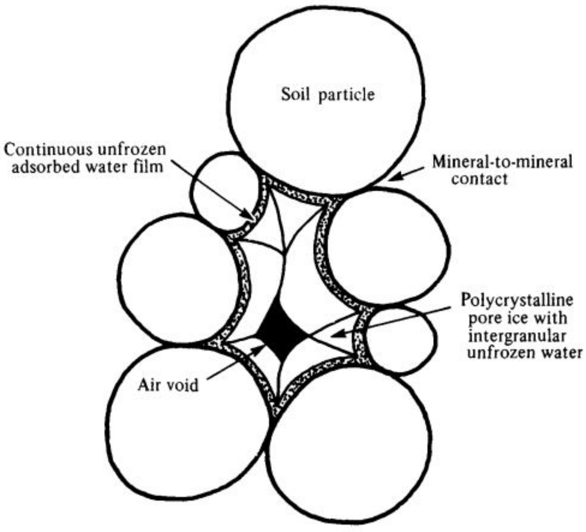


Figure 2.1: Structural elements of a frozen soil (Ting et al., 1981).

In a natural setting is it not unusual for a soil to experience cyclic periods of freezing and thawing, depending on its location on the globe (Williams & Smith, 1989). These FTCs could be long term with several months in the frozen- or unfrozen stage as a result of cold winters and warm summers. In very cold locations, close to the poles or in high mountain areas could the ground be permanently frozen. This is referred to as permafrost (Tsytovich, 1960). Raised temperatures due to global warming will result in a thawing process of permafrost. This could result in changed geotechnical conditions in often remote locations (Jorgenson et al., 2010), which could require increased geotechnical knowledge of the frozen soil and its connection to slope stability.

The change or time interval of each phase could also be quite shorter with temperature changes throughout the day and night. These slow or rapid phase changes could result in a number of different phenomenons causing deformations and stability changes to the soil itself. The freezing or thawing soil could also cause deformations and pore pressure changes that will affect stability of soil formations, as slopes (Williams & Smith, 1989). Soil deformations could cause damages to structures in, or around, the soil as retaining walls, piles, buildings and roads (Williams & Smith, 1989). This chapter will firstly explain the general freezing and thawing behavior of the soil and further how it could be implemented into a finite element analysis. Lastly will the freeze-thaw process be related to the potential impact on slope stability and how it could be calculated.

2.1 In Situ Freezing of Soil

The freezing of soil could be the cause of several different factors. Occurrence of frozen soil is often dependent on the local climate, as mentioned above will the soil have to experience sub 273.15 K (0 °C) temperatures to begin to freeze. In a natural soil without buried or surrounding structures is the main cause of temperature change the temperature change of the air above ground (Pal Arya, 1988). Another way for frozen soil to develop is artificial freezing. Artificially frozen soil could in larger scales exist as a result of cold pipes or cold houses (Williams & Smith, 1989). Artificial freezing is also used in construction projects as it increases the strength and stiffness of the affected soil (Wang et al., 2008). However this thesis will only focus on cyclic seasonal freezing caused by changing air temperatures in the air above the ground.

2.1.1 Seasonal Cyclic Freezing and Thawing of Soils

Typically the freezing of soil start when air temperatures drops below 273.15 K. On the northern hemisphere this usually occur in the fall or winter. In the start of the freezing process the soil retain heat from previous the warmer period (Badache et al., 2016). This will result in a freezing process where the very top layer of the soil will start to freeze first, as it is in contact with the cold air. As the cold persist will the depth of the frozen layer start increase with depth (Badache et al., 2016). The speed of the freezing is determined by a number of factors; the starting temperature of the soil, the temperature of the air and the water saturation of the soil (Williams & Smith, 1989). It has been observed that the temperature 5- 10 m down in the ground rarely deviates far from the yearly average temperature, depending on the soils ability to transfer heat (Badache et al., 2016). Thus creating a lower boundary with a fairly constant temperature (Badache et al., 2016). In areas without permafrost this temperature exceed 273.15 K and thereby stop the advancement of frozen soil (Williams & Smith, 1989) which will limit the potential maximal thickness of the frozen layer.

The thawing process in a similar manor also start from top as the main driver of the change is air temperature and sun radiation (Badache et al., 2016). Measured thawing rates is 90% from above and 10% from below (Williams & Smith, 1989), resulting in a uneven thawing process where different parts of the soil will have different temperatures and therefore be in different phases. During the thawing could the soil stratification be simplified into three different layers, see Figure 2.2. In an seasonal thawing soil the bottom layer of the soil will be unfrozen as a result of the constant temperature around the yearly average. The second layer above the permanently unfrozen bottom, consists of a thawing frozen layer. The top layer will be the first to thaw.

Figure 2.2: The potential stratification of a thawing slope, authors own illustration.

2.1.2 Stability Changes to Seasonal Freezing and Thawing of Soils

The unfrozen top layer above frozen soil could cause stability problems (McRoberts & Morgenstern, 1974), especially in slopes. The freezing of soil could cause deformations and geometry changes of slopes. Frozen soils does also have an increased saturation limit, potentially further destabilizing the slope when thawing by releasing water and thereby increasing the pore-pressure in the top part of the soil (McRoberts & Morgenstern, 1974). Fast temperature changes as the difference between night and day will also result in phase changes that just affect the very top layer. This could cause other phenomenons as wondering soil (Williams & Smith, 1989).

2.2 Physical Behavior of Frozen Soil

During the freezing will the water experience a volume increase of approximatly 9% (Burström, 2007). This volume increase alone is known to be powerful enough to break stone and concrete (Burström, 2007). Even tough this is not the only problematic effect from a geotechnical standpoint, the expanding effect from ice in the soil is further increased by frost heave due to cryogenic suction.

2.2.1 Frost Heave

The formation of continuous ice bands or lenses, as seen in Figure 2.3, is often referred to as frost heave (Williams & Smith, 1989). Frost heave, as name implies, cause a heave or displacement of soil that is mainly vertical. Predicting the scale of the heave with given conditions is peculiar as the mechanisms behind the formations of ice bands is not fully understood. In theory could the thickness of the ice lenses grow to be infinite, but in practice does the volume increase of a sample rarely exceeded 20% (Ghoreishian Amiri et al., 2016; Williams & Smith, 1989). The heave could together with the pure volume increase cause deformations and breakage on surrounding structures for example buildings, roads and retaining structures. Frozen soil itself is usually quite strong as will be discussed in Section 2.3. This could result in that the severity of frost heave related damages are not apparent until the thawing of the soil (Williams & Smith, 1989). During thawing could the bearing and stability of soil be additionally weakened by excess water from the increased saturation limit of frozen soil (Rempel, 2010). Large pore water pressures could be accumulated depending on draining capacity of the soil and thereby lower the cohesion. The melting of the ice will also cause a shrinkage back to the normal soil volume. Every freeze-thaw cycle could also reduce the strength of inter-molecular and cementing bonds between soil grains, reducing strength further (Rempel, 2010).

Figure 2.3: Frozen soil experiencing frost heave, showing ice-lenses/bands (Williams & Smith, 1989)

2.2.2 Crygenic Suction

The cause of the ice-lens formation is mainly due to a phenomena known as Cryogenic suction (Thomas et al., 2009). The effect of cryogenic suction is the formation of premelted water formed around soil grains as a skin or film. The cryogenic suction is lowering the bulk temperature required to freeze water by increasing the pressure and mainly affects water very close to soil grains. This effect is the result of two mechanisms: curvature-induced premelting and interfacial premelting (Ghoreishian Amiri et al., 2016; Rempel, 2010), illustrated in Figure 2.4.

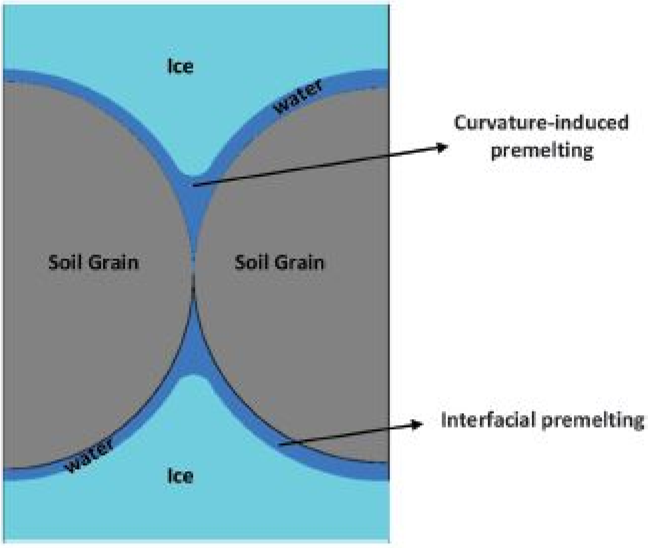


Figure 2.4: Illustration of premelting mechanism (Ghoreishian Amiri et al., 2016).

The curvature-induced premelting is created by surface tension and the interfacial premelting is an effect of repelling force between the ice and grains, often widening the gap between particles and sucking in more water (Ghoreishian Amiri et al., 2016). Additional water can also be sucked in from surrounding sources and adjacent layers through premelted canals in the soil skeleton (Yersov, 2004). The amount of additional water absorbed by the frozen soil could greatly exceed the amount of water the unfrozen soil could absorb (Williams & Smith, 1989). According to Yersov (2004) could the maximum moisture capacity be 3-4 times higher than the normal upper plastic limit. In a fully saturated material could the equilibrium between water and ice be described as a function of cryogenic suction. The cryogenic suction is described by the Clausius-Clapeyron equation, Equation 2.1. Accordingly could the ice content in the soil be calculated as an effect of the cryogenic suction (Aukenthaler, 2015), (Ghoreishian Amiri et al., 2016).

$$S = p_i - p_w = -\rho_i L ln \frac{T}{T_0} \tag{2.1}$$

S = cryogenic suction
p_i and p_w = pressure of ice and water
ρ_i = density of ice

L = specific latent heat fusion
T = de facto temperature
T_0 = freezing/thawing point at given pressure

The water skin exciting in-between particles and the ice in frozen soils does imply that the surface area of the grains them self have a large impact on the content of ice vs. water, as the amount premelted water is dependent on the surface area of the soil grains. The frozen water content for some different soil fractions is described by Williams and Smith (1989) in Figure 2.5. This is also described by Anderson and Tice (1972) in Figure 2.6. Anderson and Tice (1972) also confirms that the unfrozen water content in ice is dependent on the soil type but also temperature, pressure, surface area of the soil grains, the compositing of the soil and other physio-chemical characteristics. Although temperature is still the most important factor (Tsytovich, 1960).

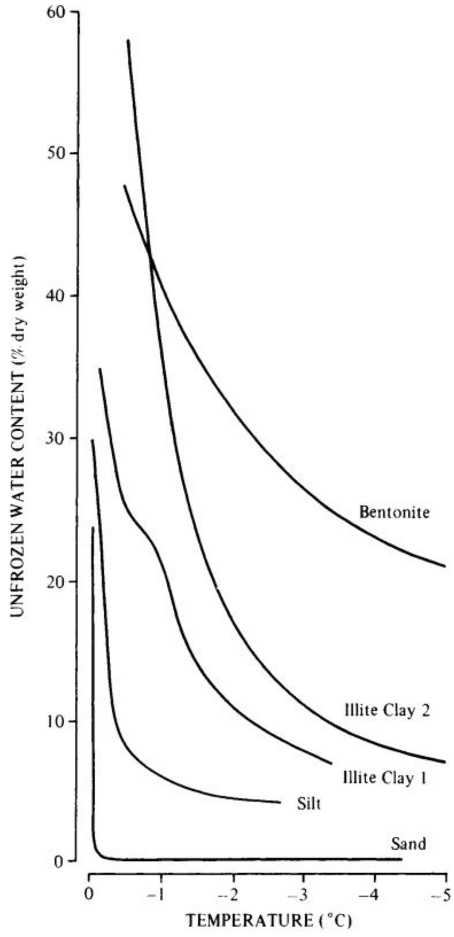


Figure 2.5: Amount of unfrozen water in different soil types at approx -5°C to 0°C (Williams & Smith, 1989).

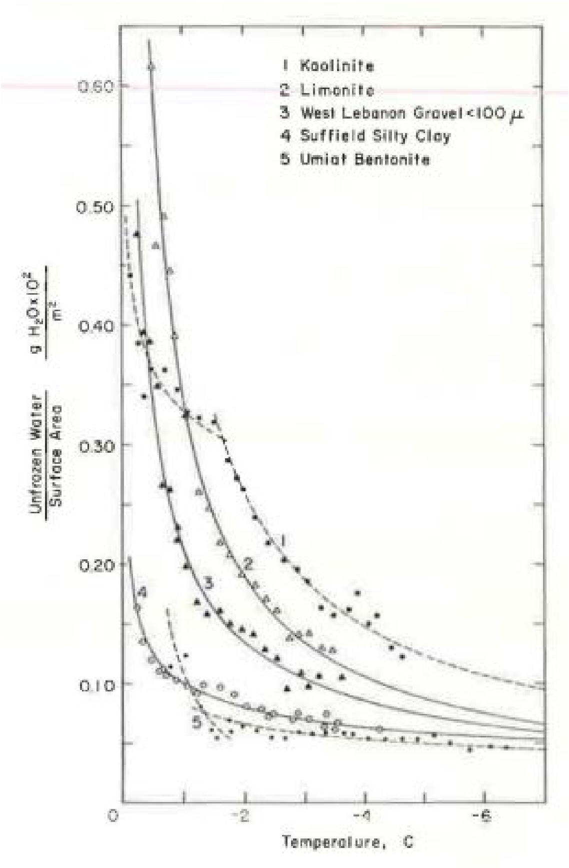


Figure 2.6: Ice saturation curves of different soil types at approx -5°C to 0°C (Anderson & Tice, 1972).

