THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Pore pressure response in the uppermost part of a clay soil slope -

# Two case studies in the Gothenburg region

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Göteborg, Sweden 2017

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## ABSTRACT

In this research project the pore pressures in the uppermost 5 to 10 meters of clayey soils in southwestern Sweden are studied. The focus is on natural, short time variations, such as yearly variations due to precipitation, frost and evaporation. The long term benefit with the study is the ability to make better and more reliable predictions of pore pressure variations in clay slopes and thereby improving the reliability of the stability analyses. Field measurements have been performed at two sites in the greater Gothenburg area. In total 35 piezometers were installed in three slopes and they were monitored during 1.5 to 3 years. Installation depths varied between 0.5 to 49 meters, with a majority of the piezometers installed at depths less than 5 meters. The correlation between the measured pore pressures and precipitation was studied. Simulations with the computer software SEEP/W were performed in order to investigate how well the pore pressure regime in a slope can be predicted. Results from the simulations are compared with measured values, with special focus on the uppermost 5 to 10 meters. Three types of prediction levels are defined, depending on how detailed information is needed. Recommendations are given for a methodology that the practicing engineer can use when faced with the task to measure and predict the design pore pressure.

**Keywords**: clay, pore pressure, slope stability, yearly variations, simulation, precipitation

## ACKNOWLEDGMENTS

Work on this thesis was performed at the Division of Geology and Geotechnics at Chalmers University of Technology. Support for the work was provided by The Swedish Civil Contingencies Agency (MSB), the Swedish Geotechnical Institute (SGI) and Chalmers University of Technology. Thank you for giving me the possibility for this study.

The work was initiated by Victoria Svahn and Professor Göran Sällfors and was completed under the supervision of Göran Sällfors, whom provided me with his knowledge and time and guided me during the project. Special thanks to my co-supervisor Karin Lundström at SGI for all your support and patience during this journey. Thanks to the members of the reference group: Victoria Svahn (Tyréns, formerly SGI), Marius Tremblay (Tyréns, formerly SGI), Karin Odén (SGI, formerly Geosigma) and Margareta Nisser-Larsson (MSB), who has shared their thoughts and encouraged me along the way. Also thanks to David Schälin (SGI) for help with some of the field work and to Professor Claes Alén (Chalmers) for your contribution to the project.

I also wish to thank my colleagues at SGI and Chalmers for inspiration, discussions and for joyful coffee breaks.

I would like to thank my parents for all your support and encouragement.

Finally, Carl and Klara - I love you.

Göteborg, May 2017

Hanna Blomén

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## LIST OF NOTATIONS

The following notations are used in the thesis:

**Roman letters**

$A$ cross section area of the soil specimen [m$^2$]

$c'$ cohesion intercept

$c_u$ undrained shear strength [kPa]

$c_v$ coefficient of consolidation [m$^2$/s· m$^2$/year]

$F_c$ factor of safety, undrained analysis [-]

$F_{komb}$ factor of safety, combined analysis [-]

$g$ gravity [m/s$^2$]

$i$ hydraulic gradient [-]

$K$ hydraulic conductivity [m/s]

$k$ permeability [m/s]

$k_h$ permeability in horizontal direction, [m/s]

$k_v$ permeability in vertical direction, [m/s]

$M$ modulus [kPa]

$Q$ flow rate [m$^3$/s]

$u$ pore pressure [kPa]

$z$ depth below ground surface [m]

$z'$ depth below groundwater level [m]

$\Delta h$ change in hydraulic head [m]

$\Delta x$ distance [m]

## Greek letters

$\rho$ density of the soil [kg/m$^3$]

$\rho_w$ density of the pore water [kg/m$^3$]

$\sigma$ total stress [kPa]

$\sigma'$ effective stress [kPa]

$\varphi'$ friction angle [°]

## Abbreviations

CPT Cone penetration test

LLW Lowest measured water level

OCR Over consolidation ratio

SGI Swedish Geotechnical Institute

NGI Norwegian Geotechnical Institute

# 1. INTRODUCTION

In this chapter the background to the study is presented together with the objective and scope. Also the limitations for the thesis are stated.

## 1.1 Objective and scope of the study

For many clay slopes in which the stability is unsatisfactory, high pore pressures are one of the main potential factors causing a landslide. The main purpose of this research project is to study the change in the pore pressure profile with time, especially in the upper 5 to 10 meters of the soil profile for different precipitation scenarios and for geological sites typical of southwestern Sweden. The long term benefit with the project will be the ability to make better and more reliable predictions of the pore pressure in the entire soil profile, and thereby improving the validity of the stability analysis. The otherwise often made assumptions on the safe side regarding the pore pressure profile is thereby avoided. In the long run this implies that some slopes might not unnecessarily be classified as unsafe, and thus costly remedial work might be avoided. The pore pressures must not be underestimated as the prediction of the slope stability then could be on the unsafe side, indicating a fictitiously high factor of safety. When a detailed stability analysis is made for a slope, and expected effects of climate change are accounting for, these results will be very important from an economical point of view.

This study is focused on the uppermost part of the soil profile, including the dry crust clay and Aquitard 1, which for the studied cases consists of clay. Those parts of the soil profile are in most cases saturated, but sometimes unsaturated due to both the dry crust and clay having cracks and fissures which results in a higher permeability. The uppermost part of the soil profile is also affected by precipitation, drying and wetting, frost, roots, plants etc.

In order to perform field tests and obtain long series of pore pressure observations, two typical areas in the greater Gothenburg area in southwestern Sweden were chosen.

## 1.2 Limitations

The study is limited to clay slopes with mainly positive pore pressures. Areas with e.g. silt in which the negative pore pressures are of great importance, have not been included.

The study does not include pore pressure changes related to external loading, settlement and consolidation. The slopes studied have been exposed to pore pressure variations during several hundreds of years, and thus the resulting stress changes occurring in the clays are solely within the overconsolidated region.

The study focuses on conditions related to the temperate climate in Sweden. Research performed in tropical and subtropical areas are therefore not relevant here and thus left out.

Only short time changes of the pore pressures are studied. This includes natural yearly changes and precipitation. More permanent changes due to loading or unloading are not treated.

No changes in soil parameters due to temperature change in the soil are accounted for.

# 2. PARAMETERS IMPORTANT FOR THE PORE PRESSURE REGIME IN CLAY SLOPES

In this chapter background information about geology, clay formation, hydrologic properties and pore pressure are described. There are also comments regarding stresses and strength in soils and the relation to pore pressures.

## 2.1 Geological background of western Sweden

Almost all soils in Sweden derive from the latest deglaciation, which took place more than 10 000 years ago, or are younger than that. When the ice melted, soil material that had been transported by the ice was deposited near the ice front as glacial or glaciofluvial deposits. The finest particles could be transported further away with the water before they settled as marine glacial clays. Due to the amount of water released by the melting ice the sea level raised during this periods. This rise was first smaller than the isostatic uplift, so the land rose from the ocean. Years later (approx. 9000 years ago) the ocean level rise was greater than the land lift, and consequently many areas were flooded. Around 7000 years ago the system changed again so the land lift was once again dominating. Those processes affected the areas situated below what is called “the highest coast line”, situated approx. 100 meters above the present sea level in the Gothenburg area (Fredén 1994).

