Effect of Environmental Factors on Pore Water Pressure in River Bank Sediments, Sollefteå, Sweden

Påverkan av miljöfaktorer på porvattentryck i flodbanksediment, Sollefteå, Sverige

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Abstract

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Pore water pressure in a silt slope in Sollefteå, Sweden, was measured from 2009-2016. The results from 2009-2012 were presented and evaluated in a publication by Westerberg et al. (2014) and this report is an extension of that project.

In a silt slope the pore water pressures are generally negative, contributing to the stability of the slope. In this report the pore water pressure variations are analyzed using basic statistics and a connection between the pore water pressure variations, the geology and parameters such as temperature, precipitation and soil moisture are discussed.

The soils in the slope at Nipuddsvägen consists of sandy silt, silt, clayey silt and silty clay. The main findings were that at 2, 4 and 6 m depth there are significant increases and decreases in the pore water pressure that can be linked with the changing of the seasons, for example there is a significant increase in the spring when the ground frost melts. As the seasons change, so do the temperature and amount and type of precipitation. Other factors that vary with the season are the amount of net radiation, wind speed and relative humidity, all of which affect the amount of evapotranspiration. At greater depths the pore water pressure is most likely affected by a factor/factors that varies from year to year, possibly the total amount of rainfall. Therefore, the anticipated increase in precipitation in Scandinavia due to climate change could be an important factor influencing slope stability.

What precipitation, temperature and evapotranspiration have in common is that they affect the amount of water infiltrating the soil, and thereby the soil moisture content. How the soil moisture is distributed and flows through the soil (sub-surface flow) is governed by the different soil types and their mutual order in the slope, as well as by factors affecting the structure of the soil, e.g. animal burrows and aggregation. The formation of ground frost also affects the way in which the water present in the soil is redistributed.

At c. 14 m depth in the slope, there is a saturated layer with positive pore water pressures, which could be one of several such layers. The overall groundwater situation in a silt slope is complex; several different bodies of water can develop, and to get a complete picture of the ground water situation (and thereby also the pore water pressure variations) thorough hydrological surveys are needed.

Keywords: negative pore water pressures, matric suction, silt slope, slope stability, pore water pressure variations

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Påverkan av miljöfaktorer på porvattentryck i flodbanksediment, Sollefteå, Sverige

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I en siltslänt är porvattentrycket vanligtvis negativt vilket bidrar till stabiliteten i slänten. I den här rapporten är variationerna av porvattentrycket analyserade med hjälp av enkel statistik och en koppling mellan variationerna och geologin samt parametrar så som temperatur, nederbörd och fukthalt i marken diskuteras.


Vad nederbörd, temperatur och evapotranspiration har gemensamt är att de påverkar mängden vatten som infiltrerar marken, det vill säga de påverkar markens fukthalt. Hur vattnet är födelat i marken beror på de olika jordarterna och deras inbördes ordning i slänten, men också av faktorer som påverkar markens struktur så som aggregation och uppluckring av jorden på grund av marklevande djurs aktivitet. Även formationen av tjälle på vintern har troligtvis en viss inverkan på hur vattnet i marken omfördelas.

På 14 m djup finns ett vattenmättat lager med positiva porvattentryck vilket skulle kunna vara ett av flera sådana lager. I en siltslänt är grundvattensituationen mycket komplex, flera magasin av vatten kan bildas. För att få en bra bild av grundvattensituationen (och där med också porvattentrycksversionerna) behöver noggranna hydrologiska undersökningar genomföras.

Nyckelord: negativa porvattentryck, siltslänt, släntstabilitet, porvattentrycksversioner

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1. Introduction

1.1 Problem description

Founded in 1998, the Swedish Commission on slope stability (Skredkommissionen) has published recommendations for calculations, including both laboratory and field testing, and measurements of slope stability in the field for clay and sand, but not particularly for silt. Due to the special characteristics of silt as a soil material with geotechnical properties somewhere in between those of sand and clay, neither of these recommendations is suitable for determining the stability of silt slopes. In silt slopes the pore water pressures are generally negative when above the groundwater table which contributes to a strength increase in the soil and an increase of the stability of the slope. Most often in engineering practice, negative pore water pressures in silt slopes are not accounted for in the calculations of the stability of the slope, which may result in unnecessary and expensive measures taken to stabilize it.

1.2 Aim and purpose

This work is based on the results of pore water pressure measurements reported in a research project by Westerberg et al. (2014). In the project, the Swedish Geotechnical Institute (SGI) monitored pore water pressures in a silt slope by the river Ångermanälven in the municipality of Sollefteå. In addition to pore water pressure, they also measured air temperature, ground temperature and soil moisture. The emergency services in Höga kusten-Ådalen supplied the project with precipitation-data. SGI has continued to measure the pore water pressure, soil moisture and air- and ground temperature at the site since the research project by Westerberg et al. (2014) was finished.

The aim of this work is to study and compare the geological properties of this silt slope with the pore water pressure variations, as well as to evaluate how other parameters (precipitation, soil moisture, air- and ground temperature) affect the pore water pressures and relate this to the geology. The purpose is to get a better understanding of how the pore water pressure varies in a silt slope and what could be the main factors driving the variation.
2. Background

2.1 Study area

The slope at Nipuddsvägen is located next to the river Ångermanälven in the municipality of Sollefteå in the district of Ångermanland, Sweden (figure 1 and 2).

Figure 1. Sollefteå is located in the district of Ångermanland, Sweden (data from ©Lantmäteriet, modified in ArcGIS).
The black line indicates where the slope is located along the river Ångermanälven, Sollefteå. The map is showing the topsoil layer displayed on the terrain-map, modified in ArcGIS with data from ©Lantmäteriet (The Swedish National Land Survey) and SGU (Geological Survey of Sweden).

The slope is approximately 50 m high with an average slope angle of 35°, and the majority of the slope is covered with deciduous trees and grass (figure 3 and 4) (Westerberg et al., 2014). The slope has been stable during the years it was monitored. For how long it has been stable before 2009 is unknown, but there is a landslide scar at the crest which today is covered with grass (personal conversation with Rebecca Bertilsson and Bo Westerberg).

Behind the crest of the slope is a housing area, and some distance from the slope toe is a camping site (Westerberg et al., 2014).
Figure 3. Photograph from Westerberg et al. (2014) showing the slope from the toe of the slope.
2.2 Quaternary deposits

The Quaternary deposits found in the Swedish landscape today were mainly deposited during the last glaciation (Weichsel III) with maximum areal cover approximately 20 000 years ago. During a glaciation there are warmer periods where the ice melts, called interstadials, and cooler periods where the ice grows which are called interglacials. During Weichsel III the landmass of Sweden was covered by a kilometer-thick (in Ångermanland c. 3 km thick) ice sheet (Smith & Mikko, 2016) which alternately grew and melted. In Ångermanland the coast was free of ice c. 10 500 years ago (Berglund, 2004).

When the ice was active it moved slowly over the bedrock and broke the top into bits and pieces of different sizes, it also picked up already loose material. This material was transported by the ice and later deposited elsewhere if the ice came to a standstill or started to melt. This is known as till and is normally an unsorted Quaternary deposit with a variety of particle sizes overlaying the bedrock (Gembert & Ericsson, 1996).