2.3 Properties of Freezing and Thawing Soil

As mentioned in Section 2.1 does the freezing of soil create a composite material consisting of several components. The transition between frozen and unfrozen soil is referred to as a phase change and is governed by the Clausius-Clapeyron equation, Equation 2.1. The behavior of this new frozen material is quite different from the ordinary unfrozen soil. Unfrozen soil is a granular material, the strength and stiffness is related to contact between particles and the compressibility of the spaces between the grains of the soil (Yersov, 2004). Frozen soil on the other hand, acts as more of a solid porous material, with much higher strength and stiffness (Yersov, 2004). According to Yersov (2004) is the strength of the frozen soil is usually several times higher than the unfrozen soil. The exact strength increase is mainly dependent on two separate factors: temperature and grain-size distribution (Tsytovich, 1960). Finer soils as clay has larger amount of unfrozen water in the premelted water film, this will result in a lower strength compared to soils with larger grains as sand in the frozen phase (Tsytovich, 1960). The ice creates a solid where the behavior of a water skin developing around soil grains will result in water-filled pores. The effective stress in this material is refereed to as solid phase stress and should be viewed as the combined stress of soil grains and ice. Solid phase stress is defined by Equation 2.2 (Aukenthaler, 2015).

$$\sigma * = \sigma - S_w P_w I \tag{2.2}$$

$\sigma *$ = solid phase stress tensor
σ = total stress tensor
S_w = unfrozen water saturation
P_w = pore water pressure
I = unit tensor

Solid phase stress is through the water pressure (P_w) linked to the cryogenic suction (S), which subsequently dependent on the temperature. This creates a frame work to describe the amount of ice versus water and thereby the material stiffness and strength through the elastic response. In the finite element modeling through PLAXIS, and *the frozen and unfrozen soil model* (F-U) by Ghoreishian Amiri et al. (2016) is the elasticity ϵ of the solid phase represented by Equation 2.3. In the model is the deformations set to a function of the elastic response of the solid material and is constructed by four individual strain components; dϵ^{me}, dϵ^{se}, dϵ^{mp} and $d\epsilon^{sp}$.

$$d\epsilon = d\epsilon^{me} + d\epsilon^{se} + d\epsilon^{mp} + d\epsilon^{sp} \tag{2.3}$$

dϵ = any strain increment
dϵ^{me} = elastic strain due to solid phase variation
dϵ^{se} = elastic strain due to cryogenic suction variation
dϵ^{mp} = plastic strain due to solid phase variation
$d\epsilon^{sp}$ = plastic strain due to cryogenic suction variation

2.4 Modelling Freezing and Thawing

How to model the behavior of a frozen soil is well described by Aukenthaler (2015) and Ghoreishian Amiri et al. (2016). In short can it be said that the thermo-hydro-mechanical (THM) behavior of frozen soils is highly complex and requires sophisticated modeling techniques.

This section explores the numerical simulation of key THM processes, such as heat transfer, water flow, mechanical deformation and their interactions in frozen soils (Ghoreishian Amiri et al., 2016). This thesis focuses to the modeling of FTC, thermal gradients, saturation and pore water pressure variations, as these factors significantly affect slope stability. The F-U-model in PLAXIS is a numerical modeling approach used to simulate the behavior of freezing and thawing soils under undrained conditions. The following key features and assumptions are used in the F-U model:

- Soil Behavior: The F-U model assumes the soil to be a saturated, isotropic, and elastic-plastic material that can undergo both frozen and thawed states.
- Temperature Distribution: The model takes into account the temperature distribution within the soil mass, considering variations due to external factors and internal heat generation or dissipation. Thermal gradients and phase changes between frozen and unfrozen states are considered.
- Mechanical Deformation: The F-U model simulates the mechanical deformation of frozen and thawed soils under undrained conditions. It considers both elastic and plastic deformations, including the effects of temperature and pore water pressure variations.
- Material Properties: The F-U model requires input parameters such as thermal conductivity, specific heat capacity, unfrozen water content, frozen water content, shear strength parameters, and yield criteria. These properties are crucial for accurately simulating the behavior of frozen and thawed soils.

The F-U model offers several advantages, including its ability to consider the temperature -pore pressure-mechanical deformation interaction, simulate the behavior of frozen and thawed soils and provide valuable insights into the stability of geotechnical structures in cold regions (Aukenthaler, 2015). However, it is important to note that the model has certain limitations, such as the assumption of isotropy, neglecting the anisotropic behavior of frozen soils and potential simplifications in representing complex thermal and hydraulic processes.

2.4.1 Calculating the Slope Stability

Slope stability is usually described with a safety factor (SF). SF is a equilibrium between the sum of resisting forces (M_R) over the sum of driving forces (M_A) described in Equation 2.4 (Craig & Knappett, 2012).

$$FS = \frac{\sum M_R}{\sum M_A} \tag{2.4}$$

The risk of slope failure can thereby be expressed as a single number, the SF. SF<1 implicate that the slope should fail while SF>1 indicates that the slope is stable, the lower the SF the higher risk of failure (Craig & Knappett, 2012). It is important to note that pure numerical value of the SF is restricted to the stability of a certain failure plane in the slope and does not include any information about the size or impact of the potential slide (Craig & Knappett, 2012). Usually is the location of the weakest failure plane tried to be identified and its SF is considered as the SF for the whole slope. The size and location of the critical failure planes are therefor also an integral part of understanding the analysis (Craig & Knappett, 2012).

Unfortunately will some of this understanding be lost in this thesis. The normal parameters used to calculate driving and resisting forces are transformed in the F-U model. Thereby is it impossible to use the normal SF calculation methods. In this thesis, the safety factor will be estimated based on the so-called 'gravity increase' using the FEM. The stability in this method will be assessed by increasing the gravity 'i.e. soil weight' until failure. How much increase in gravity is needed to cause failure will be the safety factor.

3

Verification and Case Study

The freezing and thawing of the soil was modeled through finite element analysis with the *Frozen and Unfrozen soil model* of Ghoreishian Amiri et al. (2016) developed by Norwegian University of Science and Technology and PLAXIS vd and further devoloped by Aukenthaler (2015). The modeling in this thesis was done in a three step process:

1. Firstly was the model behavior verified by testing a 1x1 m cube with soil values from the PLAXIS manual itself (Ghoreishian Amiri et al., 2016). Which is referred to as *Verification of the Frozen Soil Model.*
2. Secondly was cite specific soil properties evaluated and changed. Which is referred to as *Modelling of the soil at Bispgården.*
3. In the last step was the F-U model applied to the cite specific slope in Bispgården, using the derived soil properties from the second step. The geological history and a description of the cite is also presented. The stability of the slope during the freeze- thaw process was evaluated by increasing the weight of the soil until failure. This step is referred to as *Case Study.*

3.1 Step 1: Verification of the Frozen Soil Model

To verify the F-U model a 1x1 m cube was created in PLAXIS. The user defined model *frozen_soil64.dll* was loaded. Soil and model parameters were assigned according to the FTC from the manual by Ghoreishian Amiri et al. (2016), see Appendix A. Unfrozen water saturation curve was assigned, see Figure 3.1. The groundwater table was kept at the bottom boundary of the model.

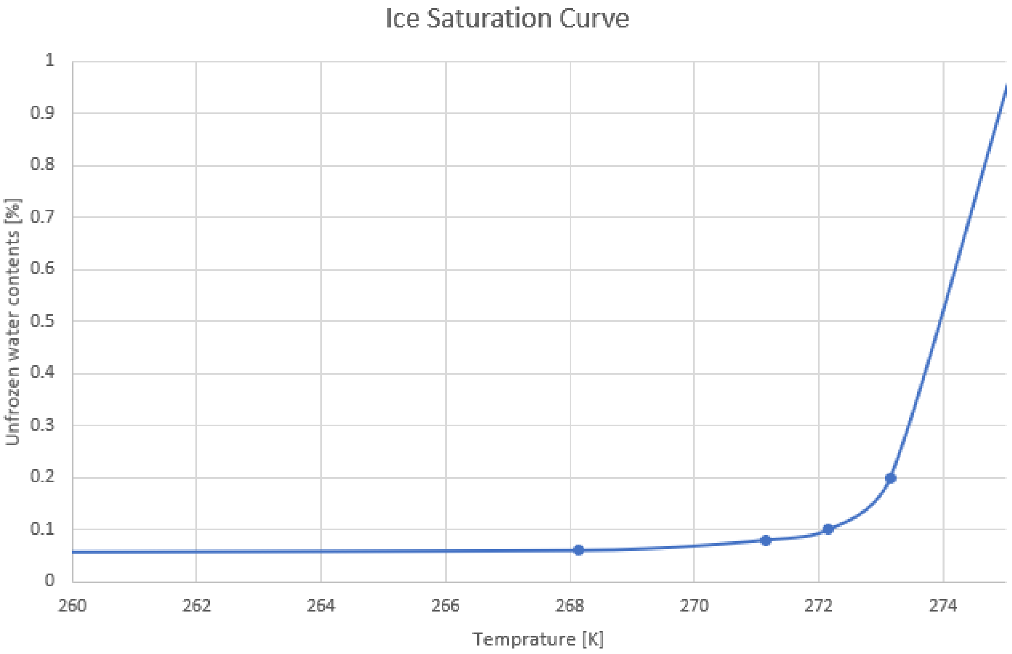


Figure 3.1: Assigned ice saturation curve

3.1.1 Boundary Conditions and Time Frame

The hydraulic boundary conditions (BCs) were set to *closed* for the left and bottom boundary and *seepage* to the top and right boundary. The thermal BCs was setup to be *closed* for all boundaries except the top boundary where temperature changes were applied to the system. The temperature at the top boundary was set to vary according to Table 3.1, to simulate a 12 h freezing period, representing a cold night. Two extended cold periods were also tested by applying temperatures according to Appendix B, Tables B.1 and B.2, to get a further understanding of the system.

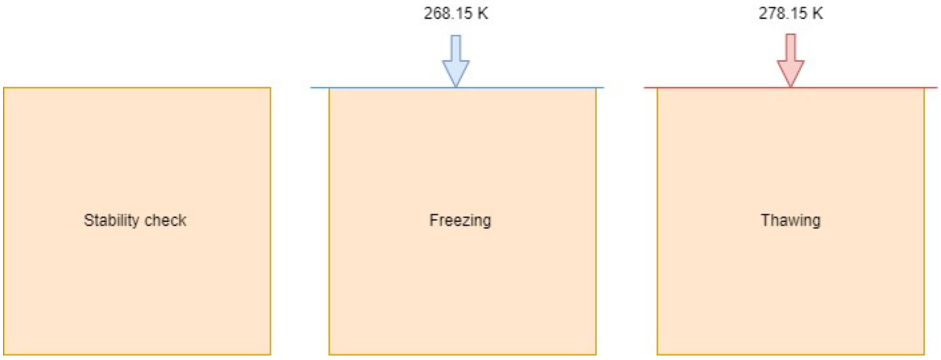


Figure 3.2: Steps of the freezing and thawing

t(h)	t (s)	T (K)	T (°C)
0	0	273.15	0
1	3600	272.15	1
2	7200	271.15	2
3	10800	270.15	3
4	14400	269.15	4
5	18000	268.15	5
6	21600	267.15	6
7	25200	268.15	5
8	28800	269.15	4
9	32400	270.15	3
10	36000	271.15	2
11	39600	272.15	1
12	43200	273.15	0

Table 3.1: Temperature variation 12h test

3.2 Step 2: Modelling of the Soil at Bispgården

The second step of the modelling was to assign the site specific soil. The data was limited to the SGI report *Växter som skydd mot erosion och ytligaras i branta jordslänter - Demonstrationsförsök i Bispgården och Bydalen* (Lundström & Andersson, 2008). The geotechnical parameters evaluated in the report are in large limited to cone penetration tests (CPTs), evaluated through the analysis software Conrad. In addition to this was also the following soil evaluations available in the report: a soil type evaluation by Lundquist (1969), water contents test by Vägverket and evaluation from auger tests. The soil evaluation can be further complemented by soil type map by SGU, Figure 3.3

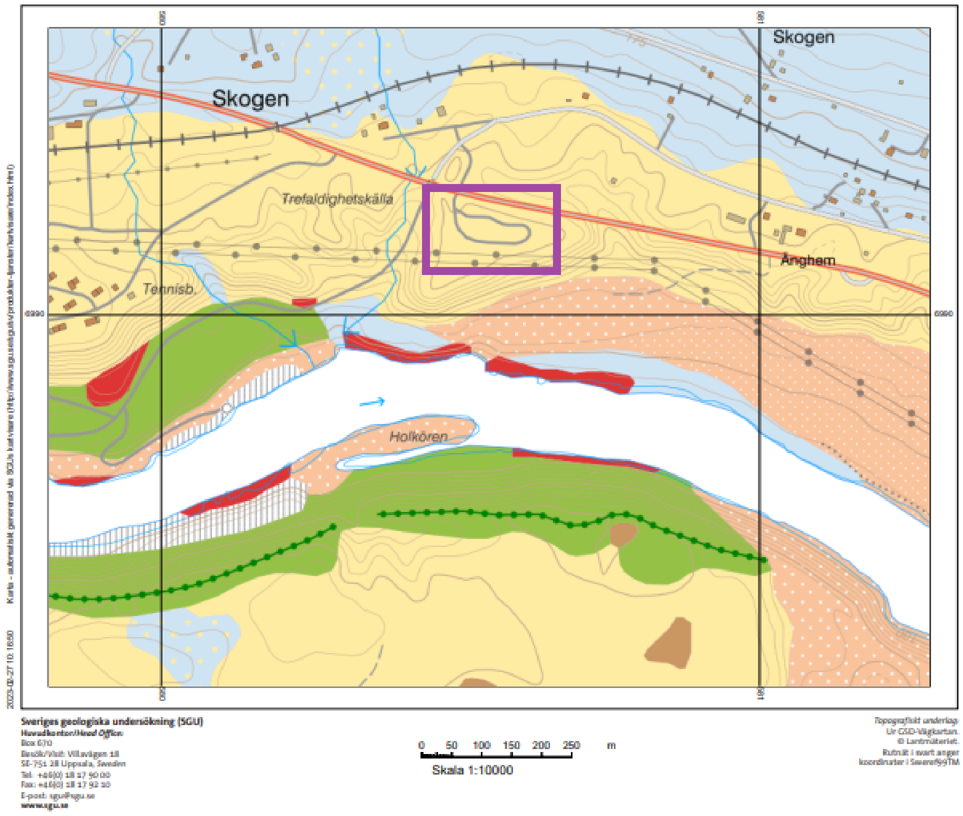


Figure 3.3: An overview of the soil types in the area, the area for the demonstration trails are marked in purple (Geological Survey of Sweden, n.d.)