When the fine grained glacial and post glacial deposits were formed, different particle sizes settled at different times resulting in laminations with clay and silt in different layers. In marine areas, such as the Swedish west coast, this is not the case and the laminations of the soil are not so pronounced. However, locally layers of different materials can be present. This is due to the flocculation of clay particles, which increases with the salinity in the water, and therefore particles of different sizes will settle together in marine areas. A typical soil profile in southwestern Sweden (Gothenburg area) can look like in Figure 2-1. At the very bottom there is bedrock with a layer of friction material on top. The main part of the soil profile consists of clay, sometimes with layers of silt or sand. On top of the soil profile the clay has formed a dry crust caused by seasonal swelling and shrinking due to freezing, precipitation and evaporation (Ringesten 1988). In the Gothenburg area the uppermost 10 to 15 meters are usually postglacial clay and the underlying clay are of glacial origin. The glacial clays layer can be up to 100 meters thick.

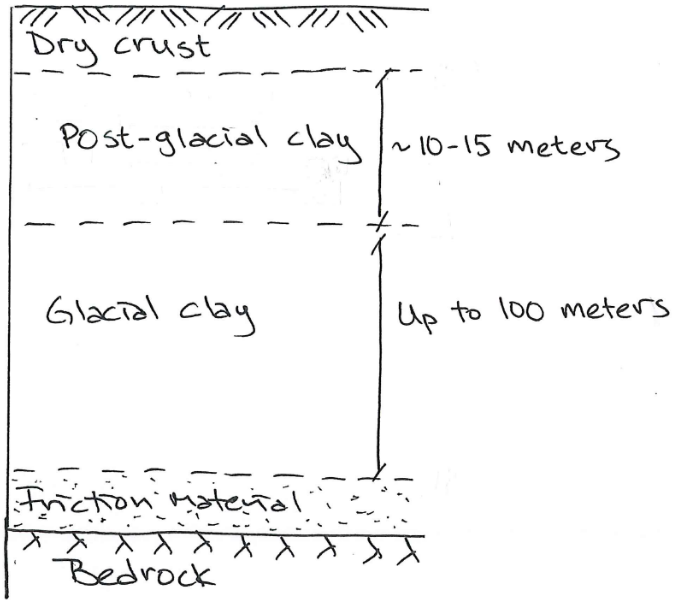


*Figure 2-1. Example of soil profile for southwestern Sweden.*

## 2.2 Clay- formation and attributes

Clay is a three phase material containing clay minerals, water and gas. The most common clay minerals in Sweden are illite, some kaolinite and traces of montmorillonite. Clay minerals are thin, flake formed and surrounded by firmly bonded waters. Two of the most important factors for the micro-structure of the clay are its stress history and the salinity when it was deposited. There are some differences in the structure of the clay depending on if it is formed in salty or fresh water. The clays deposited in salty water has larger and denser aggregates connected by weaker links and separated by larger voids compared to clays deposited in fresh water, Figure 2-2.

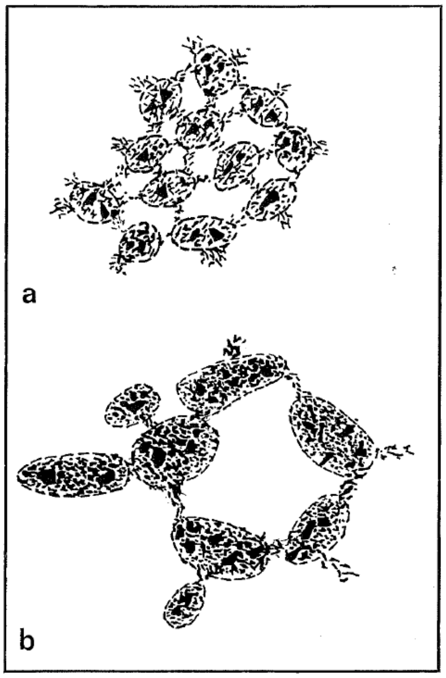


*Figure 2-2. Structure of **a**. Clay formed in fresh water and **b**. Clay formed in salty water. Adopted from Pusch (1970).*

The *hydraulic conductivity*, *K* [m/s], of a soil is a measure of its ability to transport water and is the largest in saturated conditions, meaning when the total pore volume is filled with water (Grip & Rodhe 2000). The term *permeability, k* [m/s], is often used in geotechnical literature for the hydraulic conductivity in saturated conditions and is the term mostly used in this study. The permeability in clay is mainly affected by the particle size distribution of the soil and the stress level, but also to a certain extent by the structural anisotropy.

The permeability in a soil can vary between the horizontal and vertical flow direction. However, according to (Löfroth 2008) "*several researchers … have shown that the permeability of homogeneous soft marine clays is practically isotropic and remains so for strains up to at least about 25 %, independent of the type of compression applied.*" The paper by Tavenas et al. (1983) investigated natural soft clays from Canada, USA and Sweden, and concluded that the horizontal permeability is not much different from the vertical and that the variations between different specimens can explain the measured anisotropy. In varved clays with layers of silt a difference between the permeability in different directions can be seen. For those cases the permeability in the horizontal direction can be much larger than the one in the vertical direction, (Larsson 2008).

## 2.3 Hydrologic cycle

The hydrologic cycle, see Figure 2-3, is an endless circulation of water between ocean and lakes, atmosphere, land and rivers. Inflow to the aquifers comes from precipitation and infiltration, whereas outflow occurs due to evaporation from land & water, transpiration by plants or outflow to streams, lakes etc. The radiation from the sun is the force that drives this system.