Under the ice sheet, rivers of meltwater developed that transported loads of material and deposited them in the form of eskers. These can be found throughout Sweden, and in Ångermanland they are usually seen following the valleys. The material in eskers is well sorted due to the decrease in velocity of flow at the mouth of the ice-river. The clay that was deposited is called glacial clay, and it is layered since it obtained different colors depending on season. As the mouth of the river retreated, and the ice
melted, an esker formed with coarser material as a center (glaciofluvial deposits) and with the finer glacial clay on top and at the edges (Smith & Mikko, 2016).

A consequence of the ice melting was a higher and more varied sea level in the Baltic Sea. In Näsåker northwest of Sollefteå, the ‘highest shoreline’ (or Marine Limit) is 240 meters above the current sea level. When the glaciofluvial deposits were subjected to the erosive forces of the waves, the fine clay was washed away and deposited as post glacial clay on the ocean floor (Smith & Mikko, 2016).

As the ice sheet diminished, the land mass was relieved of a lot of pressure, resulting in an isostatic rise that continues to this day. In the beginning the rise was fast, about 8 cm/year. However, at 9000 years BP it started to slow down (Berglund, 2004) and today it is merely c. 9 mm/year in Ångermanland and Västerbotten (Westerberg et al., 2014).

The river Ångermanälven runs in a valley that was originally a local fracture in the bedrock, but which was deepened in its form under the influence of the repeated erosion of the ice. From Sollefteå up to Näsåker an esker of glaciofluvial material stretches along parts of this valley. Due to the isostatic rise, a fjord formed in the valley eroding parts of the finer sediment away, which exposed the esker at several locations. But the water running through the fjord continued to deposit clay in this valley. Since the ice sheet was still melting, variation in the flow velocity resulted in a varved deposit of clay, silt and sand. That said, the deposit is still called and behaves as a clay, since it consists of more than 15 % clay minerals (Smith & Mikko, 2016).

Eventually, the melting water from the ice gradually decreased in Ångermanälven, and post-glacial sediments started to deposit. The river eroded much of the antecedent sediments and deposited them as fine sand by the coastline, as post-glacial silt at medium depths of the Baltic and as fine clay at greater depths of the Baltic. As the land mass was still rising, this whole process was displaced downstream as new land surfaces were exposed and the coastline was relocated (Smith & Mikko, 2016).

Above these fine-grained sediments, alluvial sediments were deposited due to fluvial activity and flooding of the river, and alluvial plains developed along the river valley. These layers are usually less than 15 m thick and consist mainly of fine sand and silt, although in some places sand and gravel are present. As the landmass continued to rise, the river continued to erode into these alluvial plains resulting in terraces as high as 40 meters above the river cutting into older alluvial plains and the underlying finer sediments. Figure 5 shows a schematic cross section of what a typical valley in Ångermanälven might look like (Smith & Mikko, 2016).
2.3 Pore water pressure and stability

2.3.1 Pore water pressure

Soil consists of three major components; a solid phase, a liquid phase and a gas phase. The solid phase is mainly mineral particles but can also include organic material in various content. The pores in between the grains can be filled with water or air, and therefore represent the liquid or gas phase.

Soil saturation refers to the proportion of pore spaces that is filled with water. Below the groundwater table, the pores are completely filled with water, i.e. the saturation is 100% and the pore water pressure is positive (zone of saturation). Above the groundwater table, the pores can also be completely filled with water, but the pore water pressure is negative. This occurs when the water has risen by capillary forces to fully or partly fill the pores (why this results in a negative pore water pressure and a more precise definition of groundwater table will be presented). This zone is called the capillary zone (or tension-saturated zone) and the top limit is called the capillary fringe. The zone closest to the ground surface is called the soil water zone, and the saturation here depends on how much precipitation and evapotranspiration there is, how much water the roots of trees and plants take up, etc. Beneath this zone is the intermediate zone, which is where the water percolates down under the influence of gravity to the groundwater table. The saturation in the intermediate zone is dependent upon how much water infiltrates the zone of soil water (Grip & Rodhe, 2016; Tremblay, 1996). Figure 6 show a graphic illustration of the distribution of subsurface water.
Figure 6. Distribution of subsurface water (Tremblay 1996, originally published in Bear 1979).

Water in the pores in the saturated zone is referred to as groundwater, and water in the pores in the unsaturated zone is called soil moisture. The boundary between these two zones is called the water table. The water table is defined as “the level where the pore water pressure is equal to the atmospheric pressure”. However, in fine grained soils like silt and clay, the pores can be fully saturated several meters above the water table due to capillary forces, but still would not count as part of the saturated zone because the pore water pressure is not atmospheric (c. 100 kPa) at the capillary fringe (Tremblay, 1996).

For simplification, the pore pressure at the ground water table is set to 0, which makes values of <100 kPa negative and >100 kPa positive. Negative pore water pressures are also called matric suction (Tremblay, 1996).

In a physics example to demonstrate the phenomenon of capillary rise, a thin glass tube, representing a capillary, is placed vertically in a bucket of water. The water surface in the tube obtains traction forces due to the attraction forces between the water molecules at the surface (surface tension). Because the water has a certain contact angle with the glass, a concave meniscus will form at the surface. This causes the water level in the tube to rise, since the pressure at the meniscus is now less than the atmospheric pressure. The water level is rising because the pressure on the free water surface is larger (it is still exerted to the atmospheric pressure). It will stop rising when the hydrostatic pressure of the water pillar has countered this difference (Hillel, 2004). The rise corresponds to a vacuum (u) in the water as follows:

\[ u = -\gamma_w h_c \]  

(eq. 1)

where \( \gamma_w \) is the saturated unit weight of soil, and \( h_c \) is the height of the water column.

Thus in the capillary zone, there is always a vacuum (matric suction) in the pores (Axelsson, n.d.). In reality, however, this relationship cannot be used for soils since the pores are of varying sizes and shapes, and only direct measurements can tell what the capillary rise and matric suction is. But, in general, the capillary rise is greater the smaller the pores are; thus the matric suction is greater the smaller the pores are.
A rough estimate of the capillary rise in a certain soil-type could be obtained with the help of water retention curves, which show the capacity of different soils to hold water. Westerberg et al. (2014) did a simulation of the pore water pressures with the help of water retention curves, compared the results to their field data, and found that the results did not agree. One main issue is the hysteresis effect—something that is difficult to account for when there is no way of knowing if the soil in the field is in a wetting or drying phase. The hysteresis effect means that the effect on the capillary rise is larger when the soil is wetting than when it is drying (Tremblay, 1996).

Another reason the matric suction cannot be calculated based on capillarity alone is that matric suction is also dependent on the effect of adsorption, and these two mechanisms are difficult to separate. Adsorption is the phenomenon where water molecules attach to the surface of the grains, due to the bipolarity of water molecules, and create a film of water around the grain (figure 7). While this effect is negligible in coarser materials like sand, where capillarity plays a more important role, in clay the water is almost exclusively bound to the soil particles by adsorption. Commonly, both phenomenon are lumped together as capillary rise (Hillel, 2004). It is a result of adsorption that soil that contains water, but which has no contact with the ground water table, can also have a negative pore water pressure value.