3.2.1 The Soil at Bispgården

From the evaluated CPTs and the complementing tests is the top 10 m of soil evaluated to consist of many often very thin layers of sand, silt or clay. One common trait of all these layers is a relatively high content of silt, making them frost and erosion sensitive (Lundström & Andersson, 2008). According to soil type map from SGU is the top soil consisting of clay to silt. Due to the complexity of the F-U model was this compiled into one material. The used soil parameters are presented in Appendix A. The soil at Bispgården was much less course than the test soil, to reflect this were parameters changed accordingly. Moreover was the accuracy of these changes limited by the data provided and modeling limitations. Resulting in an iterative process balancing "wanted" parameters and "working" parameters. Note that the material composition of the soil also was changed from *course* to *medium fine*. The saturation curve was kept as it was, as it was firstly generated with soil at Bispgården in mind.

3.3 Step 3: Case Study

This section will describe the case study.

3.3.1 Area Description

The site studied is located in between the village of Bispgården and the former rapids, *Döda fallet*, in the county of Jämtland, Sweden, see Figure 3.4.

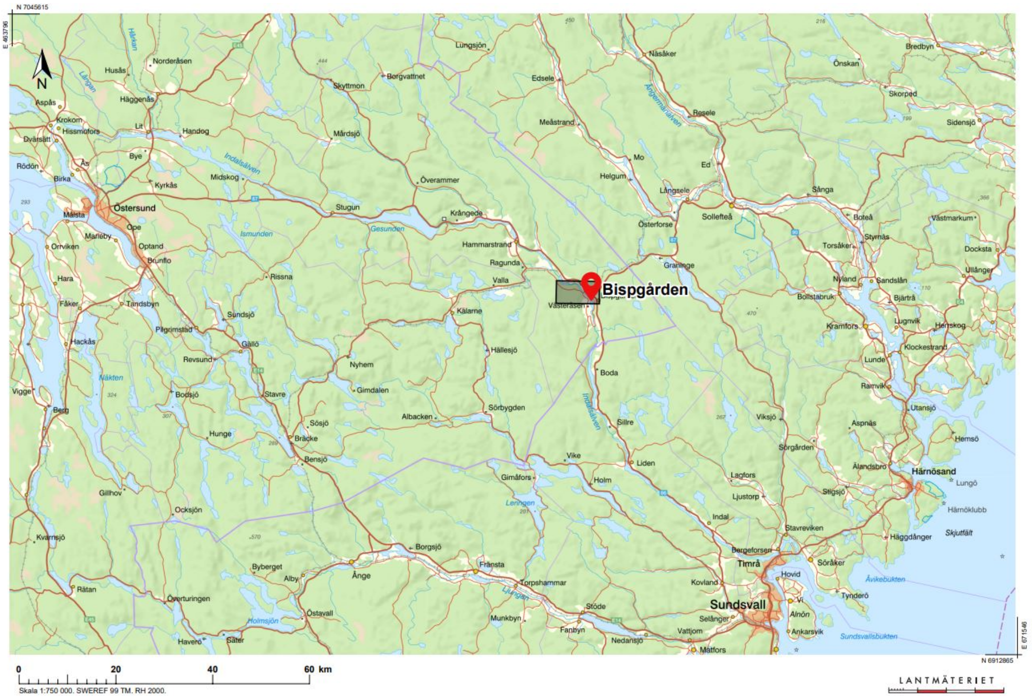


Figure 3.4: General location of the site (Lantmäteriet, n.d.)

The area is characterised by the river Indalsälven and the river valley it has created through the otherwise hilly landscape predominately consisting of moraine and bedrock (Lundquist, 1969). The valley itself stretches in a NNW-SSE direction and is clearly lower than the surrounding areas. It mainly consists of silty and sandy sediments deposited during and after the last ice age (Lundström & Andersson, 2008). The sorting of the sediments can be assumed to be quite esker-like with larger fractions at the bottom and smaller fractions at the top since most of the sediments where deposited in a fjord as the ice-cap retracted after the last ice age (Lundquist, 1969). The fjord has since then transformed in to the river that is today, as a consequence of the land upheaval, creating a river valley with often high and step sides (Lundström & Andersson, 2008). Human activities has also had a large impact on the area. Farms and small villages are located along the river sides together with roads and a railway track as seen in Figure 3.5. The river is used as a power source with several hydro-plants controlling the water surface level. An accidental draining of a lake upstream in the late 1700s re-routed the water course and caused a large flooding and flushing of the river valley (Lundquist, 1969).

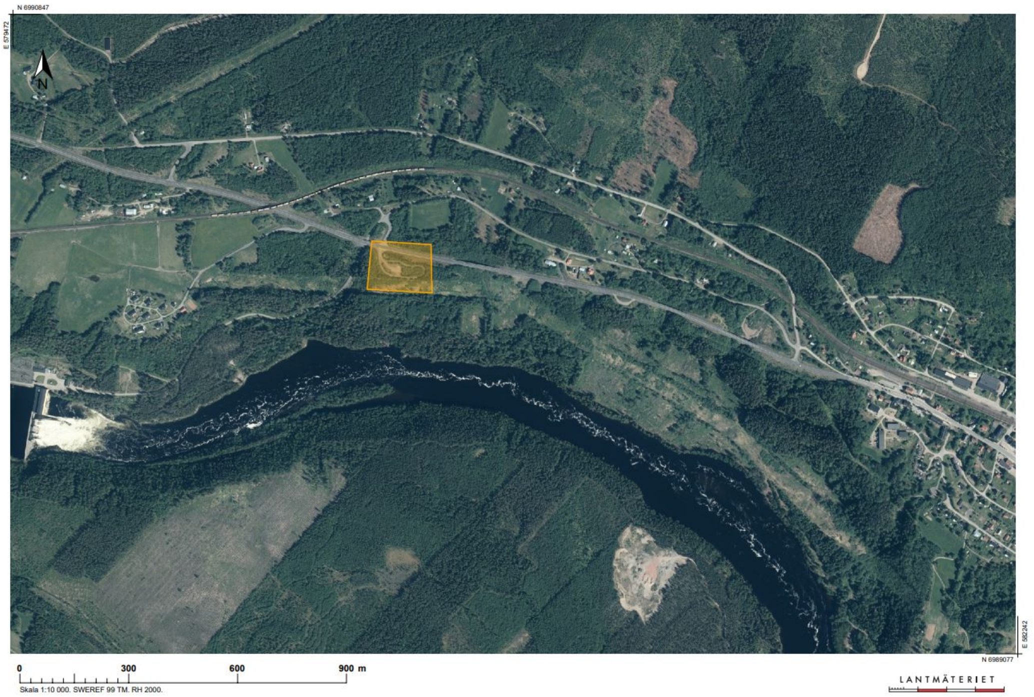


Figure 3.5: An overview of the study area, the area for the demonstration trails are marked in orange. To the left is Svarthålsforsen Water Plant present and to the right, parts of the village Bispgården (Lantmäteriet, n.d.).

3.3.2 Geologic History

The underlying cause or prerequisite conditions for land slides to occur are often specific for different regions in Sweden, it is therefore important to know and understand the local geological history of the cite studied (Cato & Engdahl, 1982). Cato and Engdahl (1982) did rough mapping of the most slide prone areas of Sweden, Figure 3.6, which can be compared to areas beneath the highest shore line, Figure 3.7, and the existence of silt dominated river valleys, Figure 3.8.

Figure 3.6: Landslide frequency in Sweden (Cato & Engdahl, 1982).

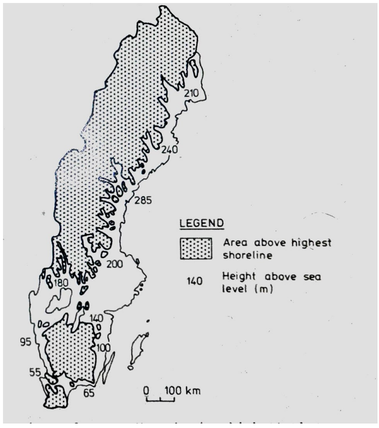


Figure 3.7: Area above highest coast line (Cato & Engdahl, 1982).

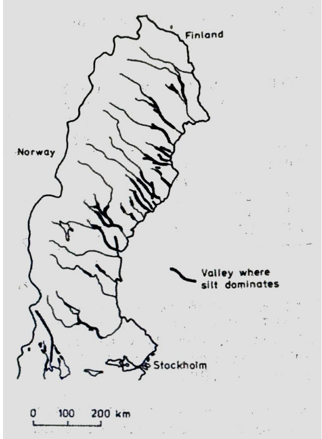


Figure 3.8: Location of silty river valleys (Cato & Engdahl, 1982).

When comparing the areas beneath highest shore line and the areas with high risk of slides, is there a clear correlation. If clay or silt was deposited under the highest shore line does it pose higher risk of developing slides. This case study is focusing on one of the silty river valleys that emerged in the central and northern part of Sweden since the last ice age, categorized in the area with a relatively low land slide frequency according to (Cato & Engdahl, 1982).

Silty river banks are prevalent along the larger rivers located under the highest coast line in northern Sweden. These where created as the ice-sheet retracted during the last ice-age and glacial sediments where deposited at sea (Viberg, 1989). Water velocity is highly related to the size of sediments deposited with larger particles sedimenting at higher velocities and smaller grains at lower velocities. The velocity of the water is higher closer to the ice cap, thus creating a fairly sorted strata with larger particles in the bottom, deposited close to the ice and smaller particles at the top, deposited later and further from the ice cap margin. With land upheaval where these esker-like stratas lifted from sea and with water erosion from the rivers were the river valleys created (Viberg, 1989). Although that the soil is sorted is the layer of clay often very thin or missing, creating slopes of mainly silty material without a protecting layer of clay. These silty slopes are very susceptible to frost intrusions (Sällfors, 2013) and are highly erodible. Despite the sensitive nature of these silty slopes could they reach heights of 40-50 meters and almost vertical inclinations due to negative pore pressures (Viberg, 1989). The safety factor of these silty slopes is often very low indicating that they are marginally stable and prone to failure during unfavorable conditions. Calculated safety factor for many of these slopes are in some cases below 1, for extreme cases as low as 0.6 (Westerberg et al., 2014). Indicating that the stability often is undervalued or miss interpreted with conventional calculation methods, especially when including the negative pore water pressure (Westerberg et al., 2014).

3.3.3 Slope Geometry

The specific site of the demonstration trails studied consist of a cut slope facing north and away from the river. It is placed on a small plateau consisting of mainly silty sediments in between the edge of the moraine and the river it self, see Figure 3.5 for the exact location of the slope and Figure 3.3 for soil types. The width of the slope is about 150 meters and its height is varying from 5 to 7 meters with an approximate inclination of 30°, a more detailed map of the area can be seen in Figure 3.9.

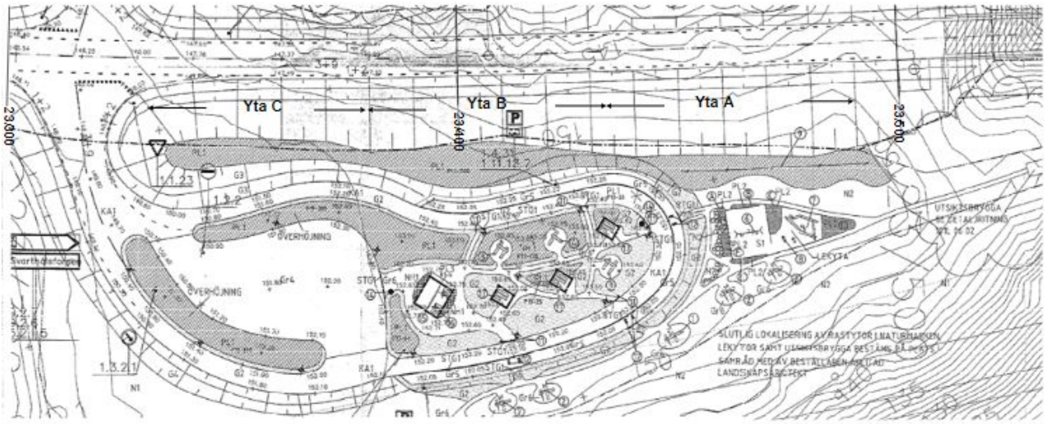


Figure 3.9: Map over the are used for demonstration trails (Lundström & Andersson, 2008)

In the cut slope at Bispgården was a S-N section drawn, resulting in the basis for the modeling. The material was assumed to be homogeneous enough to be modeled as one single layer. The height of the model was set to 15 meters with 30°inclined slope ending 5 meters further down. Lengthwise was the geometry simplified to extend 15 meters horizontally backwards from the top and 15 meters horizontally forward from the toe of the slope, see Figure 3.10. The used mesh of finite elements was carefully chosen to get mesh-independent results.