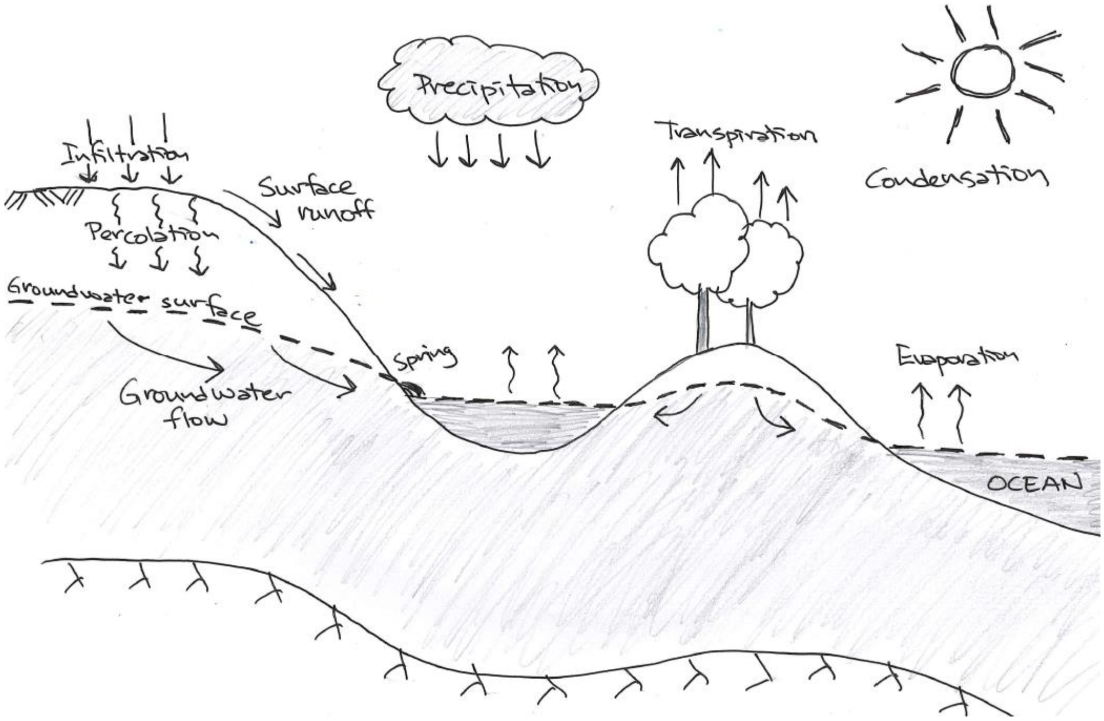


*Figure 2-3. Schematic overview of the hydrologic cycle.*

In natural areas the groundwater levels are related to geology and weather. Rain and melting snow causes infiltration, which raises the groundwater levels, and draught, evaporation and transpiration reduce the levels. In a clay slope with low permeability water pressures at the boundaries of the clay, i.e. the underlying friction material and the dry crust, governs the pore pressures. The pressures at the boundaries are in turn governed by the flow from infiltration areas and the run-off conditions. Knowledge about the general hydrogeological situation in the area is important when determining the pore pressures in a slope. In clay deposits the pore pressure fluctuates over the year due to the weather and yearly precipitation variations.

## 2.4 Darcy’s law and groundwater flow

Darcy´s law was formulated by the French scientist Henri Darcy in 1856. Initially it was intended to describe groundwater flow, but it has later been shown that it also is valid also for unconfined conditions. The principles for flows in saturated and unsaturated conditions are essentially the same, but more complicated to handle in the unsaturated zone due to varying degrees of saturation. In porous media the water flow is generally governed by Darcy´s law, which is dependent on the hydraulic conductivity of the soil and the hydraulic gradient. If the soil is saturated the hydraulic conductivity is basically a constant and flow becomes dependent only of the hydraulic gradient (Öberg 1997).

Darcy´s law postulates that the flow between two points in the ground is proportional to the change in potential between the points (Grip & Rodhe 2000). This implies that the groundwater flows from an area with a high pressure level towards an area with lower pressure level, see Equation 1 and Figure 2-4.

$$Q = -K \cdot (\Delta h / \Delta x) \cdot A \qquad (1)$$

Where $Q$ = flow rate [m$^3$/s]

$K$ = hydraulic conductivity of the soil [m/s]

$A$ = cross section area of the soil specimen [m$^2$]

$\Delta h$ = change in hydraulic head [m]

$\Delta x$ = distance [m]

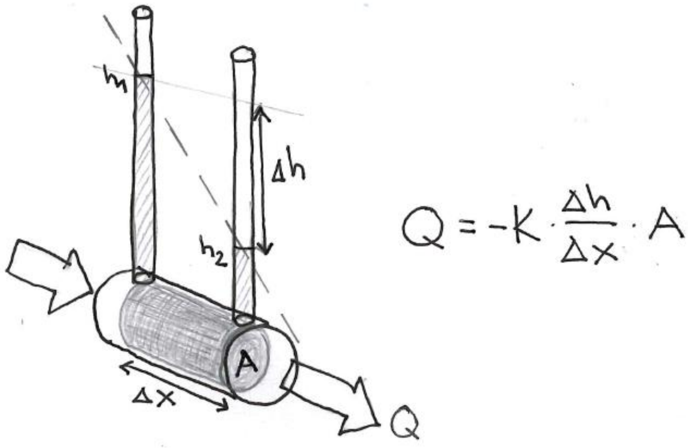


*Figure 2-4. Illustration of the variables included in Darcy's law.*

Darcy´s law implies that the gradient is constant, independent of the magnitude of the gradient. Some researchers have observed that the hydraulic conductivity might decrease for very small gradients. Others have even suggested that there exists a threshold value, below which no flow occurs at all. However, generally within geotechnical engineering Darcy´s law is assumed to be valid.

## 2.5 Groundwater zones, aquifers and aquitards

When describing a soil profile it is often divided into regions with different properties. The term *aquifer* is defined by Freeze & Cherry (1979) as "*a saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients*". Often the word is used only for formations from where groundwater can be extracted; in that case clay should not be considered as an aquifer even if it contains groundwater. In an *unconfined* (or open) *aquifer* the groundwater level coincides with the upper limit for the groundwater zone, that is the most common type of groundwater magazine. A *confined* (or closed) *aquifer* can e.g. be present where a sandy soil, or other friction materials, is overlain by clay or any other low permeable soil and the clay works as a cap since it is almost impermeable compared to the sand. There is often an overpressure (artesian pressure) in the sand in those cases. Freeze & Cherry (1979) call the layers or deposits not permeable enough to withdraw significant amounts groundwater *aquitards*.

The principal soil stratification for clay areas along the Swedish west coast is described in four zones by Berntson (1983), see Figure 2-5. The uppermost layer, the *Upper (open) aquifer*, is the dry crust clay and has a cracked structure, high permeability and therefore rapid pore pressure responses. Below that is *Aquitard 1,* containing clay with small, mainly vertical cracks, roots etc. Here the pore pressures are often hydrostatic (Berntson 1983). The next layer is called *Aquitard 2* and is often the thickest layer, containing homogenous or layered clay with low permeability. In this zone the pore pressures often follow a straight line between the pressure in the bottom of Aquitard 1 and the pressure at the top of the lower confined aquifer. The bottom layer, *Lower (confined) aquifer*, contains friction material with usually high permeability and rapid pore pressure responses. Here the pore pressure has a hydrostatic distribution and is affected by the conditions in the infiltration areas in the rim of the area.