![Figure 7. Illustration of pore water as adsorbed and capillary (Hillel, 2004).](image)

In this report the terms pore water pressure and pore pressure will be used interchangeably.

### 2.3.2 Stability

To determine the stability of a slope a so called safety factor ($F_s$) needs to be calculated (eq. 2), following:
Equilibrium refers to when the volume change of the soil is essentially complete after shearing, or when the soil is 99% drained. A slope with a safety factor $> 1$ is considered stable. Since the value of the shear strength is a highly uncertain factor, it needs to be accounted for. Thus, a safety factor higher than 1 is desirable, a safety factor of 1.5 would mean that the shear strength could be 33% lower but the slope would remain stable. The shear strength of a soil is related to the effective stress in the following way:

$$s = c' + \sigma'_f \tan \phi'$$

(eq. 3)

where

$s =$ shear strength  
$c' =$ effective stress cohesion  
$\sigma'_f =$ effective stress on the failure plane at failure  
$\phi' =$ effective stress angle of internal friction

The effective stress is all the forces supported by the grain skeleton of the soil and the total stress is the effective stress plus the pore water pressure. The relationship is shown in equation 4:

$$\sigma' = \sigma - u$$

(eq. 4)

where

$\sigma'$ = effective stress  
$\sigma =$ total stress  
u= pore water pressure

(Duncan, Wright & Brandon, 2014)

As can be seen from equation 2, 3 and 4 a negative pore water pressure (all other factors remaining the same) results in a higher effective stress, which in turn increases the shear strength and results in a higher factor of safety.

The negative pore water pressures in the slope at Nipuddsvägen contributes to a high shear strength that prevents the slope from failing even though the angle in parts is steeper than the normal angle of shearing resistance of the soils.
2.4 Silt

Silt is a sediment and particle size that has been deposited by running water with a low velocity, and has a grain fraction of 0.02-0.006 mm. It is distributed across Sweden, both as pure silt and as a component in another sediment or soil type. Under the so-called ‘highest shoreline’ (Marine Limit) the silt deposits are especially large since much was deposited at the edge of glaciofluvial deposits, as washed-out and flooding deposits and around former ice lakes. Usually, layers of silt are varved with layers of clay and/or fine sand, though the amount of silt is large enough for it to be classified as a silt sediment. In river valleys like that of Ångermanälven, silt-rich layers are usually on top of deposits of clay (Knutsson et al., 1998). Even pure silt has an internal layered structure, probably as a result of seasonal variations and changes in the depositional environment caused by the isostatic rise. That in turn results in shifting flow velocities that lead to the deposition of different grain sizes, varying oxygenation in the deposition environment and different amounts of organic content in the sediment (Larsson et al., 2007).

Silt has some special characteristics because it is a gradual transition between clay (cohesion soil) and sand (friction soil). In clay, the grains are not in direct contact with each other, rather, there is always a thin film of water around them such that the strength is dependent upon attracting molecular forces between the grains as well as upon its history of tension (if it is currently experiencing less, more, or the same amount of stress as the maximum amount of stress to which it has ever been subjected). In friction soils, the grains are in direct contact with each other, and the strength is therefore dependent upon the angle of internal friction. With regard to grain size and therefore also permeability, capillarity, compressibility and mineral composition, silt in a sense behaves as something in between clay and sand (Knutsson et al., 1998).

An important characteristic of silt when it comes to pore water pressure and stability is the combination of the relatively high capillarity and permeability. The capillary rise can be several meters (0.3-12 m) in silt, but is in fact higher in clay (>8 m) (Axelsson, n.d.). However, since silt has a higher permeability than clay, the water supply is larger and faster, and the capillary rise can therefore develop faster in silt. Figure 8 shows the capillary rise in clay, silt, sand and gravel over a 24 hour period.
Figure 8. The solid line shows the capillary rise after 24 hours for clay, silt, sand and gravel. The dashed line shows the maximum capacity for capillary rise. The x-axis displays grain size (mm) and the y-axis displays capillary rise (cm). Lera= clay, Silt= silt, Sand= sand, Grus= gravel (Knutsson et al., 1998).

This combination of high capillarity and permeability is favorable for ground frost formation since the limited supply of water during the winter can be supplied relatively quickly in silt, in comparison to clay. Ice lenses then form, leading to upheaval of the ground. When the temperatures rise again in the spring, the lenses melt and the ground becomes unstable. Figure 9 shows a diagram of susceptibility of different soils to ground frost (Knutsson et al., 1998).

Figure 9. The relationship between capillarity (kapillaritet) and permeability (permeabilitet) with the hatched area showing which relationship favors ground frost (tjälfarligt). Lera= clay, Silt= silt, Sand= sand, Grus= gravel. (Knutsson et al., 1998).
3. Methods

To achieve the stated purpose, a conceptual hydrological model is discussed in chapter 3.1. It is based on a geological model by Westerberg et al. (2014) and the collected pore water pressure data.

Pore water pressure data from a seven year period (2009-2016), the first years reported in Westerberg et al. (2014), has been studied in this report (monitoring of the pore water pressure at the slope is ongoing). There were three main measuring points: R1 (2 m behind the crest of the slope); R2 (10 m behind); and R3 (20 m behind the crest of the slope), (Westerberg et al., 2014). At these points the pore water pressure was measured at depths of 2, 4, 6, 10, 14, 15, 19, 21 and 25 m.

A BAT-peziometer was used for the pore water pressure measurements. A BAT Vadose filter tip was used In all measuring points except at 19 m depth in R1, where a BAT Standard tip was used.

The moisture content of the soil was measured at 0.5, 1, 2, 3 and 4 m depth at measuring point R2 (November 2010 to November 2015) with a ThetaProbe Soil Moisture sensor ML2x (Westerberg et al., 2014). The accuracy of the sensor is ±0.01 m³/m³ (1%) (ThetaProbe user manual).

Ground temperature was measured at 2, 4 and 6 m depth in R1, R2 and R3 respectively.

Air temperature and atmospheric pressure was measured by the ground at R1. There were other field measurements and geotechnical field and laboratory tests conducted of the soils in this slope, however; they are not presented in this report but can be studied in detail in Westerberg et al. (2014).

Next, precipitation, soil moisture, air and ground temperature, and the influence of these parameters on pore water pressure variations, are discussed with the aid of graphs based on basic statistics. The statistical method used to analyze the pore pressure data was moving average. The purpose of using this method is to smooth out the data so that the general trend can be more easily visualized. The mean for a chosen number of data points in a time series is calculated and these means are used to create a new time series (Mathworks, 2017). When analyzing the pore pressure, 30-40 data points were used, corresponding to 15-20 days of measurements, with two measurements made every 24 hours. When plotting this in a diagram small fluctuations disappear and the general trend over a year is more easily seen. The mean of 30-40 data points was chosen after comparing both smaller and larger intervals. The judgement was made that the deviations from the original curve were small enough to be irrelevant, while still giving a smooth curve where significant increases and decreases in pore water pressure could be identified.

MatLab R2016b was used for calculating the moving average, and Excel 2013 was used for analyzing the correlation between soil moisture and pore water pressure.