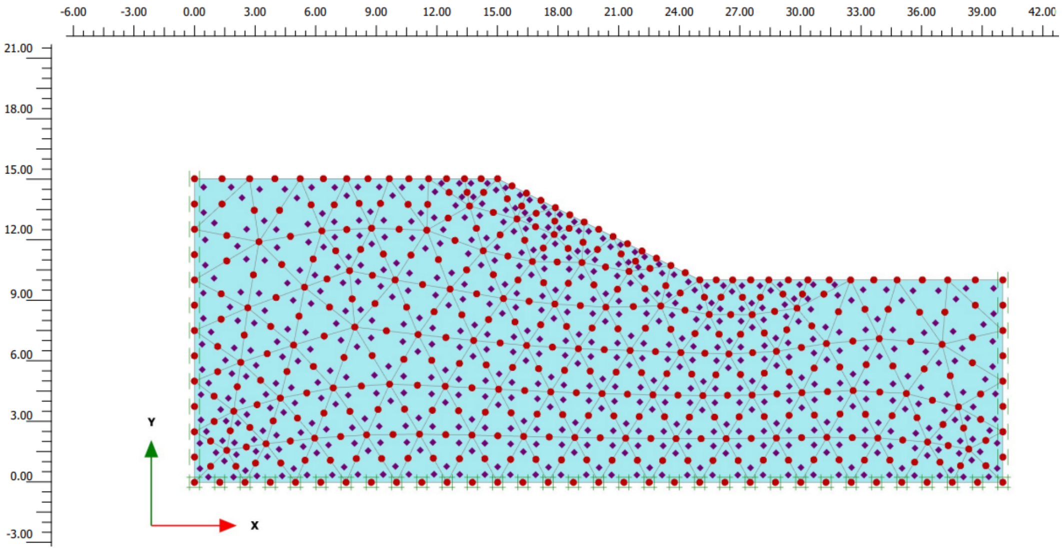


Figure 3.10: Geometry of the slope with nodes and links (Authors own work).

3.3.4 Climate and BCs

Northern Sweden, the location of Bispgården, has a subarctic climate that is characterized by long, cold winters and short, mild summers. The region experiences temperature changes throughout the year, with the warmest months being June, July, and August when the average temperature ranges from 10 to 20°C (Nylén et al., 2015). The coldest months are December, January and February when the temperature can drop considerably below freezing, with an average temperature of around -15 to -5°C (Nylén et al., 2015).

Thermally was the bottom boundary set to be equal to the average annual temperature at 275.15 K (0°C) according to theory, the bottom boundary of the model was therefore kept unfrozen. The temperature at the top boundaries were set vary over time to simulate the weather changes trough-out the FTC. This was done in a three step process:

- Firstly was the temperature lowered to 163.15 K (-10°C) for a week, at the top boundary.
- Secondly was the temperature lowered to 163.15 K (-10°C) again, but for 150 days, and brought up to 178.15 K (+8°C) in the last day, roughly simulating a cold winter and a rapid thaw process in the spring.
- Thirdly was the same heat signal used as in the second step, but the warm period in the end was extended to 10 days. Resulting in a total of 10 days with warmer spring temperatures.

The temperatures applied at to top boundary can be seen in Appendix B. Stability of the slope was tested by increasing the weight of the model until collapse iteratively, as discussed in Section 2.4.1.

4

Results and Discussion

In this chapter the results of the model will be presented and discussed. Firstly the separate results will be presented and discussed. Lastly there will be an broader overall discussion. Figures presented in this chapter are generated from the authors own PLAXIS-model.

4.1 Verification of the Frozen Soil Model

The 1x1 m cube with constant temperature in all points was created in the first step of analysis, see Figure 4.1. The reference and starting temperature was set to 174.15 K (+1 °C) to be able to see the direct impact of the temperature changes applied to the model.

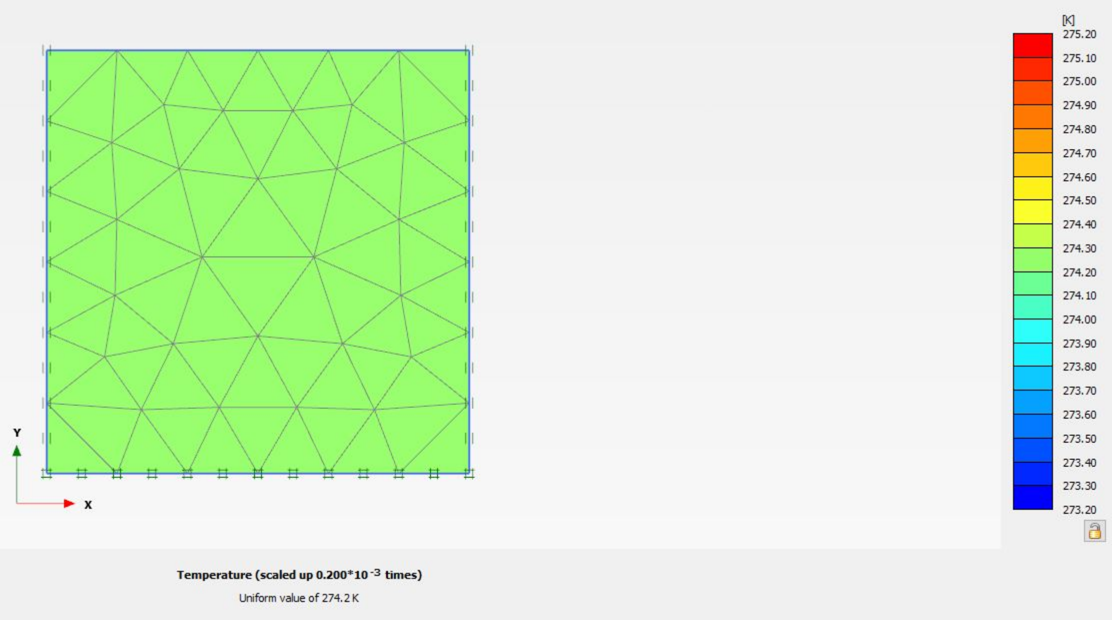
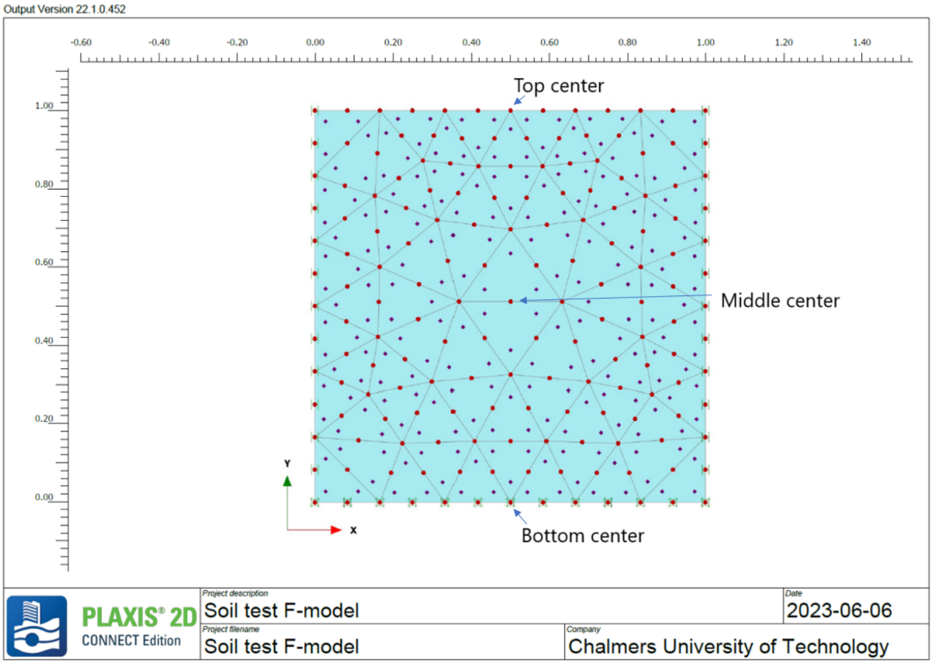


Figure 4.1: Starting cube with constant temperature.

Three points of interest were chosen to act as reference point during the testing (Top center, Middle center and Bottom center), these are shown in Figure 4.2. These will act as a measure of how the model will behave together with complementary figures from the PLAXIS-program itself.



Project description: Soil test F-model

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Project filename: Soil test F-model

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Figure 4.2: Selected points for analysis

4.1.1 Heat Analysis of the Test Soil

Three different scenarios, with different heat signals, where conducted on the test soil. The temperature over time for all these three time periods are presented in Figure 4.3, 4.4 and 4.5. The temperature distribution in the model is acting as mostly presumed. Generally for the three scenarios does the top boundary strictly follow the heat signals that were applied. The 12 h and 24 h periods of cold does not have time to affect the two measuring points, Middle center ant Bottom center, and the temperature in these points is hence unaffected by the temperature change to the top boundary. This is somewhat unexpected as the temperature change applied to the top boundary should affect the temperatures further down in the test after some time. This is governed by the thermal conductivity of the soil.

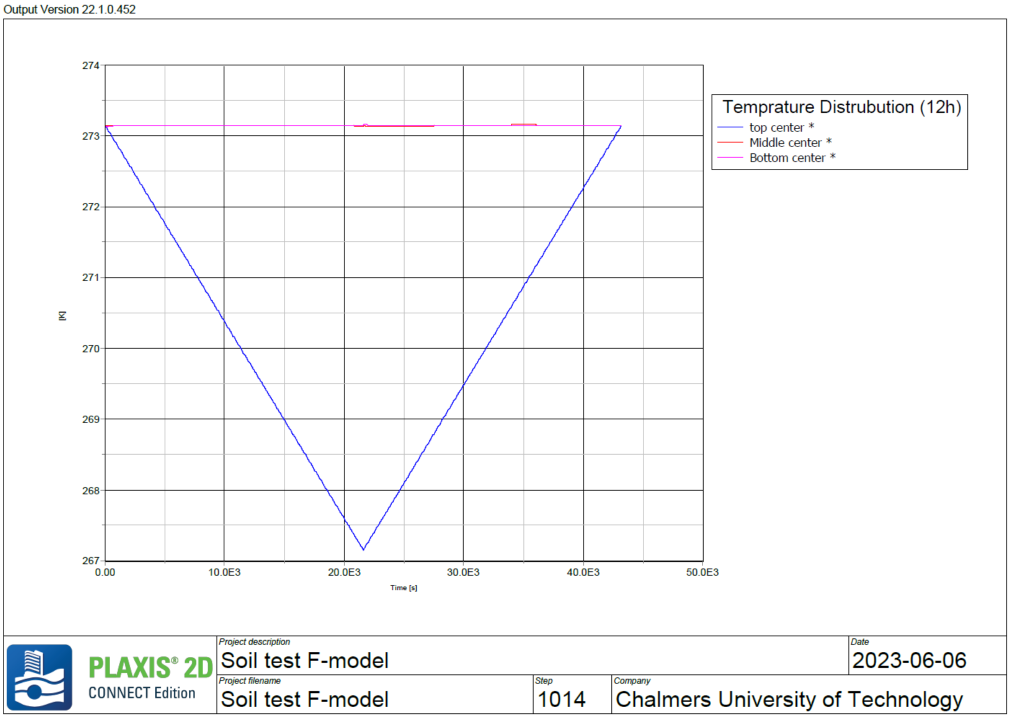

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Figure 4.3: Changes in the temperature during the 12 h test.

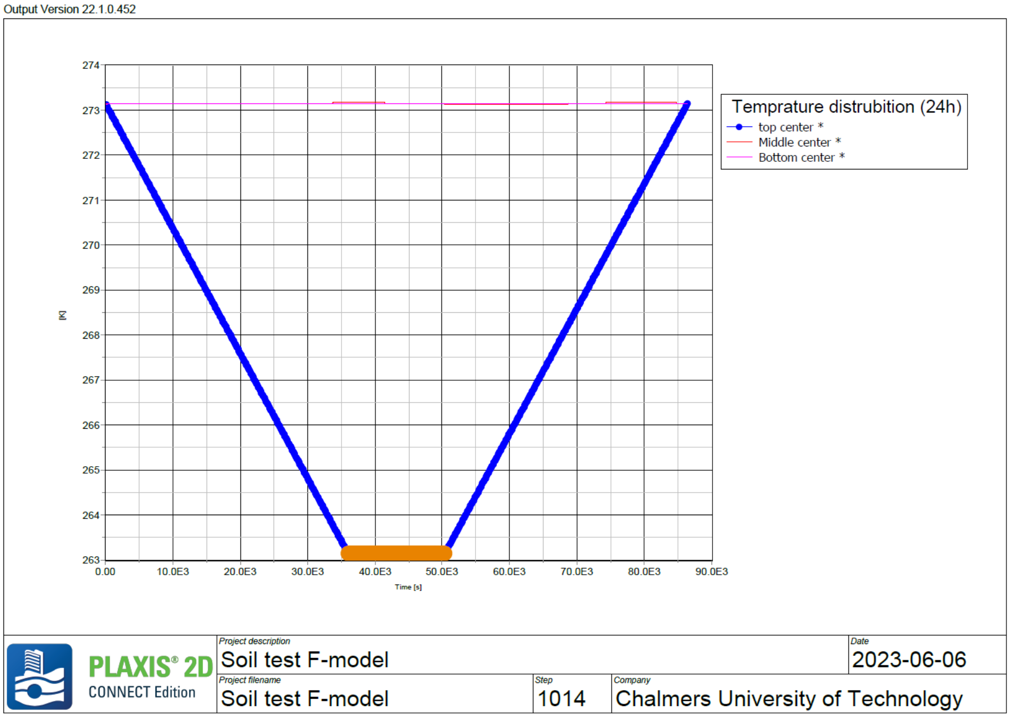

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Figure 4.4: Changes in the temperature during the 24 h test.

In the 1 week test does the temperature still follow the heat signal on the top boundary. Further down is the temperature at Middle center affected after approximately

24 h and starts to drop. It is followed by Bottom center approximately 48 h later, implying that the whole test is frozen after approximately 3 days. This is quite a reasonable time for the sample to freeze.