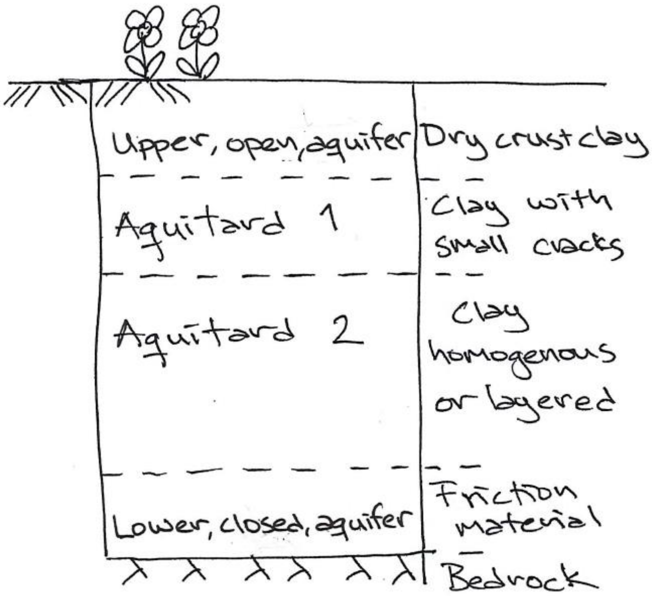


*Figure 2-5. Classification of groundwater zones (inspired by Berntson (1983)).*

## 2.6 Pore pressure profiles

Three different pore pressure profiles for short time variations in clay areas in western Sweden are described by Berntson (1983). Short time variations of practical implication include e.g. natural, yearly variations in the pore pressures in the upper and lower aquifers and the time span for those are usually one to three months. In general a pressure change in the aquifer will lead to a pressure gradient in relation to the aquitard and a “pressure wave” will move through the pore pressure profile. There will also be an inflow or outflow of water to the aquitard. The occurrence of layers with higher permeability in the soil profile will be important to the process. When a permanent change occurs in a pore pressure profile it is often a result of a long-term pressure change in the upper or lower aquifer. This can be caused of e.g. a lowering of the groundwater pressure due to a change of the natural balance at the site, with time this change will lead to a new, pore pressure equilibrium. It should here be pointed out that the type of pore pressure profiles included in this study are limited to pore pressure profiles with natural variation. Pore pressure changes caused by either external loading or a lowering of the ground water table or pressure are not included.

The three pore pressure profiles presented by Berntson and further by Persson (2008) are called: *hydrostatic, artesian* and *split pressure profile* and they correlate to different types of boundary conditions. In the hydrostatic, or uninfluenced, pore pressure profile, see Figure 2-6, common in flat areas, the pore pressure distribution is uniform throughout the entire soil profile. The artesian pore pressure profile, see Figure 2-7, is common in areas surrounded by higher situated infiltration areas or in areas with reduced clay thickness due to e.g. erosion and the profile imply hydrostatical conditions in the uppermost meters but with artesian pressures towards depth. The split pressure profile, see Figure 2-8, occurs in areas where erosion in e.g. a stream has been going on for a long time and the groundwater has drained out resulting in a split profile with hydrostatic pore pressure distribution at the top and in the bottom but with a downward gradient in between. Both the boundary conditions in the dry crust (upper aquifer) and in the underlying friction material in the bottom of the profile (lower aquifer) are consequently affecting the pressure profiles in the clay (aquitard 1 & 2). In all three types of pore pressure profiles the pore pressure is mainly hydrostatic in the upper and lower aquifer, and in layers with friction materials, due to relatively high permeability there. The variations will be largest in the upper and lower aquifer because of the instant connection to precipitation events. In the clay the pore pressures will differ a lot between different sites due to the variation in boundary conditions in the upper and lower aquifer at that site.

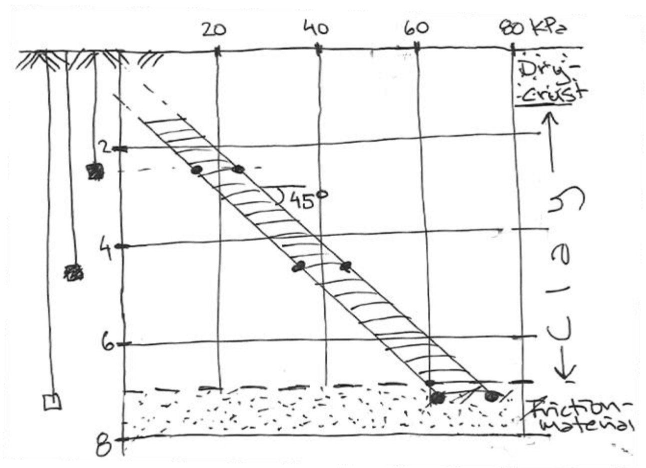


*Figure 2-6. Pore pressure profile in clay, hydrostatic conditions (inspired by Berntson (1983)).*

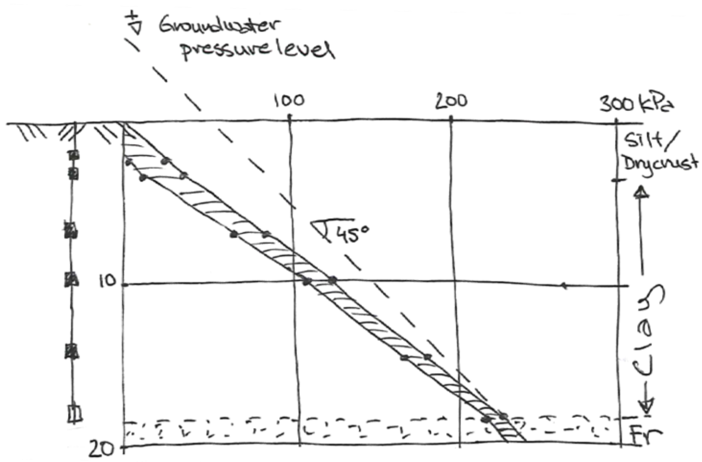


*Figure 2-7. Pore pressure profile in clay, artesian conditions (inspired by Berntson (1983)).*

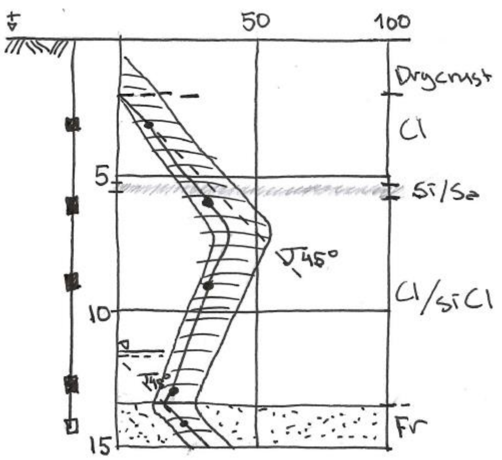


*Figure 2-8. Pore pressure profile in clay, split pressure profile (inspired by Berntson (1983)).*

## 2.7 Stresses in a soil

The stresses at a certain depth in a soil profile depend on the weight of the overlying soil and were the groundwater level is situated. In a soil, such as clay, consisting of soil particles, water and air, the sum of the pressure from the soil particles and the water is called total stress, *σ*. It consists of the effective stress, *σ'*, which is the part carried by the soil particles and particle contacts, and the pore pressure, *u*, see Figure 2-9. Most clay in western Sweden contains very little air, and therefore the air pressure is neglected.