Other possible statistical methods for comparing the moving average mean of the pore water pressure with precipitation, soil moisture, and air and ground temperature data were covariance, cross-correlation and PCA (principal component analysis). However, after studying these methods the conclusion was made that these types of data are not comparable with each other. For example: rainfall data is given as an absolute number, i.e rain falling during one day results in a point with one value. If there is no rain
the next day, that day is blank- it has no value. But when the rain has fallen it slowly infiltrates the soil resulting in a gradual change in pore water pressure. The pore water pressure will have one value the day the rain falls, another value the next day and so on, as a response to this one rain event. There are also technical issues. For example: MatLab cannot handle missing data when analyzing covariance, which is the case with several of the pore water pressure series.

The series of pore water pressure data from Nipuddsvägen are incomplete since the tensiometers would occasionally stop working. The tensiometers measure the total pressure in the ground, which is equal to pore pressure plus atmospheric pressure. To evaluate which data were reliable, the total pressure was compared with the atmospheric pressure, and when they did not co-vary, it was regarded as a result of a malfunctioning tensiometer and that data was discarded (Westerberg et al., 2014).

3.1 Scope and limitations

The pore water pressure was measured with tensiometers, which would occasionally malfunction. For this reason, there are few periods where the pore water pressure series are complete; sometimes there are gaps for days, and sometimes data for several months is missing.
4. Results and discussion

4.1 The slope in Sollefteå, a conceptual model

When the pore water pressure was measured in the slope at Nipuddsvägen, there was also geotechnical surveys, Cone penetration tests (CPT), conducted to enable an interpretation of the stratigraphy of the slope. The cone penetrating tests were conducted in September 2009 at R1, R2 and R3 from a depth of 2 m to a depth of 19-27 meters, the results are obtained in the form of cone resistance. To make an interpretation of the stratigraphy, the lab results of grain size distribution analysis of collected soil samples were used together with the software Conrad. Figure 10 shows the suggested model of the soil stratigraphy of the slope (Westerberg et al., 2014).

This interpreted model fits well with the known geology of this area discussed in chapter 2.2. Fluvial sediments of sand and silt overlays finer postglacial silts and glacial and postglacial clays, exposed at this slope due to the erosive forces of the river. In this chapter the model will be discussed in an order from small to greater depths.
4.1.1 2-6 m depth

The measurements of the pore water pressure at 2 m depth are according to the model by Westerberg et al. (2014) in a sand layer. The values are therefore as expected around 0, between 1.7 kPa to -5.6 kPa, since the capillary forces are weaker than in more fine grained soils.

The measurements at 4 and 6 m depth are all in a sandy silt layer, and are therefore expected to be mainly negative and roughly the same. However, at 6 m depth the pore water pressure is generally slightly higher than at 4 m depth- at 4 m they range from -5.4 kPa to -18.3 kPa and at 6 m they range from -0.3 kPa to -16.8 kPa. This could indicate that this layer is slightly more fine grained at the level of the 4 m than at the 6 m measuring point. Alternatively, it could be that the water at 4 m depth percolates downwards relatively fast, and at 6 m depth it accumulates somewhat since it is prevented from percolating with the same rate into the next layer, which is silt (finer than sandy silt). A similar situation will be discussed more in detail in the following section (3.1.2).

4.1.2 10-14 m depth

At about 12 meters depth there is a layer with silt and clay enriched with sulphide. These kind of soils form when organic rich sediments are deposited in an anaerobic environment. In Sweden they are commonly found along the east coast and the grain size is generally smaller the further north and the closer to the coast they are found (Larsson et al., 2007). These sulphide soils formed 14 000-9 000 years ago, probably in depressions in the seafloor of the Baltic where turnover was absent, leading to a lack of oxygen. Due to the isostatic rise, these soils can now be found above the current sea level, sometimes by as much as 50 meters (Larsson et al., 2007). To find a layer of sulphide soil in the slope at Nipuddsvägen is therefore not surprising.

At c. 11 m (at R3), 12 m (at R2) and 14 m depth (at R1) there is an interpreted groundwater level. This is partially based on the CPT, but mainly that the pore water pressure measurements showed positive values at 14 and 15 m depth (Westerberg et al., 2014). At 10 m depth, the pore water pressure is negative, and at greater depths (19, 21 and 25 m) it is negative as well. It is therefore reasonable to say that this is not a groundwater storage reaching all the way down to the bedrock, but a temporary saturated layer in the slope. Not temporary in time, it is present all year around, but temporary in the vertical direction. Since the pore water pressures are positive in both R1, R2 and R3, where R1 and R3 are 20 meters apart, this groundwater level is probably not local but reaches further away in a horizontal direction as well.

As can be seen in the model of the slope by Westerberg et al. (2014) (figure 10), this saturated layer is located approximately directly above the sulphide silt and clay-rich silt layer. The layer above the sulphide-enriched layer, where the saturated layer is at the bottom, is interpreted as being silt. Since the infiltration rate is smaller in clay-rich silt than in silt, a saturated layer could back up in the silt (Kirkby, 1978). In addition, there could be organic remnants in the sulphide soil layer, acting as a lid leading to back up of the water in the silt layer. In R1, the saturated layer is interpreted as being in the sulphide soil layer instead of right above it. This might be a misinterpretation of where the interface between the
silt and the sulphide soil layer should be. If the temporary saturated layer is in fact exactly where the model by Westberg et al. (2014) suggest it is, there could be a local layer of silt or coarser material in the sulphide soil around R1 where the water accumulates. The overall groundwater situation in a silt slope is complex; several different bodies of water can develop, and to get a complete picture of the groundwater situation (and thereby also the pore pressure variations) many observations are needed (Knutsson et al., 1998).

There are pore water pressure measurements made at 10 meters depth in R1, R2 and R3. There is quite a lot of data missing from these series, but an interesting overall-observation is that even though they are all in the silt layer, the values between R1, R2 and R3 differ substantially. In R1 the pressure is around -30 kPa, in R2 around -18 kPa and in R3 it’s about -11 to -6 kPa (2010). This could support the interpretation that the aforementioned temporary saturated layer is inclined, leading 10 m depth at R3 to be closer to the saturated layer than R1 is at 10 m depth (the higher the water is rising by capillary forces, the higher the matric suction). Another explanation could be that the R1 measuring point might be in a local clay layer, R2 in silt and R3 in sandy silt (referring to layering of silt deposits, chapter 2.4.).

4.1.3 Depths greater than 14 m

At Nipuddsvägen, two open standpipes were installed- one in R3 and one at the toe of the slope. The standpipe at R3 was bent at 39 meters depth and no new open standpipe was installed, therefore the location of the groundwater table is only known to be somewhere below 39 meters depth. (Westerberg, et al., 2014). The open standpipe at the toe of the slope shows a groundwater table fluctuating between 3 to 5 meters below the top edge of the pipe over the course of one year. This is most likely the location of the groundwater table, but if and how it is connected to a ground water level in the slope cannot be determined with the data available.

The layer at the bottom of the slope (deeper than 25 m) was not covered by the CPT, and no pore water pressure measurements were conducted at this depth. What type of soil this layer consists of cannot be said for certain. Based on the known quaternary geology of the area, a qualitative guess is that it is clay for a few more meters, and when approaching the flood plain level the clay is underlain by till or glaciofluvial sediments which are overlaying the bedrock. There was a soil/rock-probing made in 2009 which suggests that this unknown layer is a silt with some internal layering of sand. Westerberg et al. (2014) also studied data from SGU (Geological survey of Sweden) collected during well-drilling in the vicinity, which reported that the bedrock was located 57-64 m below the ground surface.