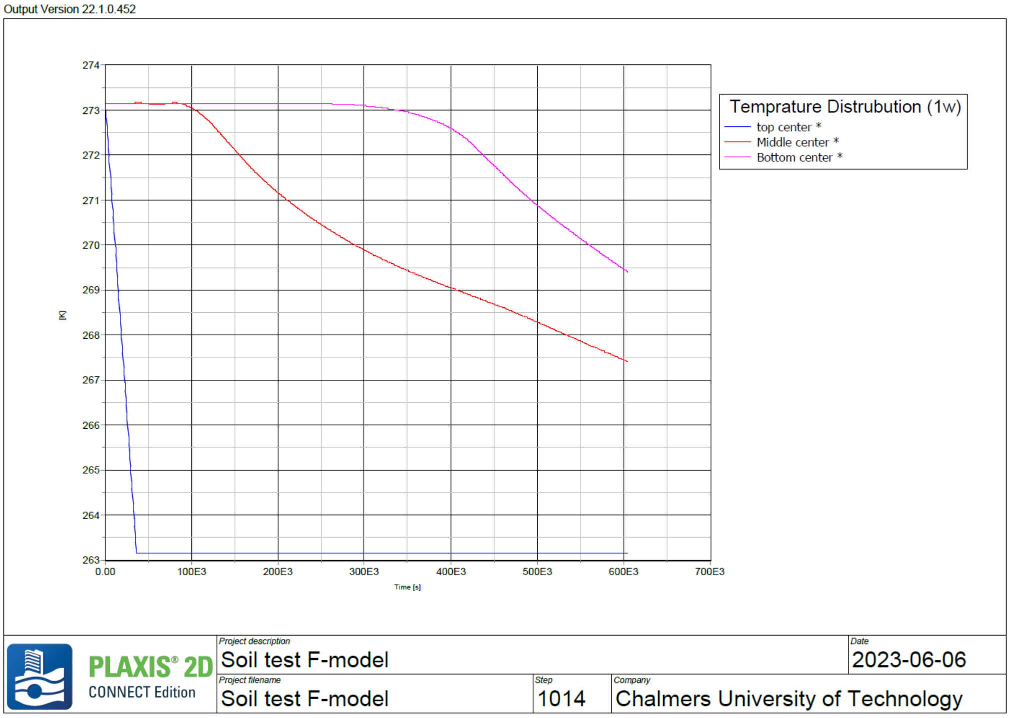

Figure 4.5: Changes in the temperature during the 1 week test.

4.1.2 Saturation Analysis of the Test Soil

The effective saturation analysis is shown in Figure 4.6, 4.7 and 4.8. The saturation in the Top center point is following the expected behavior. The effective saturation is briefly increased as the soil start to freeze and temperature is a couple of degrees sub freezing. When the temperature is lowered further does the effective saturation drop, with the saturation curve moving towards 0 %. When the temperature is increased again, at the end of the 12 h and 24 h test, does the effective saturation start to increase again as expected. For the Middle center point and Bottom center point is the saturation barely effected in the 12 h test. This is expected as it is not affected by any temperature change. The same applies for the Bottom center point in the 24 h test but the Middle center point is showing an increase in effective saturation. This could be due to an increase of water flow as the frozen layer is sucking in water. This theory is strengthened by the dip in effective saturation towards the end time of the test, when the temperature is raised and the thickness of the frozen phase is no longer growing.

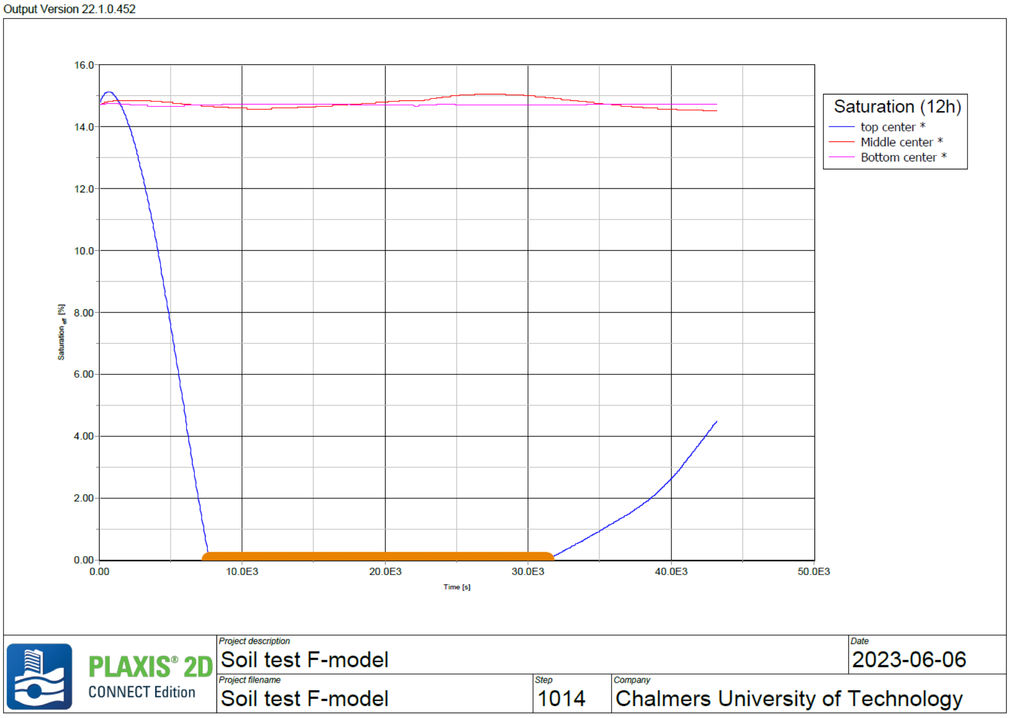

Figure 4.6: Change in effective saturation during the 12 h test.

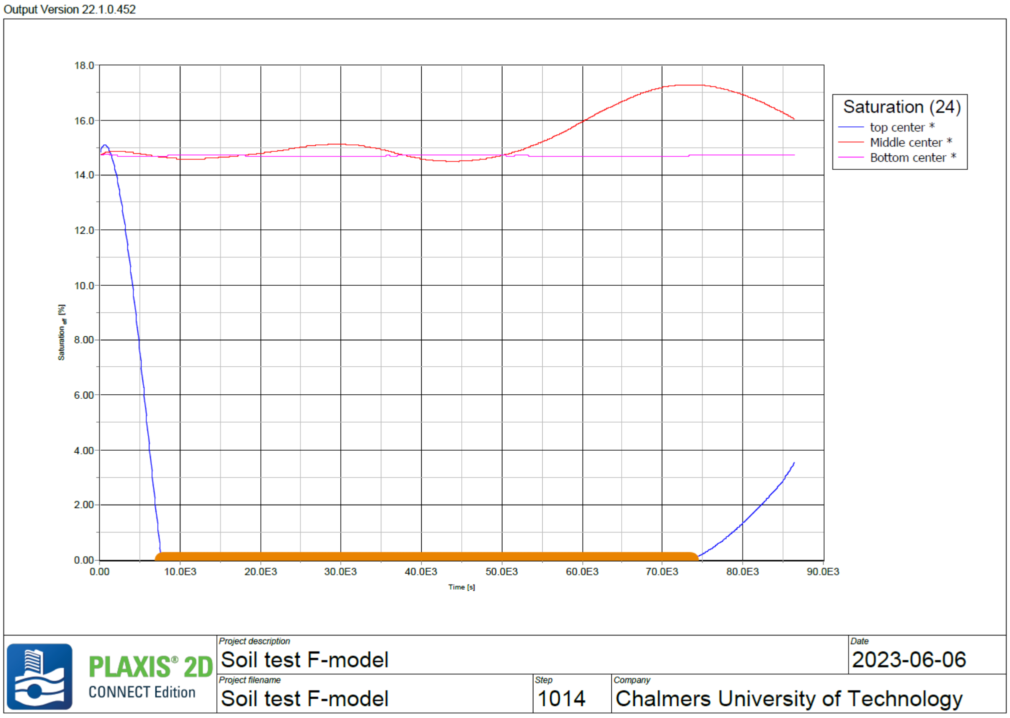

Figure 4.7: Change in effective saturation during the 24 h test.

In the 1 week test is effective saturation at top boundary constantly remaining at 0 % after it reaches 0 %, during the freeze process. The Middle center point is balancing around 15 % for approximately the first 24 h of the test. When it starts to freeze is the effective saturation decreasing to finally reach 0 %. The Middle center point is followed by the point at the bottom boundary, again with a 3 day delay, which is consistent with the temperature change. That the minimum saturation reaches 0 % is unexpected. The effective saturation should remain at low percentages for long time and for colder temperatures than tested in this thesis. This can be due to a number of different factors, one example is; the oscillating effect of the effective saturation over time (especially in the Middle center point) which indicates a vertical movement of water toward the frozen soil in the sample as expected but there seems to be a lack of water in the model creating 0 % effective saturation.

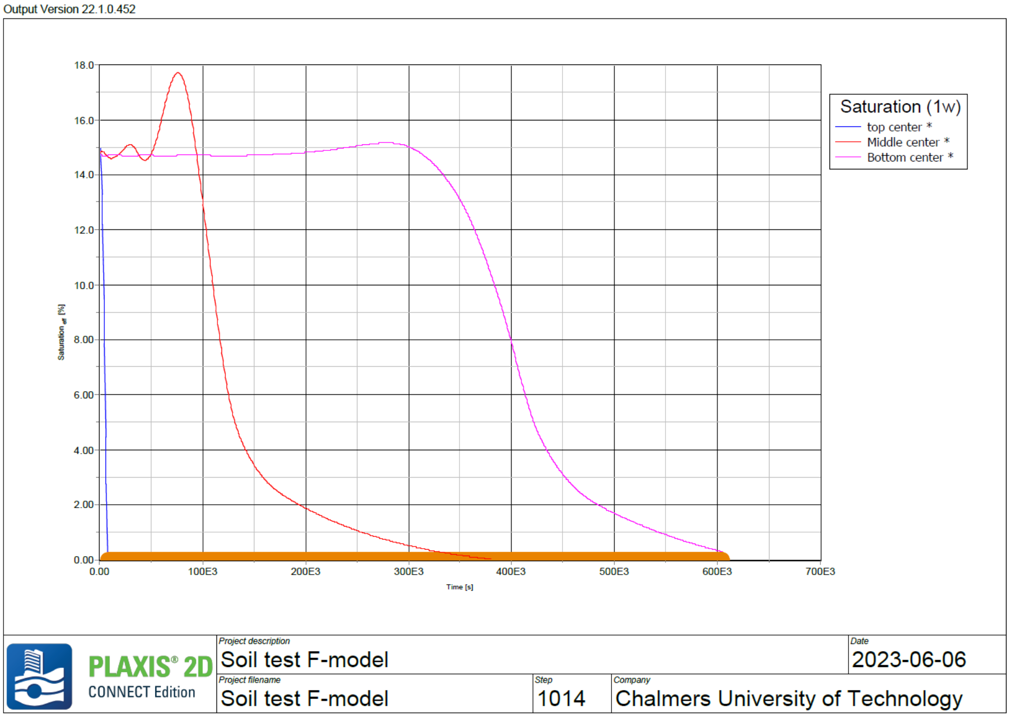

Figure 4.8: Change in effective saturation during the 1 week test.

4.1.3 Vertical Displacement Analysis of the Test Soil

The vertical displacements for the three points are shown in Figure 4.9, 4.10 and 4.11. The results of the vertical displacement are somewhat disappointing. Vertical deformations where smaller than expected throughout the modeling. This is heavily dependent on the mechanical properties of the soil, mainly stiffness. The stiffness parameters used may could have been significantly lowered. Expected tendencies are shown but the dimensions of the displacements are smaller than expected. Indicating that the ever so elusive frost heave effects have in large been unaccounted for. This can probably be explained by the lack of water in the model, an integral part of the growth of ice lenses. Eventough can some vertical displacements be discussed.

The bottom boundary is not displacing at all as expected as it is bound to the 0 level. The 12 h, 24 h and 1 week tests shows a positive vertical displacement in the Top center and Middle center points when they start to freeze. Unfortunately is this effect diminishing after the first freeze period, shown best in Figure 4.11. The diminishing effect can even cause negative displacements, as seen in Figure 4.10.

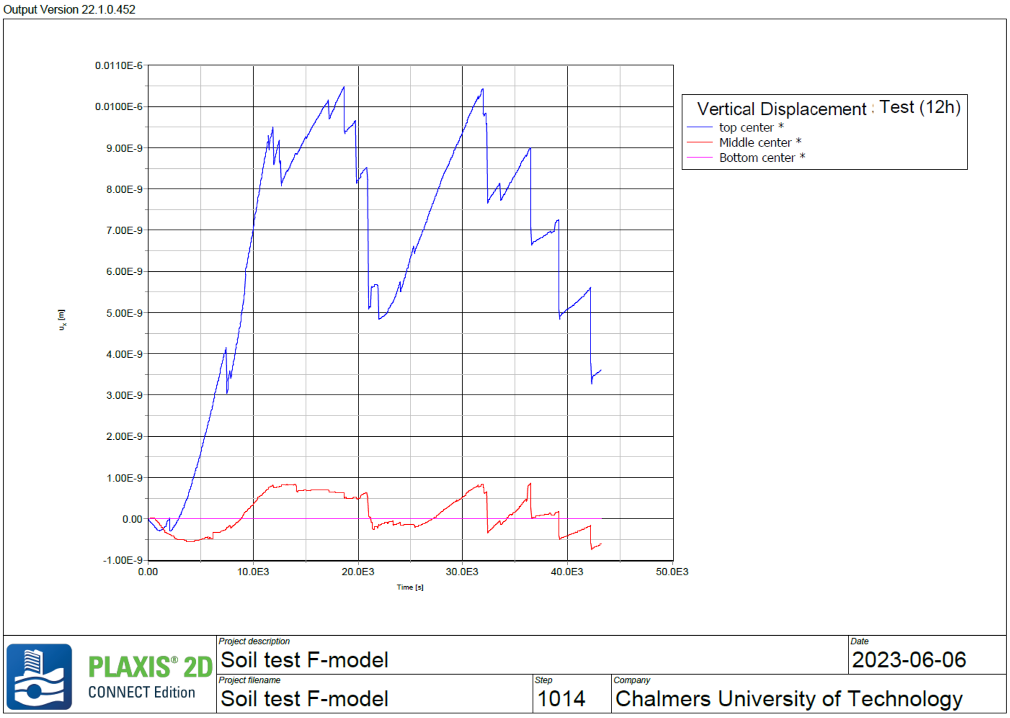

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Figure 4.9: Vertical deformation during the 12 h test.