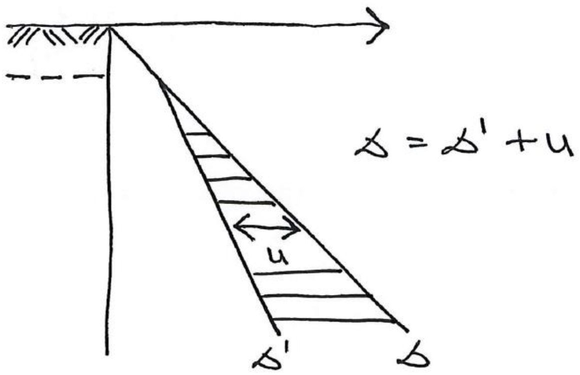


*Figure 2-9. Relation between total stress (σ), effective stress (σ') and pore pressure (u).*

The total stress, *σ*, is calculated from the overburden pressure in the soil, see Equation 2:

$$\sigma = \int (\rho \cdot g \cdot dz) \qquad (2)$$

Where $\rho$ = density of the soil [kg/m$^3$]

$g$ = gravity [m/s$^2$]

$z$ = depth below ground surface [m]

To get accurate values for the pore pressure, *u*, it can be measured in the field with piezometers. For cases with a known hydrostatical pore pressure distribution and no flow in the soil, or when only an estimate of that situation is of interest, Equation 3 can be used instead:

$$u = \rho_w \cdot g \cdot z' \qquad (3)$$

Where $\rho_w$ = density of the pore water [kg/m$^3$]

$z'$ = depth below groundwater level [m]

## 2.8 Pore pressure and its importance for the shear strength

Traditionally the stability of a slope has been studied using either effective stress analysis (drained analysis) or total stress analysis (undrained analysis). In the former analysis the pore pressures in the slope must be known, but in the latter it does not affect the results of the analysis. However, in Sweden the so called combined analysis was introduced by Larsson (1983) and is commonly used for clay slopes. The concept is that effective stress strength parameters, *c'* and *φ'*, are given as well as the undrained strength, $c_u$. In the limit equilibrium analysis, the shear strength is calculated using the effective strength as well as total strength parameters for each slice. The smaller of the two is then used as the available strength, illustrated with the bold grey line in Figure 2-10.

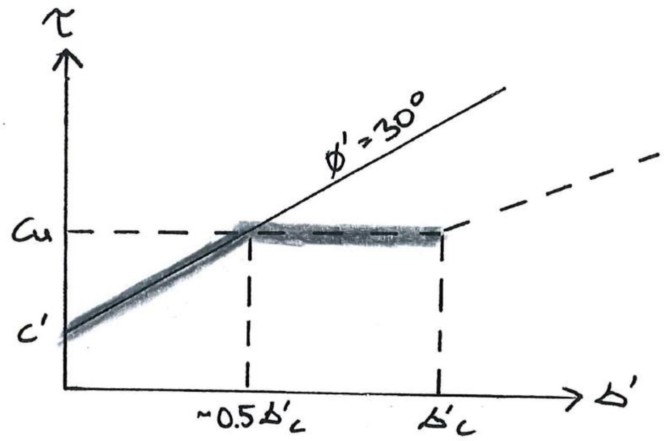


*Figure 2-10. Generalized drained shear strength in direct shear, normally compressible. Modified from Larsson (1977).*

This implies that for clay elements which are normally or moderately overconsolidated for the stress situation at hand, having an overconsolidation ratio, *OCR*, of about 2 or smaller, the undrained shear strength will be dominating. For higher OCR, the drained shear strength will be smaller than the undrained shear strength, and thus used in the analysis for those parts of the slope. For most clay slopes in Sweden, where the clay often has an OCR of 1.2 to 1.5, this mean that the undrained strength will dominate and the effective strength parameters will be crucial only for fairly shallow shear surfaces and for the shallow part of shear surfaces which are rather deep. For areas with overconsolidated soil, with an OCR clearly larger than 2 in the entire soil profile, the effective strength parameters will in most cases be critical.

The stipulated requirements for the safety factor of an existing slope depend on the level of accuracy of the analysis. A more detailed geotechnical investigation often allows for a lower safety factor since the amount of input data is higher and the insecurities thereby are better investigated. Often the safety factor for undrained analysis, $F_c$, shall be larger than 1.5, while at the same time the factor of safety for the combined analysis, $F_{komb}$, shall be larger than 1.35.

## 2.9 Numerical analysis

In order to perform a numerical analysis and to simulate different scenarios of the studied slopes some seepage modeling software were needed. The two programs that were used, SEEP/W and MODFLOW, are briefly described below.

When using modeling software, such as SEEP/W or MODFLOW, it is important to carefully consider which input data such as geometry, boundary conditions, soil parameters, stratigraphy etc. to use since it strongly will affect the results. The aim with the simulation is often to model a situation that is as realistic as possible, either the present situation or a possible future scenario. However, in order to facilitate the simulation, several simplifications must be made, since the reality is complicated and certainly not as 2-dimensional or homogenous as it may look in the model. There is also a lack of knowledge or uncertainty in some of the input data. When handling the results from the simulations those things must be kept in mind and precautions must be taken to minimize those errors as in order to get an as useful output as possible.

### 2.9.1 SEEP/W

The computer software SEEP/W was developed by the Canadian company GEO-SLOPE International. It is a finite element software product for analyzing groundwater seepage and excess pore water pressure problems for porous materials. SEEP/W can be used for modelling of saturated as well as unsaturated flow during steady state or transient conditions. It is also possible to analyze e.g. infiltration caused by precipitation.

When performing an analysis with SEEP/W it starts with defining the geometry followed by assigning boundary conditions and material properties. The result from the seepage analysis can be viewed in different ways with different parameters such as head, pressure, velocity vectors etc. If a transient analysis is performed the conditions over time can be seen in different time steps. A frequently used program for slope stability calculations is SLOPE/W, also developed by GEO-SLOPE International. The results from a SEEP/W analysis can be used in a SLOPE/W calculation and e.g. study the changes in stability due to changes in the pore pressure with time. SEEP/W 2016 is the version of the software used in this study. For further information see the SEEP/W manual (GEO-SLOPE 2015).

### 2.9.2 MODFLOW

MODFLOW is a three-dimensional finite-difference code developed by the U.S. Geological Survey. The code is a free, open-source software for simulating and predicting groundwater conditions and the interaction between groundwater and surface water. As in SEEP/W the user defines the geometry, materials and boundary conditions for the simulation. The user interface used in the simulations for this study is GMS 10.1 by Aquaveo.

# 3. LITERATURE REVIEW

In this chapter a survey of literature is presented. The objective of the survey is to summarize the present knowledge about pore pressure profiles in clay slopes relevant for this study. The focus has been on the conditions in Sweden but also a limited overview of international literature has been done.

## 3.1 "Pore pressure variations in clay soil in the Gothenburg region" (Berntson 1983)

Berntson (1983) studied a number of soil profiles in marine glacial and postglacial clay deposits in the Gothenburg area and their natural pore pressure variations. The results were described as being representative for mainly the southwestern part of Sweden. In total twelve field test areas were included in the study, five of them focused on short-term variations (e.g. yearly variations) of pore pressures, six on long-term variations and one both short- and long-term. The soil profiles in the test areas had somewhat different geological and geotechnical properties such as soil depth, soil properties etc. In all areas piezometers were installed in the clay and groundwater pressure measurements were also performed in the cohesionless soil below the clay. No measurement of, or correlation to, precipitation was performed. In all his field test areas Berntson confirmed the presence of aquitard 1, a zone characterized of almost instant pore pressure changes situated below the dry crust.