4.2 Variations of pore water pressure over the year

In this section, the variations of the pore water pressure in the slope is discussed in the context of different climatic parameters of which data is available from Nipuddsvägen: temperature, precipitation and soil moisture. Sections 3.2.1 - 3.2.3 will focus on shallower depths (2 - 6 m), discussing the climatic
parameters separately. In the last section, 3.2.4 (depth >6 m), the same climatic parameters will be discussed but integrated with each other.

4.2.1 Temperature and ground frost thawing/formation

In figure 11, the pore water pressures in R2 at 2 m depth is presented, for 2010-2014.

![Figure 11. 40-points moving average of pore water pressure measurements in R2 at 2 m depth for 2010-2014.](image)

The main thing observed in measuring point R1, R2 and R3 at 2, 4 and 6 m depth is the significant rise in pore water pressure in the spring, starting in approximately March-April (graphs displaying pore water pressure measurements from depths and measuring points other than that in figure 11 can be studied in appendix 1.) Unfortunately, there is no single year where the 2, 4 and 6 m pore pressure data-series, in a single measuring point (R1, R2 or R3), are all complete. However, when studying the different pore pressure series from depths of 2-6 m available, a pattern where the pore water pressure in the spring first starts to rise at 2 m depth, followed by 4 m and lastly rise at 6 m depth, is observed.

The reason for this sudden rise is most likely the thawing of ground frost, which increases the moisture content of the soil (Westerberg et al., 2014). The data of the temperature in the ground, measured at 2, 4 and 6 m depth, show that the ground frost does not reach 2 m depth (figure 12), but as the frozen water melts it infiltrates the unfrozen soil and thereby affecting the pore pressure at these depths as well. It is not only meltwater from the ground frost that contributes to the rise: when the ground frost is gone the soil is permeable again, making it possible for the water that have been stored as snow during the winter to infiltrate the ground.
An interesting observation is that the ground frost thawing (or more precisely the response in pore water pressure due to ground frost thawing), occurs before the temperature in the ground starts to rise. This is true for all the years, and at all depths, where there is data available for both ground temperature and pore water pressure. The pore water pressure starts to rise in March-April, but the ground temperature does not start to rise until May-June (example from 2010 at 4 m depth in figure 13). This is because the warmer temperatures in the air affects the snow melting and thawing of the ground frost at the surface faster than they affect the temperature of the soil at 2 m depth. Therefore, measuring exclusively the temperature in the ground does not tell us when to expect a significant rise in pore water pressure in the spring.
Figure 13. 40-points moving average of pore water pressure and the temperature in the ground at 4 m depth in measuring point R1 2010.

The air temperature, on the other hand, could possibly be used as an indicator of when the pore water pressure is expected to increase. When the air-temperature has fluctuated around 0 °C for a certain amount of time, the ground will start to thaw, and the pore water pressure will rise due to the increase of water in the soil. The amount of time passing before the pore pressure starts to rise depends on how much below and above 0 °C the temperature has been fluctuating, and how thick the insulating snow cover has been. Based on the data from Nipuddsvägen, it is roughly about a month from the first > 0 °C reading to the response in a rising pore water pressure (example in figure 14).
Related to ground frost thawing is ground frost formation. When water in the soil turns into ice, the amount of pore water decreases in this zone, which leads to a higher matric suction. The higher matric suction increases the energy potential gradient in the soil, creating an upward flow of pore water towards the ground frost fringe (Grip & Rodhe, 2016).

According to Zhang et al. (2016), a special pattern is noticeable in the pore pressure data when ground frost formation first begins. From their study they concluded that when the topsoil starts to freeze, it exerts a pressure on the unfrozen soil beneath it. At first, the compression of the unfrozen soil leads to a rise in pore water pressure in the unfrozen soil. Eventually, the pore water pressure decreases again as the water extruded during compression migrates up to the frozen zone due to the energy potential gradient. In the data from Nipuddsvägen, this rise-and-fall pattern is found at some of the depths some of the years, but it is not a definite trend.

The most continuous dataset for all years is from measuring point R3, where the trend over the years is most visible (figure 15). The black lines in figure 15-18 are estimated periods of ground frost.
Figure 15. 40-points moving average of pore water pressure in measuring point R3, 2010-2015. The black lines are estimated periods of ground frost. Note: the black lines actually do not have a y-value, the intention is to mark the time along the x-axis.

Figure 16. 40-points moving average of pore water pressure in measuring point R2, 2010-2015. The black lines are estimated periods of ground frost. Note: the black lines actually do not have a y-value, they only mark the time along the x-axis.
Figure 17. 40-points moving average of pore water pressure in measuring point R2, 2010-2015. The black lines are estimated periods of ground frost. Note: the black lines actually do not have a y-value, they only mark the time along the x-axis.

For estimating these possible periods of ground frost, the assumption was made that the ground frost starts to form when the average daily air temperature is < 0 °C and does not start to thaw until the average daily air temperature is > +2 °C. The 2 °C-mark was chosen because temperatures in early spring fluctuates substantially between -2 °C and +2 °C. Short periods of a few days with warmer temperatures in an otherwise obvious winter climate were ignored (e.g. in the middle of January when a short period of positive temperatures was both preceded and followed by temperatures well below 0 °C). Bear in mind that the black lines in the following graphs are only what they say; an estimation, or possible period of ground frost.

One noticeable trend in figure 15-18 is the increasing pore water pressure in the spring that was discussed earlier, and which correlates well with the end of the estimated ground frost periods, i.e. the significant rise in pore water pressure in the spring starts at the end of the black line representing the ground frost-period. The changes in pore water pressures are smallest at 2 m depth, since there is sand at 2 m depth. Sand has a high permeability and thus drains well, so the magnitude of pore water pressure fluctuations is small. It is difficult to see the fluctuations at all depths during the autumn and winter in the low resolution of five years; therefore, figure 18 only displays one year, 2010, for measuring point R3 for better visualization.
At 2 m depth, the phenomenon of increasing pore water pressure at the beginning of the ground frost formation followed by a decrease in pore water pressure as the frost formation continues, as suggested by Zhang, et al. (2016), may perhaps be represented by the last peak in the middle of November (figure 18). However, the increase in pore water pressure is very small, about 1 kPa, and the pore water pressure does not follow the same pattern at 4 and 6 m depth. In the laboratory trials of Zhang et al. (2016), the increase was in the order of 5-20 kPa at the start of ground frost formation. There is a rise at 4 m depth (figure 18), but it had already started in the beginning of October, which is about one month before the estimated start of ground frost formation, indicating that the reason for this rise might be rain fall. Looking at data for the following years, there is a possible rise-and-fall pattern; however, it is difficult to determine since the exact starting point of ground frost formation is unknown. It is possible that the pore water pressure is not affected by ground frost formation at depths greater than 2 m. Zhang et al. (2016) only measured at 7.8, 8.0 and 9.8 cm depth so perhaps 2 m and deeper are not affected in the same way.