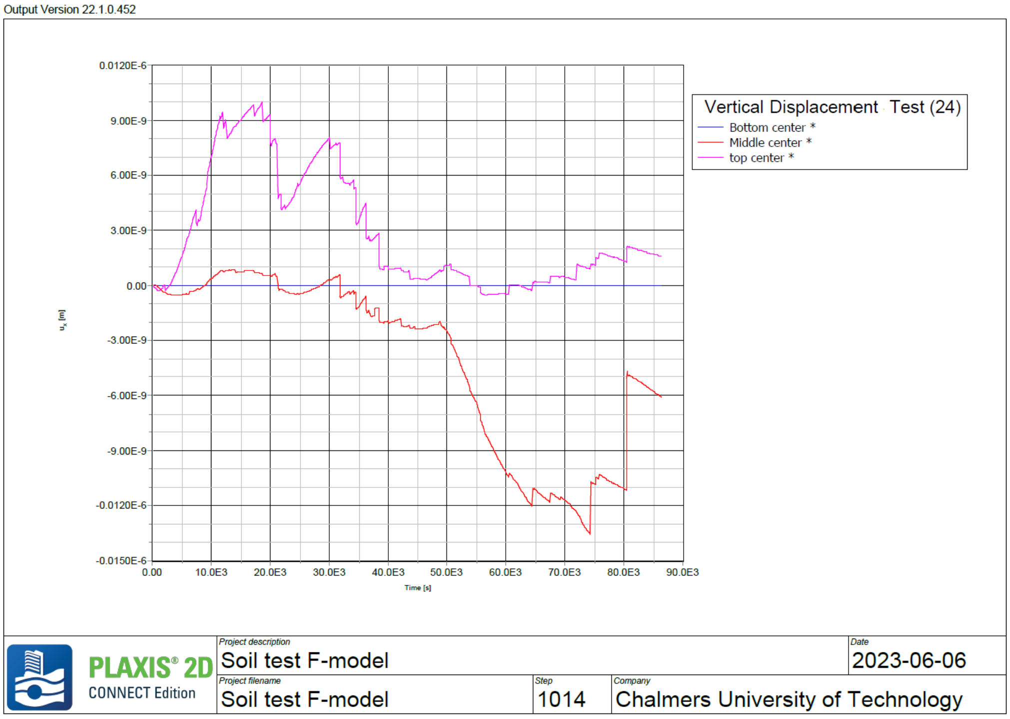


Figure 4.10: Vertical deformation saturation during the 24 h test.

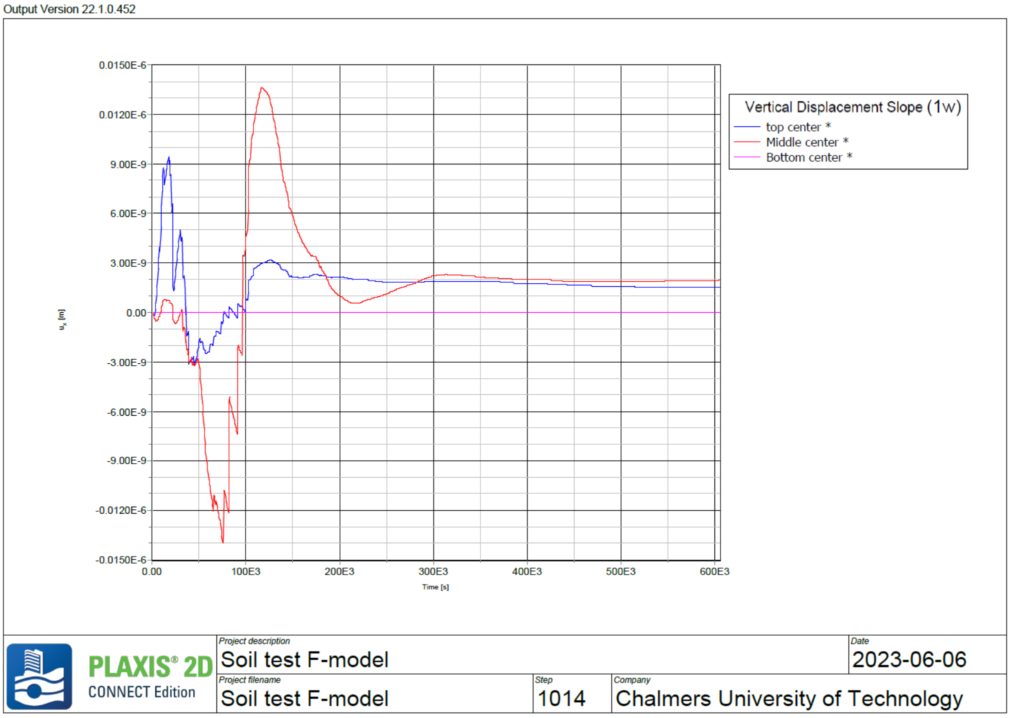
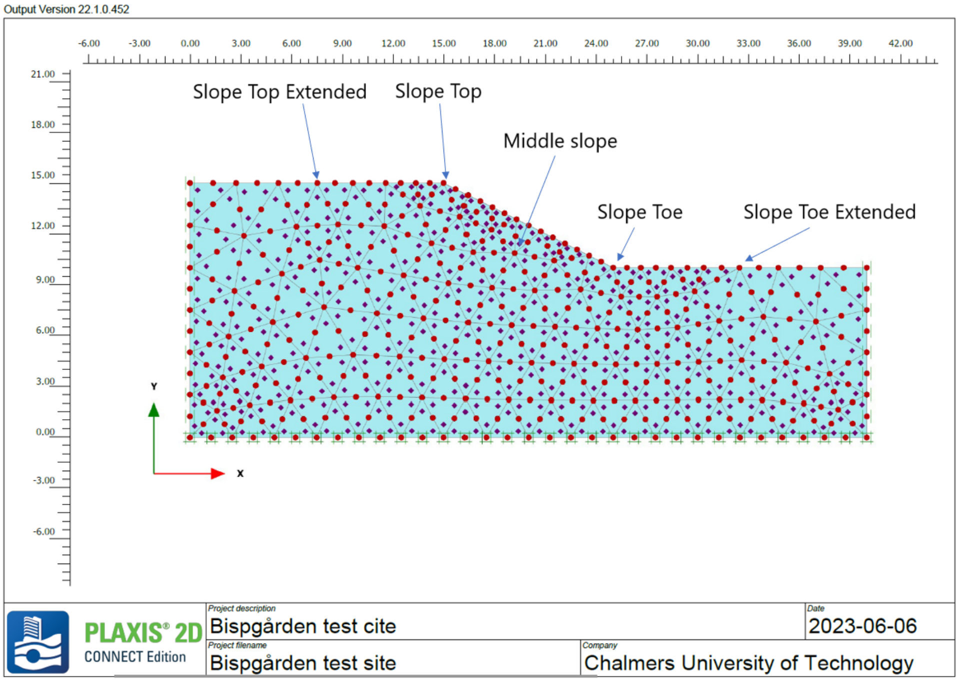


Figure 4.11: Vertical deformation saturation during the 1 week test.

4.2 The Case Study

Points were in a similar manor as in the test soil chosen for the case study, these are shown in Figure 4.12. For the slope where 3 new heat signals applied, lasting for 1 week, 151 days and 160 days respectively, since the shorter freeze periods had minor effects in Section 4.1. The applied heat and flow boundary conditions can be seen in Figure 4.13 and 4.14.



Project description
Bispgården test cite

Date
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Project filename
Bispgården test site

Company
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Figure 4.12: Selected points for analysis

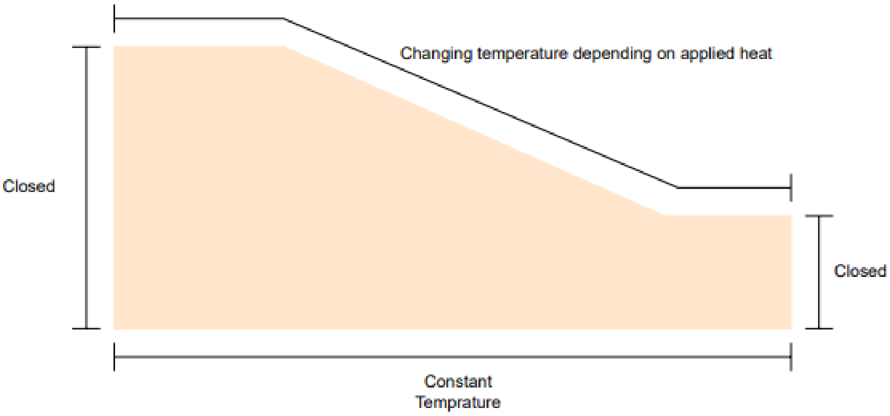


Figure 4.13: Selected thermal BCs

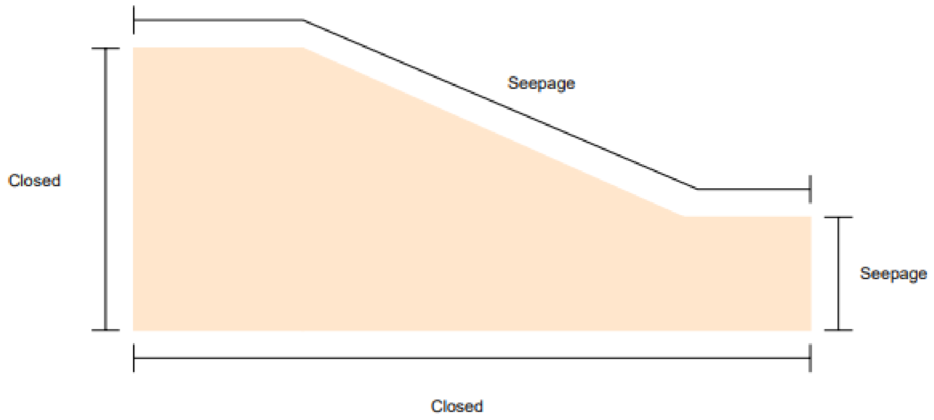
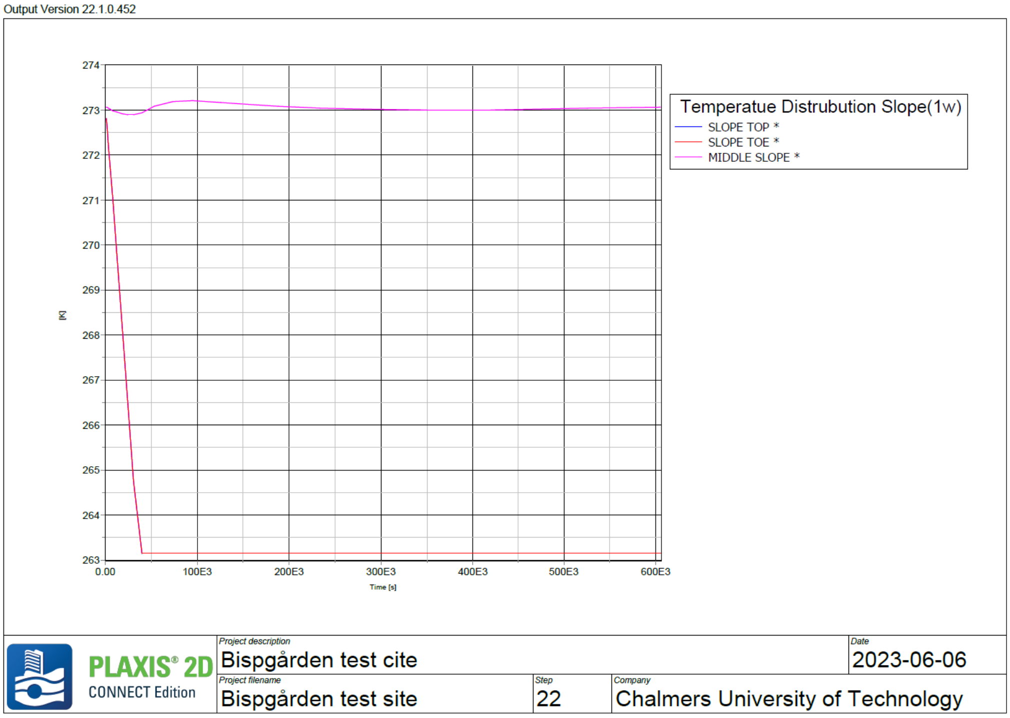


Figure 4.14: Selected water flow BCs

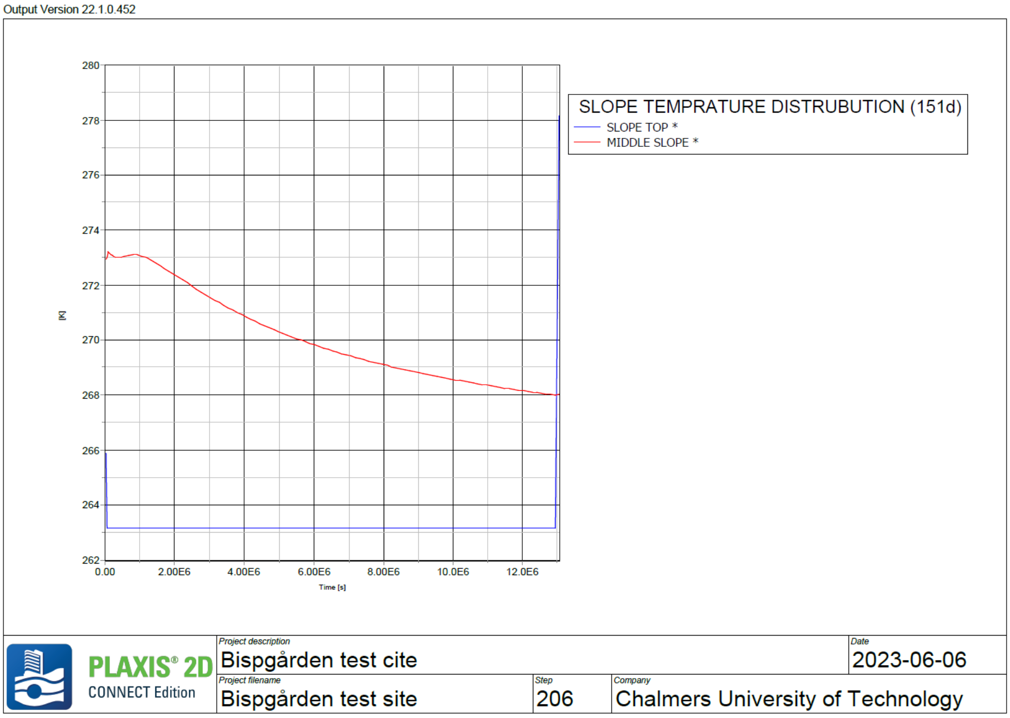
4.2.1 Heat Analysis of the Slope

The temperature change over time in the chosen points are shown in Figure 4.15, 4.16 and 4.17. Since all points except the Middle slope point are on the surface of the model will only the Middle slope point and the Top slope point (representing all points on the top boundary) be shown in this analysis. The Top slope point will follow the applied heat signal, as shown in the soil test analysis. The temperature on the Top boundary follows the heat signal as expected. The Middle slope point temperature is unstable throughout the scenario in the 1 week test (for the Slope) with a temperature at around 273.15 K (0 °C). For the 151 och 160 day scenarios does the temperature in the middle of the slope show a clear decrease during the freezing. In the 160 day scenario is there also a minor increase shown in the end of the time period.