Of the twelve field test areas presented by Berntson, the one in Flöjelbergsgatan, in Mölndal just south of Gothenburg, is one of the most relevant for this study. It is also the test site for another project described by Berntson (1980). In the area five stations with in total 29 piezometers and groundwater pipes were installed and they were monitored between March 1977 and November 1979. The division of the soil layers at the test site follows the principle with aquifers and aquitards (presented above in Section 2.5) and the boundary between aquitard 1 and 2 is here situated 5 to 6 meters below the ground surface. According to the measurements the pore pressures are hydrostatical in aquitard 1, which is an important observation.

Berntson also made a theoretical analysis and calculation of three typical pore pressure profiles (hydrostatic, artesian and split pressure profile) with the program POR-82. There he presumed that all profiles had a starting situation resulting from a longer period with comparatively stable conditions. For the hydrostatic and artesian profiles calculations were made with an increasing groundwater pressure, 15 kPa, during the first three months in both the upper and lower aquifer, and then during the next three months decreasing pressure with 15 kPa back to the start values. This was tested for soil depths of 10 and 20 meters respectively. The results by Berntson show that the pressure changes are visible in the entire soil depth for the 10 meter profile. For the cases with 20 meters soil depth the pressure changes in the simulation did not reach the center of the soil profile. The explanation given is that a too low value of the modulus, $M_O$, was used in the calculation even though the value was assumed to represent the loading in the overconsolidated region. A higher modulus would have resulted in quicker pressure changes in the soil. For the split pressure profile the situation was more complicated and the theoretical calculation of a 10 meters soil profile showed that no natural, yearly fluctuations will exist between 5-7.5 meters depth in that profile. This is thus not the case in some of the field tests conducted by Berntson, which show yearly pore pressure fluctuations in the entire profile. Also this discrepancy between the field tests and the calculations can be attributed to a too low assumed value of the modulus.

When Berntson compared his computed pore pressure profiles with the measured ones from field tests, the only way to obtain good correlations was to divide the clay into two parts, aquitard 1 and 2, with different permeability. In the calculations he found that a high value of the permeability should be used in aquitard 1, for clays in western Sweden reasonable values seem to be in the order of (10-15) $\cdot 10^{-9}$ m/s. These values have thus not been confirmed by Berntson during laboratory testing due to the small test samples used there compared to the macro structure present *in situ*, which makes the comparison irrelevant. According to Berntson the groundwater situation in aquitard 2 differs from aquitard 1 depending on different attributes, such as the permeability ($k$) and the modulus ($M$), in the two zones. Important for the rate of the pore pressure changes is the current stress level related to the pre-consolidation pressure. It is also important to bear in mind that the compression modulus is extremely high when the stress change is reversed.

Berntson concluded that there are good possibilities for predicting pore pressure variations, but in order to obtain practically usable predictions for the pore pressure there must be good knowledge about the magnitude of the used parameters, and especially about the boundary conditions for the top and bottom. He also concluded that as the pore pressures in aquitard 1 and the underlying confined aquifer vary with time, the changes of the pore pressure in aquitard 2 respond very quickly due to the very high compression and swelling modulus for small and reversed stress changes. The conclusion by Berntson about pore pressures often being hydrostatical in aquitard 1 has been widely used by practicing engineers in western Sweden since then.

## 3.2 "Estimation of pore pressure levels in slope stability calculations: Analyses and modelling of groundwater level fluctuations in confined aquifers along the Swedish west coast." (Persson 2008)

Persson (2008) primarily studied pore pressure variations in the lower, confined aquifer. This implies that he mainly described groundwater flows under saturated conditions. A confined aquifer has a much quicker response than an unconfined aquifer to the same level of rainfall, as the volume of water necessary for causing the stress change is much larger in the latter case.

In the three field test areas along the Swedish west coast studied by Persson, named Sandsjöbacka, Harestad and Brastad, the yearly groundwater fluctuations in the confined aquifer are around 1-3 meters. In confined aquifers the largest amplitudes occur in or close to the infiltration areas, and decrease towards the middle of the aquifer due to the dampening effects from the diffusivity in the aquifers and averaging effects from infiltration from different directions. If the downstream boundary conditions are governed by e.g. the sea level, they remain quite constant and play an important role since constant conditions downstream causes smaller fluctuation amplitudes in the aquifer there.

Modelling and prediction of groundwater levels with some different models; *the HBV-model, SEEP/W and the Chalmers model* are described by Persson. Also a new model was developed by Persson, called *the modified HBV-model*. It is stated that all models are based on assumptions and simplifications and gives the user a reasonable prediction. The modified HBV-model was developed in order to simplify the original HBV-model and to adjust it for simulations of confined aquifers. All three of the field test areas used by Persson, dealt with confined aquifers where the groundwater levels had been measured for several decades as a part of the Groundwater Network, run by the Geological Survey of Sweden (SGU).

Persson concluded that the modified *HBV-model* is very conceptual and he admits that it may oversimplify the processes. As a further research area he suggests some development of the modified HBV-model and the Chalmers model. Persson also identified the need for further research on the upper aquifer in order to better understand when the drained shear strength governs the soil strength, which is one of the bases for this study.

## 3.3 ”Temporal changes of groundwater pressure in a natural slope of nonfissured clay” (Kenney & Lau 1984)

Kenney and Lau (1984) presented a study of groundwater pressures measured in a natural slope of a soft varved clay in Canada over a 10 year period. They concluded that at depths greater than approximately 7 meters below the ground surface groundwater pressures remained essentially constant as an indication of the occurrence of steady-state seepage. These conditions were dominant in spite of changes of the groundwater conditions at the ground surface.

The slope studied is a part of the eastern bank of the Wabi creek in Ontario, Canada, which has eroded into a clay plain that consists of sediments deposited in Lake Barlow. Soil depth in the area is more than 45 meters. The clay has a fissured structure to a depth of about 2 meters, the frequency of jointing decreasing with depth. The joints seemed to be tight below a depth of about 0.5 meters. Below the surface-weathered zone the undrained shear strength of the soil is about 30 kPa, and then increases with depth. The soil appears to be overconsolidated with about 70 kPa. Precipitation in the area averages about 700 mm of water per year, distributed relatively uniformly throughout the year. The rate of infiltration can be estimated from knowledge of the coefficient of hydraulic conductivity of the soil ($k$<$10^{-9}$ m/s) and the hydraulic gradient near the ground surface ($i$< 1.0) to be less than 30 mm/year.

Piezometers were installed in three rows perpendicular to the river, about 30 meters apart. Installation depths varied between 3 to 23 meters below the ground surface. In total 65 piezometers were installed and measurements have been taken with two week intervals during 10 years, 1971-1980. The measured piezometric levels indicated that the groundwater flow was almost two dimensional towards the river. One important drawback with the two weeks measurement intervals are that some quick changes in pore pressures, mostly in the most shallow piezometers, may be lost.