4.2.2 Precipitation and evapotranspiration
Looking at figure 19 and 20 of pore water pressure and rain, an interesting pattern is seen. Note, two years are displayed in these graphs to get a better picture of what happens during the autumn, -winter
and early spring as compared to only displaying one year. At 6 m depth the magnitude of significant increases and decreases in pore water pressure is high but the frequency of these variations is lower than at 2 and 4 m depth.

Figure 19. 40-points moving average of pore water pressure in measuring point R3, and rain 2010-2011.
It appears that the pore water pressure at 6 m depth only responds to the thawing ground frost by rising, and then it decreases until the ground frost begins thawing the following year (Westerberg et al., 2014). That said, there is a small peak in October-December in 2011 at 6 m depth (figure 19), which could be a response to the fact that the total rainfall was roughly 450 mm that year compared to 350 mm in 2010, when there is no peak during this time. A possible explanation is that there is a threshold -value somewhere between 350-450 mm rainfall where the pore water pressure at 6 m depth is affected as well. Other years there is either no data for 6 m depth or the data shows no response to summer/autumn rainfall so there is not enough data to confirm that hypothesis.

At 4 m depth, the magnitude of the change is not as high as at 6 m depth, but the frequency of significant increases and decreases is higher. Apart from responding to the ground frost thawing, there also seems to be a response by rising some time after the rainy periods in the summer/autumn followed by a decrease during the winter. At 2 m depth, the magnitude of change in pore water pressure is, as mentioned earlier, not particularly high. The frequency is similar to the change at 4 m depth, but the peak following the rainy season has two or more “sub-peaks” at 2 m depth. This is probably because the rain period consists of several rain events, and since there is only sand at 2 m depth, it drains a bit in between the rain events.

The reason the pore water pressure decreases during the summer, at all depths and consistently through all the years, is because rain is sparse and the evapotranspiration is high during the summer months. In Sweden about half of the yearly precipitation evaporates (Grip & Rodhe, 2016). Evaporation
is governed by several factors such as solar radiation, wind speed, relative humidity, temperature, etc. (Kassim et al., 2012).

Air temperature data was collected for Nipuddsvägen (chapter 3.2.1), but no other types of meteorological data that govern evaporation were collected. The slope at Nipuddsvägen can be expected to receive a higher quantity of net-radiation than the average flat surface since it is inclined and oriented in a southward direction (Weeks & Wilson, 2006), making it a possibly important factor regarding pore water pressure variations. Kassim et al. (2012) monitored a residual soil slope in Malaysia and found that the matric suction was higher during the day than at night due to higher net-radiation during daytime. The pore water pressure was registered at 12 am and 12 pm every day at Nipuddsvägen but no such pattern was noted. Kassim et al. (2012) only measured the pore water pressure at 0.5, 1 and 1.5 m depth, perhaps the pore water pressure at depths greater than 1.5 meters are not affected by day to night-fluctuations in radiation. It could also be a result of different soil types; the silty soils at Nipuddsvägen are sedimentary while the slope in Malaysia is composed of residual soils of silty gravel and sandy silt. The most important difference is probably that there is a higher net-radiation during the day in Malaysia than in Sweden due to its close proximity to the equator.

### 4.2.3 Soil moisture

So far, a seasonal variation of the pore water pressure has been discussed in chapter 3.2. All parameters regarding seasonal variability (such as temperature, precipitation, ground frost, evapotranspiration etc.) determine the amount of water in the soil. Therefore, soil moisture variation is expected to fluctuate well with variations in the pore water pressure.

To see the relationship between soil moisture and pore water pressure, data from 2011 and 2012 were plotted as seen in figure 21 and 22 (graphs from 2013-2014 in appendix 2. 2010 and 2015 were excluded because the soil moisture data is missing from parts of these years). Only 2 m and 4 m depths were analyzed because there were no pore water pressure measurements made at 0.5, 1 and 3 m depth.
Figure 21. Pore water pressure and soil moisture in measuring point R2 2011.

Figure 22. Pore water pressure and soil moisture in measuring point R2 2012.
The actual pore water pressure measurements are plotted rather than the moving average. This was to avoid overgeneralization that would run the risk of missing a pattern in the pore water pressure series, which could be mirrored by the soil moisture series. Unfortunately, the pore water pressure data for 4 m depth is incomplete in both 2011 and 2012, but the general impression when looking at figure 21 and 22 is that the pore water pressure and moisture content seem to follow each other well.

In figure 21, the moisture content increases by c. 0.02 m³/m³ at 2 m depth in April, and the pore water pressure increases by c. 2 kPa. From January to April, there is a decrease in soil moisture content by almost 0.02 m³/m³ at 2 m depth, but the pore water pressure only decreases less than 1 kPa. The greater difference in pore water pressure during wetting than during drying is most likely due to the hysteresis effect. Measuring soil moisture is easier than measuring pore water pressure, but because of the hysteresis effect, the most reliable way of measuring pore water pressure is to measure them directly (Toll et al., 2011).

In figure 21, the pore water pressure at 4 m depth starts to rise significantly in April before the soil moisture increases. This could have two explanations: either the tensiometer stopped functioning when it was still thought to be functioning; or, it could be because the properties of the soil at the measuring points differed somewhat (soil moisture and pore water pressure were both measured in R2, but in two different holes right next to each other.) In finer materials like silt and clay, most of the subsurface flow is in structural pores (animal burrows, pores increasing in size do to aggregation, roots decaying leaving an empty space etc.) (Grip & Rodhe, 2016), so the pore water pressure might have been measured in a spot with some larger structural pores, and the soil moisture in a spot just next to it with textural pores.

Another interesting observation, seen best in figure 21 at 4 m depth, is that the changes in soil moisture are represented by a smooth curve, and the pore water pressure jumps up and down at moments when the soil moisture is constant- sometimes by as much as 2 kPa. In figure 23 and 24, soil moisture is plotted against pore water pressure at 4 and 2 m depth respectively (data from 2011), and this shows how much the pore water pressure varies compared to soil moisture (the correlation coefficient is c. 0.3 and 0.6, with 1 being perfect a correlation).
Figure 23. Pore water pressure plotted against soil moisture at 4 m depth 2011. The correlation coefficient is c. 0.3.

Figure 24. Pore water pressure plotted against soil moisture at 2 m depth 2011. The correlation coefficient is c. 0.6.

This is partially an effect of hysteresis, but could also be an effect of how the device to measure moisture content differs from the tensiometer that measures pore water pressure. The ThetaProbe Soil Moisture sensor ML2x measures the soil moisture content of a soil volume corresponding to 95% of its cylindrical form, which is 6 cm long and 4 cm in diameter, i.e. a volume of c. 72 cm$^3$ (ThetaProbe user manual). The tensiometer, on the other hand, has a filter tip, which is 2 cm high and records the pressure in its immediate surroundings. This would roughly mean that the soil moisture sensor measures a kind of

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average soil moisture content of a larger volume of soil, while the tensiometer measures the pore water pressure at a given point, or at least in a smaller volume.