Project description: Bispgården test cite
Date: 2023-06-06
Project filename: Bispgården test site
Step: 22
Company: Chalmers University of Technology

Figure 4.15: Changes in the temperature during the 1 week test for the slope.



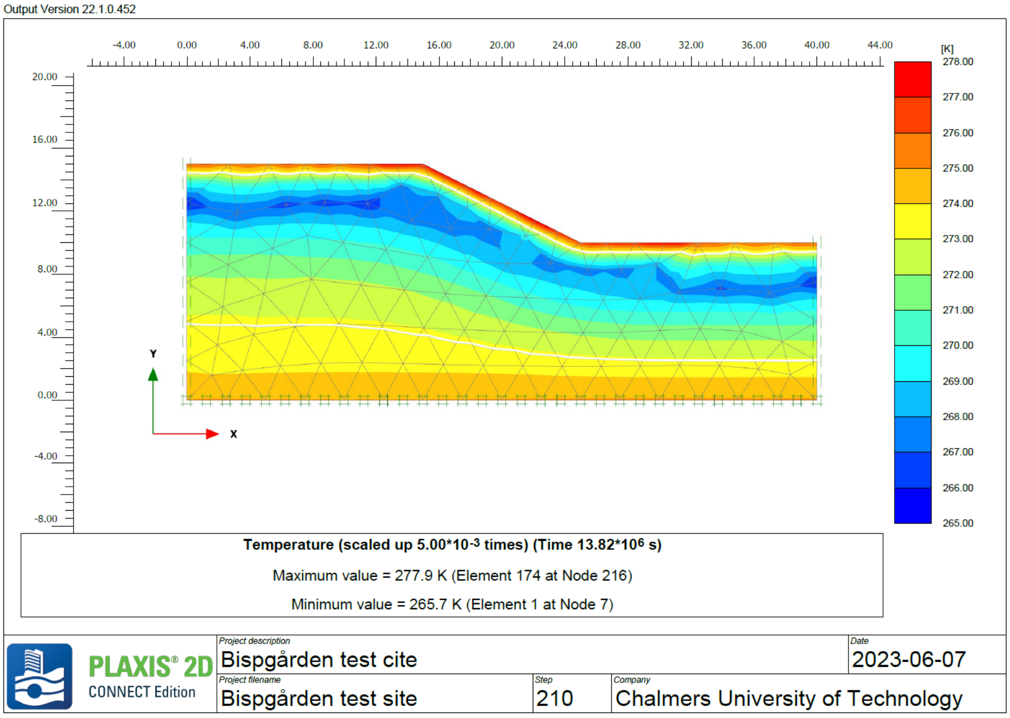
Project description: Bispgården test cite
Date: 2023-06-06
Project filename: Bispgården test site
Step: 206
Company: Chalmers University of Technology

Figure 4.16: Changes in the temperature during the 151 days test for the slope.

Project description: Bispgården test cite
Date: 2023-06-06
Project filename: Bispgården test site
Step: 210
Company: Chalmers University of Technology

Figure 4.17: Changes in the temperature during the 160 days week test for the slope.

Figure 4.18 depicts the temperature profile after the 160 day scenario with frost lines, showing the limit between the frozen and unfrozen phase, in white. This indicates that the model is at least somewhat working as expected creating a layer of unfrozen soil above the frozen layer. The thickness of this unfrozen layer is not as thick as expected, in respect to the thawing time, and is restricted by to the top part of the elements. This will make stability calculations on this stage of slope uncertain.



Temperature (scaled up 5.00*10-3 times) (Time 13.82*10⁶ s)

Maximum value = 277.9 K (Element 174 at Node 216)

Minimum value = 265.7 K (Element 1 at Node 7)

Project description: Bispgården test cite

Date: 2023-06-07

Project filename: Bispgården test site

Step: 210

Company: Chalmers University of Technology

Figure 4.18: Temperature profile for the slope at the end of the 160 days.

4.2.2 Saturation Analysis of of the Slope

The effective soil saturation in the selected points during the 151 and 160 day scenarios are presented in Figure 4.19 and 4.20. The saturation on the Top boundary is in the very start of the time period very low at 0 %. The effective saturation is then increasing towards to 3 % during the first weeks of the scenario to then stay at 3 % for the reminding time in the frozen stage. When the top layer is thawed during the thawing is the effective saturation raised drastically in both scenarios. This is expected as the saturation limit of the soil is lowered when soil thaws. Interestingly is the effective saturation on the top boundary of the model not same in all points. Especially is the point Slope toe extended, showing much lower saturation than the rest of the points. This is coherent with temperature profile, Figure 4.18, which shows a higher temperature in the extended slope toe. Effective saturation for the Middle slope point also drops towards the 3 % as it starts to freeze. The saturation for the one week scenario is not presented as it just will show the increase presented in the beginning of the other two scenarios.

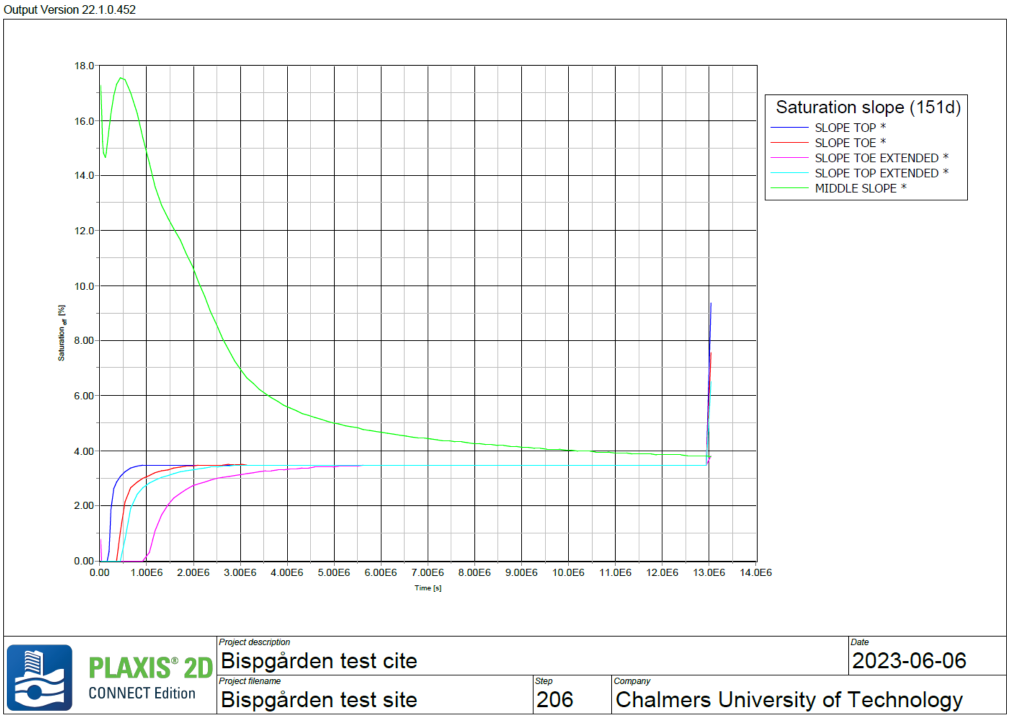


Figure 4.19: Changes in the saturation during the 151 days test for the slope.

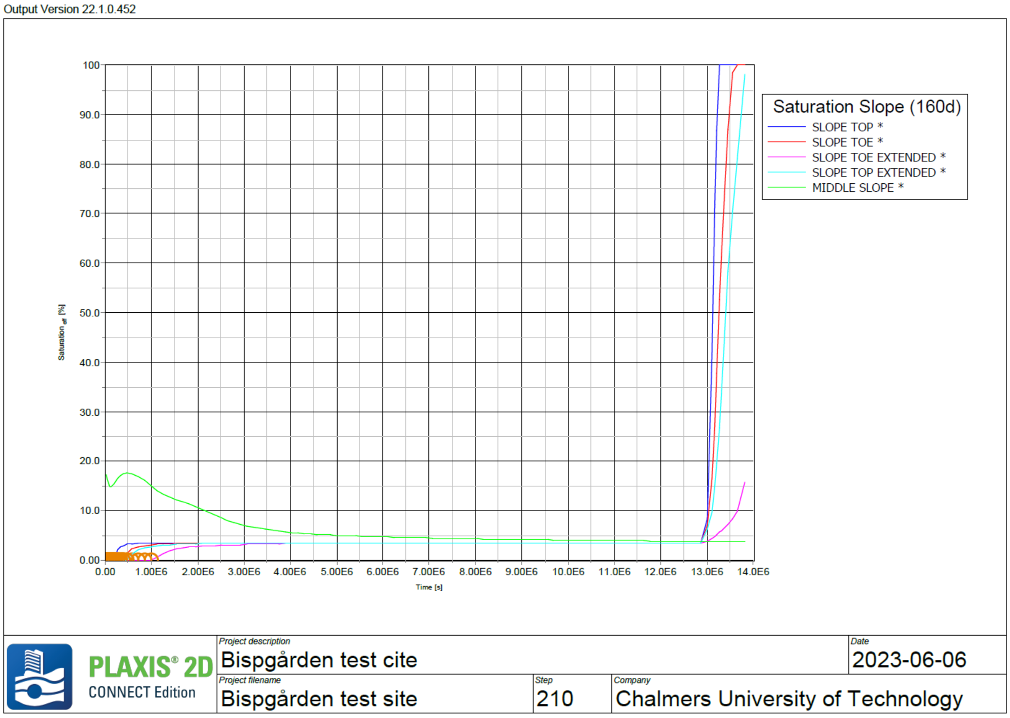
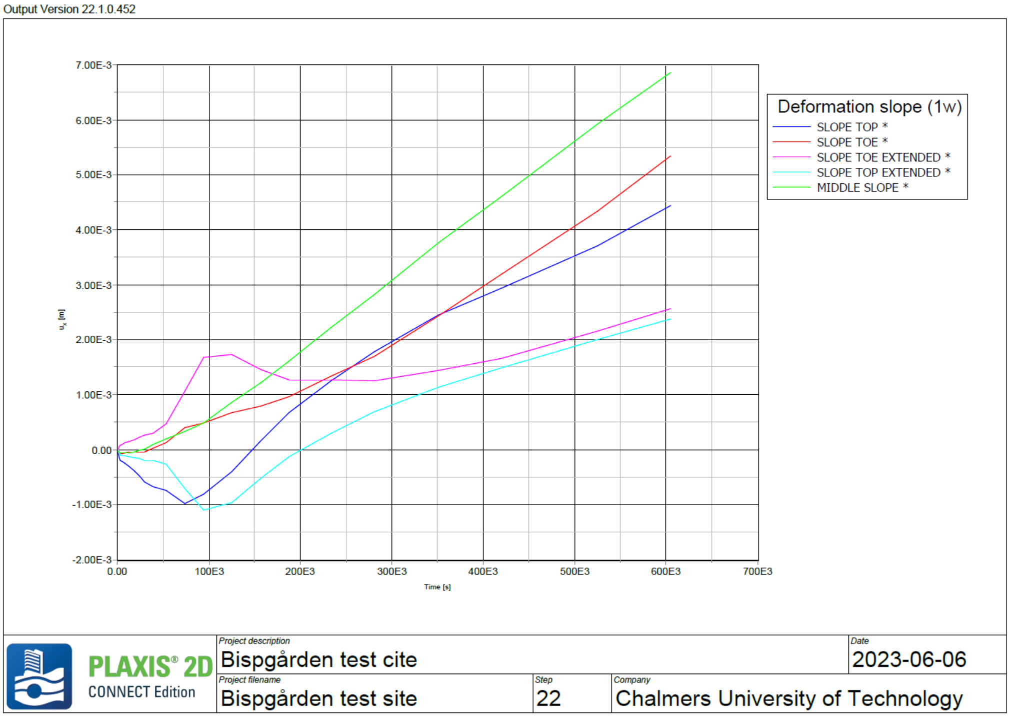


Figure 4.20: Changes in the saturation during the 160 days week test for the slope.

4.2.3 Vertical Displacement Analysis of the Slope

The vertical displacement for the 1 week and 160 day scenarios are presented in Figure 4.21 and 4.22. For the 1 week scenario are the selected point showing a small but clear positive deformation indicating that the frozen phase expansion is at least somewhat working as expected. Yet again are the displacements smaller than intended. For the Middle slope point and the Top slope point is there a negative displacement in the start of the freeze period. This could be explained by a brief period of chaos as the phase change is introduced to the model.



Project description: Bispgården test cite
Date: 2023-06-06
Project filename: Bispgården test site
Step: 22
Company: Chalmers University of Technology

Figure 4.21: Changes in the vertical displacement during the 1 week test for the slope.

In the 160 day scenario is the positive vertical displacement tendencies continued for most selected points in the model. The Slope top point shows the largest displacement with a total of 1.2 cm, again much smaller than expected. Interestingly is there an increase in the vertical displacement towards the end of the scenario when temperature is raised.