Results from the field measurements indicate that the pore pressure close to the river changes according to the variations in the river level. The largest annual fluctuations, and also the most rapid rates of changes, occurred in the piezometers installed closest to the ground surface. Surprisingly no correlation was found by the authors when comparing the precipitation with pore pressures in the piezometers at shallow depths for short times (<months).

Kenney and Lau found that the groundwater flow originates from infiltration in the area above the slope. They also conclude that the flow of groundwater initially is downwards and it ultimately discharges into the river channel. A portion of the slope has pore pressures that change very little, and therefore correspond to a steady-state seepage condition. Maximum changes of the pore pressure occur at the ground surface and annual changes do not propagate below a depth of about 7 meters. The phreatic surface can rise to the ground surface during the summer or autumn months, and fall during the winter period, the maximum depth being about 2.5 meters. It is not stated in the paper if the groundwater pressure is hydrostatic in some parts of the slope or not.

The results by Kenney & Lau indicate that, except near the ground surface, the groundwater pressures remain quite steady in the slope studied by them. The presence or absence of open fissures and other pervious features at the top of the soil profile, are of key importance to the stability of clay slopes since they may lead to rapid changes of pore pressure.

## 3.4 ”Pore-pressure response in a marine clay slope in southeast Norway” (Boyle et al. 2009)

In the paper by Boyle et al. (2009) a field study made in Romerike, Norway (40 km northeast from Oslo) from October 1969 to August 1978 is presented. As part of a program to investigate factors and processes contributing to quick clay landslides the Norwegian Geotechnical Institute (*NGI*) installed eight piezometers in a marine clay slope.

At the site there are two ridges with streams located on either side of them. The area consists of farmland and the soil depth is more than 25 meters under the streams and more than 45 meters under the ridges. The soil consists of silty clay interspersed by thinner clayey silt layers, see Figure 3-1. Agricultural activities and vegetation has modified the uppermost 0.3-0.5 meters of the soil and there is an open network of fractures down to a depth of 1-2 meters, with the number of fractures gradually decreasing with depth. The piezometers at the site were installed along a line perpendicular to the ridges. Installation depth varied from 3.7 to 20 meters below ground surface. Measurements were made 148 times over a nine year period with 3 to 75 days between the measurements. The average measurement interval was 22 days.

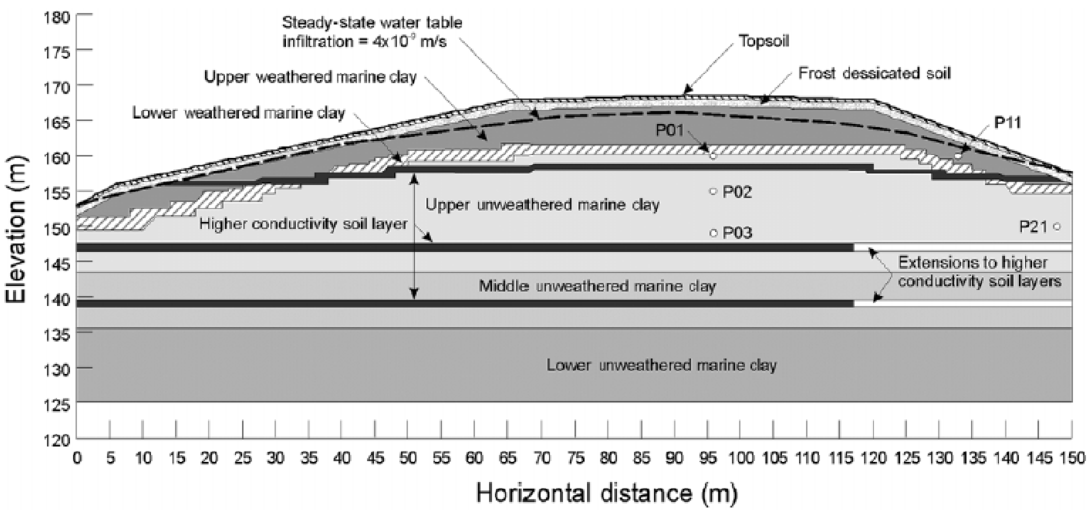


*Figure 3-1. Model of west ridge with soil profile and piezometer locations. Adopted from Boyle et al. (2009).*

According to the authors some general trends can be concluded regarding the measured pore pressure variations: the records for the piezometers generally follow the same trends up and down with the first increase in head near the stream; the shallowest installed piezometers, installed close to or in the dry crust, show the largest variations in total head; the piezometers installed at the top of the ridges have a maximum lower than the ground surface; the piezometers installed in the slopes seem to have their maximum close to the ground surface and they becomes "dry" during the summers. Results from the piezometers installed below the ridges indicate a downward seepage gradient in the measured pore pressures. For the piezometer installed in the valley between the ridges an upward gradient can be detected. The authors state that there are no obvious, direct correlations between the piezometer response and the precipitation record, temperature or snow or snowmelt conditions because so many factors are included. Streamflow and stream depth records were not reviewed for this study.

The two-dimensional finite element program SEEP/W 2004 was used by the authors to model groundwater conditions and infiltration-induced seepage through one of the ridges. First a steady state analysis was performed to evaluate the effects of including three layers with higher hydraulic conductivity in order to approximate layers of clayey silt that are common in the area. Then a transient analysis was performed with a time-varying boundary flux of $4{\cdot}10^{-9}$ m/s to simulate infiltration (see Figure 3-1). The number of fractures in the weathered clay below the frost-desiccated soil is known to decrease with increasing depth. To try to account for potential preferential horizontal flow through fractures in the weathered clay, the authors assumed $k_h > (2\text{ -}5)\cdot k_v$. The hydraulic conductivity generally decreases with depth and the conductivities in the unweathered marine clay was assumed to be $k_h = k_v$.

Also a steady-state analysis using an assumed constant boundary flux rate was performed. The assumed flux was adjusted until the model computed initial groundwater total heads for the nodes near certain piezometers that were close to the measured values for a certain date. The computed flux was less than 15 % of the daily average precipitation (based on normal annual precipitation). This boundary flux is of the same order of magnitude, but slightly higher than the typical hydraulic conductivities for the clay at the site. Another steady-state analysis was performed to evaluate conditions that would model the maximum head conditions observed in the actual piezometer records. A boundary flux less than 30 % of the daily average precipitation was found to be sufficient to fully saturate the slope. Adjustments of the boundary flux were made to correlate it to the measured piezometer values.

Modelling the groundwater regime through the use of multiple piezometers was found to be useful in interpreting the site geology. The authors suggest that vertical piezometer arrays should be installed where the seepage gradient is expected to be greatest. Although it was instructive in developing an understanding of the groundwater regime, the model was not calibrated to perfectly match the observed piezometer responses. Obtaining an exact match may not be practicable.

## 3.5 Storvreta (Swedish Transport Administration 2013)

In a project for a new highway between Uppsala and Storvreta the Swedish Transport Administration conducted geotechnical field investigations. In section 3/660 in the northern part of Uppsala a permanent sheet pile wall was to be installed and measurements of the pore pressure were done.