When comparing different years it should be noted that in 2011 and 2012 (figure 21 and figure 22), the pore water pressures at 2 m depth are roughly the same during the same months in both years, except in for example June and October, when the pore water pressure is slightly higher in 2012. But the difference in soil moisture between 2011 and 2012 is rather large; in April, when the ground frost thawing is affecting the pore water pressure, the soil moisture is almost 0.20 m$^3$/m$^3$ and the pore water pressure c.-1 kPa in 2011, but during the same period in 2012, the soil moisture is almost 0.23 m$^3$/m$^3$ but the pore pressure is still c. -1 kPa.

Figure 24 shows the soil moisture at all the measured depths for 2011.

![Soil moisture 2011](image)

**Figure 25.** Soil moisture in measuring point R2 2011.

The response of ground frost thawing in the spring is noticeable in figure 25 where the soil moisture increases at 0.5 m first, then at 1 m, then at 2 m depth etc. The response to rain in the summer/autumn is also following the same pattern with shallower depths responding earlier than bigger depths (as also found by Westerberg et al., 2014). Even if the pore water pressure series are incomplete and it is unclear if the same pattern is true for the pore water pressure, based on this and the knowledge about the relationship between soil moisture and pore water pressure discussed earlier, it can be expected that the pore water pressure follows the same pattern as the soil moisture.
4.2.4 Pore water pressure variations at 10-25 m depth

The pore water pressure measurements in figure 26 are from January 2015 to 15 July 2016.

![Pore pressure at greater depths](image)

**Figure 26.** Moving average mean of pore water pressure at 10, 19, 21 and 25 m depth in R1, R2 and R3 from January 2015 to July 2016.

The readings from 10 m depth in R1 are positive from approximately January 2016 and onwards. There is no other data from 10 m depth in R1, except in 2010 when the pore water pressure is c. -30 kPa during this same period, which is a large contrast to the positive readings in 2016. A possible explanation could be that the saturated layer at c. 11-14 m depth discussed in chapter 3.1.2 has grown in 2016 as a result of increasing soil moisture, resulting in positive pore water pressures at 10 m depth. Unfortunately, there is no soil moisture data from 2016, nor is there data from 10-25 m depth, so that comparison cannot be made. Although there is rainfall data, it does not adequately explain the big increase either, since the total rainfall in 2009 (c. 463 mm) is actually greater than the total rainfall in 2015 (c. 328 mm). Another explanation could be that the tensiometers were not functional, either in 2010 or in 2016.

Compared to the shallower depths (2-6 m), the pore water pressure at 10, 19, 21 and 25 m depth do not seem to respond to the ground frost thawing; however, this cannot be determined with any certainty since a large portion of the data is missing. The most complete series in figure 26 is at 19 m depth in R1. Here, there is an increase in pore water pressure in April of both 2015 and 2016, a trend that also can be seen in previous years where there is data from 19 m depth, but which is probably not a response to the ground frost thawing. A first-order estimate indicates that water infiltrating the soil due to the
Thawing of ground frost starting at the end of March (based on air temperature) should not reach 19 m depth in the slope at Nipuddsvägen until the end of July (c. 4 months). For simplification, the infiltration was calculated as starting from the ground level and going through 2 m of sand with a basic infiltration rate of 25 mm/h, 4.5 m of sandy silt with a rate of 15 mm/h, 6 m of silt with a rate of 6 mm/h and 7 m of clay-rich silt with a rate of 5 mm/h (layer thickness based on the geological model of the slope, figure 10). The values of infiltration rate are not measured in situ, but rather are chosen based on table 1. The intervals of the infiltration rates of the different soils are rather large, and there are many different factors that are not included in this calculation but which influence the infiltration; thus, the calculation is not precise. It is, however, safe to say that the response in pore water pressure should not be faster at 19 m depth than at 2 m depth.

**Table 1.** Steady infiltration rate of different soils (Hillel, 2004).

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Steady Infiltration rate (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sands</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Sandy and silty soils</td>
<td>10–20</td>
</tr>
<tr>
<td>Loams</td>
<td>5–10</td>
</tr>
<tr>
<td>Clayey soils</td>
<td>1–5</td>
</tr>
<tr>
<td>Sodic clayey soils</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

One speculation could be that the rise in pore water pressure in April 2015 at 19 m depth is a response to rainfall during the summer/fall of the previous year. If that were the case, then the rain falling in September-October 2014 would take c. 6 months to percolate 19 m. Since the calculation based on table 1 is very rough, it is possible that this is the case. However, there should be a response to ground frost thawing as well, since the pattern seen at shallower depths (2, 4 and 6 m) is that there is a greater response in pore water pressure to ground frost thawing than there is to the summer/autumn rainfall. That said, it is possible that since much of the meltwater and rain is used by plants and is evaporated during the spring/summer, what is left of the thawing snow and ground frost infiltrates and percolates downwards, but remains insufficient to reach a depth of 19 m. In comparison, rainwater in the summer/fall can percolate downwards while the topsoil freezes in the winter, thus allowing most of the water to remain in the unfrozen soil.

In 2013 and 2014, the pore water pressure at 19 m depth reaches positive values in April-June. In 2012, 2015 and 2016 it is close to positive (greater than −5kPa). This could indicate that the soils at this depth are arranged in such a way that they favor the formation of a temporary saturated layer. If the model by Westberg et al. (2014) discussed in chapter 3.1 (figure 10) holds true, than the measuring point at 19 m depth in R1 is located just below the clay-rich silt/silty clay layer, in the “unknown” layer. If the “unknown” layer is in fact silt with some internal sand-layers as the soil/rock-probing suggests (see...
chapter 3.1), then the measurements at 19 m depth could be in a sand-layer acting as an aquifer (positive pore water pressure values) if the supply of water is large enough.

In table 2 the total rainfall for each year and the approximate average pore water pressure in the spring (April-June) at 19 m depth are listed. During some years with ample rainfall (e.g. 2012 and 2013), there is a response of positive pore water pressures at 19 m depth the following years (2013 and 2014). However, to understand the extent of the influence of rainfall in one year on the positive/negative pore water pressures of the following year, data from additional years is required.

### Table 2. Total rainfall and an average pore pressure at R1 19 m depth in the spring respective years.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total rain fall [mm]</th>
<th>Average pore pressure [kPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>463</td>
<td>No data</td>
</tr>
<tr>
<td>2010</td>
<td>383.5</td>
<td>No data</td>
</tr>
<tr>
<td>2011</td>
<td>470.5</td>
<td>-10</td>
</tr>
<tr>
<td>2012</td>
<td>470.8</td>
<td>No data</td>
</tr>
<tr>
<td>2013</td>
<td>436.5</td>
<td>+1</td>
</tr>
<tr>
<td>2014</td>
<td>417.45</td>
<td>+1</td>
</tr>
<tr>
<td>2015</td>
<td>328.1</td>
<td>-3</td>
</tr>
<tr>
<td>2016</td>
<td>No data</td>
<td>-4</td>
</tr>
</tbody>
</table>

The values of the pore water pressure at 21 m (R2) and 25 m depth (R3) in figure 25 are representative for all years (2010-2016), regardless of rainfall and temperature variations. At 21 m, the pore water pressure values are stable over the year at c. -20 – -22 kPa, and at 25 m they’re stable at c. -8 – -10 kPa. These measurement points are, as at 19 m depth in R1, just below the clay-rich silt/silty clay –layer, and are therefore in the “unknown” layer (based on the model by Westberg et al. 2014, chapter 3.1, figure 10). The measuring point at 21 m depth is probably in a more fine-grained layer than the measuring point at 25 m depth.