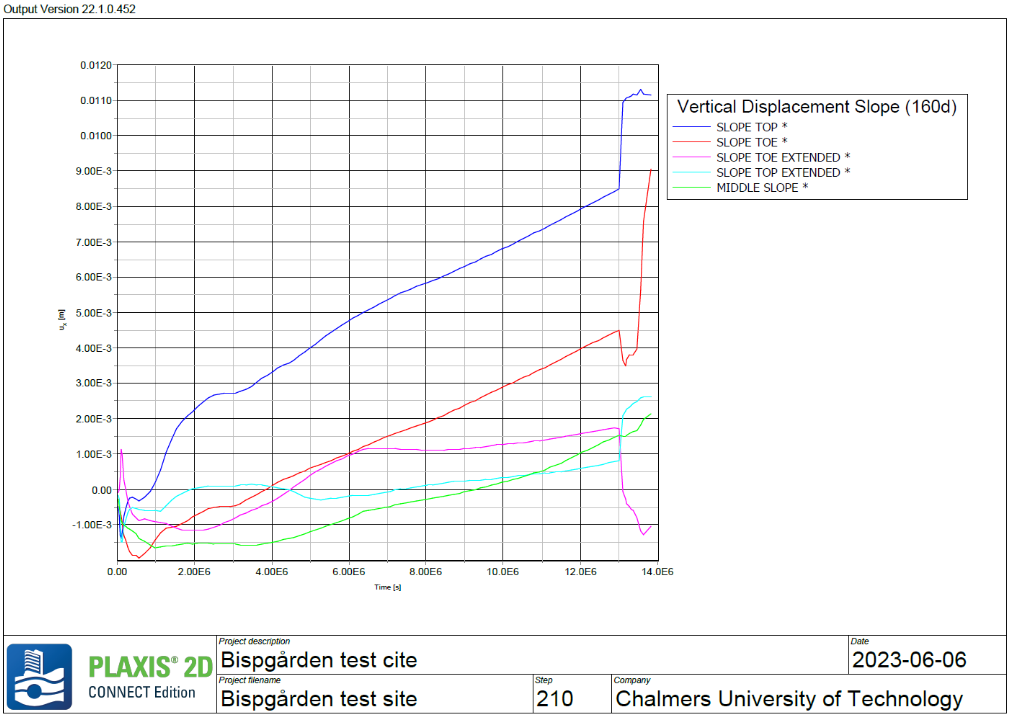


Figure 4.22: Changes in vertical displacement during the 160 days week test for the slope.

4.2.4 Stability Calculations

In the stability calculation was the slope brought to failure by adding an additional phase at the end of the 160 day scenario. This phase lasted for 1 hour and the maximum increase of gravity was found by a simple iterative process. The gravity could be increased approximately 40 times before the soil body collapsed. This can be compared to the approximate 75 time weight increase required for the totally unfrozen slope, a difference of 46.7 %. This indicates a clear stability reduction in the slope during thawing, but the results are not accurate enough draw any broader conclusions about the magnitude that could be related to the normal SF. If there is any stability reducing factor from the freezing and thawing, is it hard to prove from the results in this thesis. The unfrozen layer above the frozen soil could have been to shallow or the vertical displacements to small for the model to work as intended.

4.3 General Discussion and Reflections

Working with the F-U model has been very challenging. The model include three different behaviors that needed to be accounted for correctly for the model to work; temperature changes, water flow and the mechanical behavior of the soil including the phase change. Balancing these factors is difficult. Much of the time spent for this thesis has been to get a somewhat functioning model. Hundreds if not thousands of modulation runs has been spent on tries to get any results at all. Especially seemed factors related to water flow have large impact on the functioning of the model. Error codes have been more common than not. The research on the subject has also been quite limited, resulting in that endless variations of time steps, flow parameters and numerical control parameters were tested. This did in the end produce a result, but unfortunately a result that probably is pretty far from reality, when comparing to the real case. In the result presented in this thesis has the natural behavior of a freezing and thawing soil not been replicated to a full extent. Out of the three factors measured; vertical displacement, effective water saturation and temperature distribution, was the most concerning factor the vertical displacement. The results are overall far from pleasing, however is this one of few papers handling finite element modeling of freezing and thawing related to slope stability. Further should pore water pressures and effective stress be investigated further. This is clearly an area for future studies, especially in the light of oncoming climate change to cold regions.

The vertical displacement were much smaller than expected throughout the modeling. The explanation behind this could either be found in the soil parameters or in a faulty water behavior. The most reasonable cause is the soil parameters. This is contradicted by earlier results presented in the PLAXIS manual which uses the same parameters for the soil but get a different type of result.

The temperature distribution and effective water saturation gave overall better results than the vertical displacements. The results from these two factors could still be uncertain at times. The effective saturation was often lower than expected, maybe explaining the lack of vertical displacement. The temperature was also problematic, many modulation runs saw unexpected heat or cold develop within the model, as seen in Figure 4.18 (the cold temperatures displayed close to the surface). Why this appears could not be answered by the thesis nor the research. Still is the heat and saturation results close to satisfactory.

Despite the inaccurate results from the freezing and thawing was some kind of stability measurement generated in Bispgården with the 40 time weight increase. This result indicates that the thawing slope is stable but still more unstable than a totally unfrozen slope. Since the prior modeling results were questionable should this not be any indication of the actual SF for the slope, the real slope did after all fail in reality.

4.3.1 Specific Data

The F-U model requires a lot of specific data for a several parameters. These parameters are often unusual to use in geotechnics. This also makes working with model difficult. For the specific case at Bispgården was many of the parameters never measured, resulting in further uncertainty to the model. Standard parameters had be used and in the worst cases even values direct from the PLAXIS manual. The problem with specific data needed is probably not secluded to this case study. If extensive research or identification of frost sensibility of slopes was to be conducted, could there be a huge gap in the data needed and the data available. Gathering the data could also be troublesome as many of the parameters requires frozen samples and unusual laboratory techniques. This could be a future problem in this field of research.

In summary, the F-U model in PLAXIS can be a powerful tool for analyzing the behavior and stability of frozen and thawed soils. By incorporating temperature, pore water pressure, and mechanical deformation interactions, the model could provide valuable insights for engineers dealing with geotechnical challenges in cold regions. However are the prerequisites high.

5

Conclusion and Further Studies

This chapter presents the conclusion and suggested further studies for the thesis.

5.1 Conclusion

This thesis has shown that it could be possible to model the behavior of freezing and thawing soil with the *Frozen and Unfrozen soil model* and to relate it to a slope stability problem. This is however a hard task and it requires a lot of knowledge in both modeling with finite elements and frozen soil behaviors as well as large amounts of soil specific data. Making it barley feasible but certainly possible.

The thesis could model the heat and effective saturation over time somewhat satisfactory. The expansion from the freezing was however not implemented to the model in a satisfactory way, resulting in inaccurate calculations.

Further, the Bispgården test site did probably experience frost related damages, based on the prior signs. To model the failure on the other hand is next impossible, the data available is limited and the stability calculation is hard to implement in the *Frozen and Unfrozen soil model.* The soil model could potentially be used to solve frost related stability problems with sufficient amount of data and time, however the required amount data large and specific. The result from the thesis indicates stability changes to the slope during the freezing and thawing process; with a stability decrease of 46.6 % compared to a totally unfrozen slope.

To conclude, calculating the stability of slopes during climate driven condition changes, including altered natural temperature change through the year, will be future challenge for geothecnical engineers, otherwise stable slope can be pushed towards failure if the conditions in which they stand change. One of these potential changes could be a changed freeze thaw cycle. The *Frozen and Unfrozen soil model* could be one of tools used to solve these problems. As discussed are the prerequisites high.

5.2 Further Studies

The original topic for this thesis is still a subject that could be researched. The understanding of hydraulic and mechanical impact from vegetation could still be developed further.

The usability of the *Frozen and Unfrozen Soil Model* is something that could be researched further. Compiling related parameters and how it affects the result could be one example. A more accessible model could be more important than a more accurate one with more choices.

Climate change and its relation to the freezing and thawing of soil is something that could be researched further. Focus could be put on thawing permafrost and the potential impact on infrastructure and buildings. The speed of the thaw process and its relation to built up pore pressures in the thawed soil is another example in the same subject.

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A

Appendix

Parameter	**Test Soil**
T_{ref} (K)	274.16
γ_{water} (N/m^3)	10^4
$c_{water}(J/kg/K)$	4181
$\lambda_s 1, water(W/m/K)$	0.6
$L_{water}(J/kg)$	334×10^3
$\alpha_{water}(1/K)$	0.21×10^{-3}
$T_{water}(K)$	274.16
$c_{ice}(J/kg/K)$	2108
$\lambda_{s1,ice}(W/m/K)$	2.22
$\alpha_{ice}(1/K)$	0.05×10^{-3}

Table A.1: Model Parameters: water and ice

Parameter	**Test soil**	**Case study Soil**
General		
$\gamma_{unsat}(N/m^3)$	18 x 10^3	18 x 10^3
$\gamma_{sat}(N/m^3)$	18 x 10^3	18 x 10^3
$e_0(-)$	0.3	0.7
Groundwater		
$K_x(m/s)$	1.396 x 10^{-6}	1 x 10^{-5}
$K_y(m/s)$	1.396 x 10^{-6}	1 x 10^{-5}
Thermal		
$c_s(J/kg/K)$	2000	2000
$\lambda_{s1}(W/m/K)$	4	1.5
$\rho_s(kg/m^3)$	2200	2200
$\alpha_x(1/K)$	5.2 x 10^{-6}	5.2 x 10^{-6}
$\alpha_y(1/K)$	5.2 x 10^{-6}	5.2 x 10^{-6}
$\alpha_z(1/K)$	5.2 x 10^{-6}	5.2 x 10^{-6}
Initial		
$K_{0,x}(-)$	1	1
$K_{0,z}(-)$	1	1

Table A.2: Model Parameters: general, groundwater, thermal and initial

Parameter	**Test soil**	Case study Soil
Model-ID	15211522	15211522
$T_{ref}(K)$	273.16	273.16
$E_{f,ref}(N/m^2)$	50 x 10^6	30 x 10^6
$E_{f,inc}(N/m^2/K)$	10 x 10^6	10 x 10^6
$\nu_f(-)$	0.48	0.35
$G_0(N/m^2)$	5 x 10^6	5 x 10^6
$\kappa_0(-)$	0.3	0.11
$p*_c(N/m^2)$	-470 x 10^3	-400 x 10^3
$\lambda_0(-)$	0.4	0.4
$\gamma(-)$	0.2	1
$k_t(-)$	0.09	0.07
M (-)	1.17	1
$\lambda_s(-)$	0.4	0.5
$\kappa_s(-)$	8 x 10^{-3}	0.5 x 10^{-3}
r (-)	0.59	0.6
(m^2/N)	0.09 x 10^6	0.09 x 10^6
$\lambda_r(-)$	0.6	0.6
$\rho_r(N/m^2)$	2.4 x 10^6	2.4 x 10^6
$\alpha(-)$	9	9
$T_{ref}(K)$	273.16	273.16
$p_{ref}(N/m^2)$	-395 x 10^6	-395 x 10^6
m (-)	0.5	1
$P*_{y0}(N/m^2)$	-2.1 x 10^6	-50 x 10^3
Y_{ref}	0	0
$\Delta p *_{y0}$ $(N/m^2/m)$	0	0
$e_0(-)$	0.7	0.7
$(s_{s,seg})_{in}(N/m^2)$	8 x 10^6	8 x 10^6
$p_{at}(N/m^2)$	-100 x 10^3	-100 x 10^3
$K_w(N/m^2)$	10^9	10^9

Table A.3: Model Parameters: freezing and thawing

B

Appendix

t(h)	t(s)	T (C)	T (K)
0	0	0	273.15
1	3600	1	272.15
2	7200	2	271.15
3	10800	3	270.15
4	14400	4	269.15
5	18000	5	268.15
6	21600	6	267.15
7	25200	7	266.15
8	28800	8	265.15
9	32400	9	264.15
10	36000	10	263.15
11	39600	10	263.15
12	43200	10	263.15
13	46800	10	263.15
14	50400	10	263.15
15	54000	9	264.15
16	57600	8	265.15
17	61200	7	266.15
18	64800	6	267.15
19	68400	5	268.15
20	72000	4	269.15
21	75600	3	270.15
22	79200	2	271.15
23	82800	1	272.15
24	86400	0	273.15

Table B.1: Temperature variation 24h test

t(h)	**t(s)**	**T (C)**	**T (K)**
0	0	0	273.15
1	3600	1	272.15
2	7200	2	271.15
3	10800	3	270.15
4	14400	4	269.15
5	18000	5	268.15
6	21600	6	267.15
7	25200	7	266.15
8	28800	8	265.15
9	32400	9	264.15
10	36000	10	263.15
168	604800	10	263.15

Table B.2: Temperature variation 1 week test

t(d)	**t(h)**	**t(s)**	**T (C)**	**T (K)**
0	0	0	0	273.15
28.94	1	3600	1	272.15
57.87	2	7200	2	271.15
0.09	3	10800	3	270.15
115.74	4	14400	4	269.15
144.68	5	18000	5	268.15
0.02	6	21600	6	267.15
202.55	7	25200	7	266.15
231.48	8	28800	8	265.15
0.26	9	32400	9	264.15
289.35	10	36000	10	263.15
7.00	168	604800	10	263.15
30.00	720	2592000	10	263.15
150.00	3600	12960000	10	263.15
6.54	3601	12963600	9	264.15
6.83	3602	12967200	8	265.15
6,34	3603	12970800	7	266.15
7.41	3604	12974400	6	267.15
7.70	3605	12978000	5	268.15
6.27	3606	12981600	4	269.15
8.28	3607	12985200	3	270.15
8.56	3608	12988800	2	271.15
6.51	3609	12992400	1	272.15
9.14	3610	12996000	0	273.15
9.43	3611	12999600	1	274.15
150.5	3612	13003200	2	275.15
10.01	3613	13006800	3	276.15
10.30	3614	13010400	4	277.15
6.68	3615	13014000	5	278.15
151.00	3624	13046400	5	278.15
160.00	3840	13824000	5	278.15

Table B.3: Temprature variation 151 and 160 day test