In the discussion about water infiltrating and affecting pore water pressures at greater depths in the soil profile, it is worth noting that it is not always the actual water molecules from e.g. ground frost thawing percolating downwards that are responsible for the change in soil moisture and pore water pressure. Water infiltrating the soil also creates a pressure on water further down in the soil profile, which can create a sub-surface flow that increases the soil moisture and pore water pressure. Since the pressure propagation velocity is faster than the pore water velocity, the groundwater table can start to rise directly after a rainfall event, even if the actual water that fell during this rain event has not yet had time to percolate to the depth of the water table (Grip & Rodhe, 2016).
5. Discussion and conclusions

At 2, 4 and 6 m depth there are significant increases and decreases in the pore water pressure that can be linked with the changing of the seasons. As the seasons change, so do the temperature and amount and type of precipitation. Other factors that vary with the season are the amount of net radiation, wind speed and relative humidity, all of which affect the amount of evapotranspiration.

What all of these factors have in common is that they affect the amount of water infiltrating the soil, and thereby the soil moisture content. How the soil moisture is distributed and flows through the soil (sub-surface flow) is governed by the different soil types and their mutual order in the slope, as well as by factors affecting the structure of the soil, e.g. animal burrows and aggregation. As discussed in chapter 3.2.1, the formation of ground frost also affects the way in which the water present in the soil is redistributed.

Since most of the soil in the slope at Nipuddsvägen is sandy silt, silt, clayey silt or silty clay, the water present in the soil is bound by capillary forces leading to negative pore water pressures. At c. 14 m depth in the slope, there is a saturated layer with positive pore water pressures, which could be one of several such layers. The overall groundwater situation in a silt slope is complex; several different bodies of water can develop, and to get a complete picture of the ground water situation (and thereby also the pore water pressure variations) many observations are needed (Knutsson et al., 1998).

Soil moisture seems to be one measurable factor needed to get a good picture of the pore water pressure variations in a silt slope. As was discussed in chapter 3.2.3, there is no specific value of soil moisture that corresponds to a specific value of pore water pressure. This is primarily due to the effect of hysteresis, but could also be attributed to the fact that the devices that measure the respective values function differently when measuring different volumes of soil for soil moisture and pore water pressure. Therefore, measurements of soil moisture cannot replace pore water pressure measurements; however, they can be a good indicator of pore water pressure variations over the course of the year.

Using moving average to visualize the pore water pressure variations has made it easy to identify the significant increases and decreases during a year. However, care has to be taken when the pore water pressure is close to zero, because the moving average mean can display the pressure as being negative when the actual pore water pressure might in fact be fluctuating between small negative and small positive values. This may be an important difference, since a positive value means that the soil is fully saturated, thereby eliminating the cohesive, stabilizing effect of matric suction.

As our climate changes due to global warming, an increase in precipitation is anticipated in Scandinavia (Fallsvik et al., 2014). In the slope at Nipuddsvägen, the pore water pressure is negative some years and positive other years at a depth of 19 m (chapter 3.2.4). This means that the pore water pressure at 19 m depth is easily influenced by one or several factors which varies a bit from year to year, changing the soil moisture. One important factor might be the total amount of rain, which means that climate change could affect the stability of this slope. A layer in a slope becoming fully saturated
(positive pore water pressure) could act as a slip surface; therefore, it would be advisable to identify layers that have an unstable “tipping-point” between negative and positive pore water pressures. As was stated earlier, the pore water pressure at 2-6 m depth is clearly influenced by seasonal variations such as ground frost/snow melting and rainfall, but the values are roughly the same each year. This is likely because the water can percolate downwards, and these shallower depths can therefore maintain a more stable pore water pressure distribution from year to year.

The fact that silt is characterized as something in between sand and clay (chapter 2.4) has not been an important part of the evaluation of the results. The most important aspect of the geology seems to be that the mutual order of the different soil layers play an important role in determining the pore water pressure distribution. If a finer material is overlain by coarser material, water can back up in the coarser material, creating a saturated layer (chapter 3.1). Which material is above a saturated layer affects the height to which water can rise by capillary forces from the saturated layer, thereby determining how much matric suction there will be.
6. Concluding remarks and recommendations

This paper has reviewed how pore water pressure is determined by soil moisture, which in turn is affected by several factors: precipitation, evapotranspiration, temperature (ground frost formation/thawing), and the mutual order of the different soil layers. This was done by comparing pore water pressure data from a silt slope in Sollefteå, Sweden, with the assessed geology and climatic factors.

Because of the aforementioned factors, every slope is unique; thus, it is impossible to make a general description of the pore water pressure situation across all silt slopes. The best way to monitor the variations is by direct pore water pressure measurements with devices specifically suited to that purpose.

Since groundwater and subsurface flow (soil moisture) seem to be the factors that co-vary best with pore water pressure, it is recommended that the groundwater situation be thoroughly evaluated in further studies of pore water pressure variations, such that a more comprehensive picture than could be presented in this report can be obtained.

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8. References


Webpages:


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APPENDIX 1. Pore water pressure variations

Figure 1.1. Moving average mean of pore water pressure data from 2010-2015 at 2 m depth in measuring point R1.

Figure 1.2. Moving average mean of pore water pressure data from 2010-2015 at 4 m depth in measuring point R1.
Figure 1.3. Moving average mean of pore water pressure data from 2010-2015 at 6 m depth in measuring point R1.
Figure 1.4. Moving average mean of pore water pressure data from 2010-2015 at 2 m depth in measuring point R2.

Figure 1.5. Moving average mean of pore water pressure data from 2010-2015 at 4 m depth in measuring point R2.
Figure 1.6. Moving average mean of pore water pressure data from 2010-2015 at 6 m depth in measuring point R2.
Figure 1.7. Moving average mean of pore water pressure data from 2010-2015 at 2 m depth in measuring point R3.
Figure 1.8. Moving average mean of pore water pressure data from 2010-2015 at 4 m depth in measuring point R3.

Figure 1.9. Moving average mean of pore water pressure data from 2010-2015 at 6 m depth in measuring point R3.
Figure 1.10. Moving average mean of pore water pressure data from 2015 in measuring point R1.
Figure 1.11. Moving average mean of pore water pressure data from 2015 in measuring point R3.
Figure 1.12. In the end of 2015, some of the BAT-tensiometers were re-installed and some were replaced by new ones. Here, the moving average mean in 2016 from the different measuring points and depths are displayed.

Figure 1.13. Moving average mean of pore water pressure data from 2010-2015 in measuring point R1, R2 and R3 at 19, 21 and 25 m depth respectively.
APPENDIX 2. Pore water pressure and soil moisture

Figure 2.1. Pore water pressure and soil moisture at 2 and 4 m depth in measuring point R2, 2011.

Figure 2.2. Pore water pressure and soil moisture at 2 and 4 m depth in measuring point R2, 2012.
Figure 2.3. Pore water pressure and soil moisture at 2 and 4 m depth in measuring point R2, 2012.

Figure 2.4. Pore water pressure and soil moisture at 2 and 4 m depth in measuring point R2, 2012.