The soil in the area consists of varved clay with a density between 1.65-1.75 t/$m^3$. Results from CPT-tests show an increasing shear strength with depth, around +1.8 kPa/meter, and 32 kPa at 13 meters. The clay was lightly overconsolidated with an OCR varying from 1.1 to 1.5.

Four piezometers were installed in one section at 2.5, 3.5, 7.5 and 11.5 meters below ground surface. They have been monitored 10 times during the period May to November 2011. In Figure 3-2 the results from the measurements are shown and it can be seen that the two most shallow piezometers co-variate very well during the measuring period, and the other two shows fairly steady conditions.

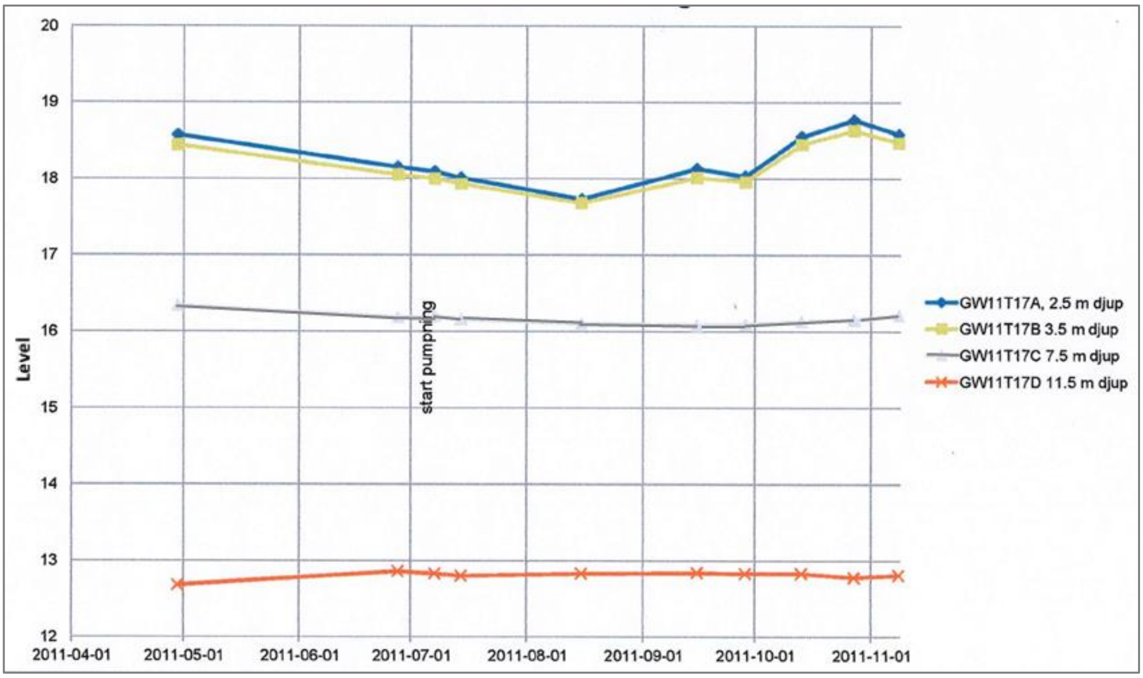


*Figure 3-2. Results pore pressure measurements at four depths (2.5, 3.5, 7.5 and 11.5 meters depth) in Uppsala 2011, manual readings.*

The pore pressure distribution towards depth with the highest and lowest measured values for each piezometer is shown in Figure 3-3. It is quite obvious that there is a hydrostatic pore pressure distribution for the two uppermost piezometers (0-5 meters), and a downward gradient with depth (>5 meters). In the figure the expected distributions are represented by the thin lines that interconnect the points. The pore pressures variations in the top five meters were most likely caused by precipitation during the measuring period.

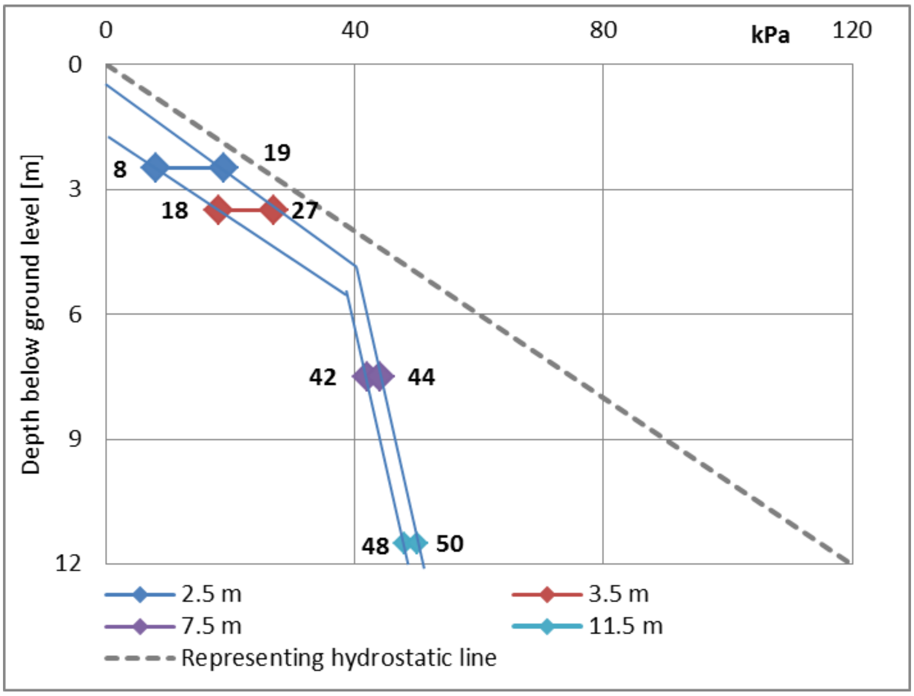


*Figure 3-3. Pore pressure profile for the Uppsala test site. Minimum and maximum value for each piezometer and lines representing possible pore pressure profiles compared to a hydrostatical line.*

## 3.6 Tropical and subtropical climate conditions

Research regarding the relation between slope stability and rainfall has been done, and is going on, in regions with tropical and subtropical climate conditions. The results from those studies are not directly valid for clayey soils in Sweden, or other regions in the tempered zone, since the clays in the tropical and subtropical zones often are of residual origin and the clay layers are just a few meters thick. Also the climate differs a lot between the zones, and the rainfall is distributed differently over the year and with different intensities. Therefore, the results and conclusions from tropical and subtropical regions were not studied in detail in this review.

For an extensive review of the existing research on infiltration analysis and slope stability analysis under rainfall infiltration in tropical and subtropical areas see Zhang et al. (2011). According to their study rainfall is one of the most important factors causing slope failures in many regions around the world. In regions with tropical or subtropical climates (e.g. Hong Kong, Taiwan, Singapore, Japan and Brazil) storm-induced landslides are common. Slope failure may occur on both natural and constructed slopes in a variety of materials. The slides are often shallow with a depth of failure less than 3 meters, but landslides deeper than that are also described.

### 3.7 Commonly accepted practice in Sweden

A question of importance to consider in relation to this study is how the codes and regulations today prescribe that the pore pressure should be used in Sweden. One extensively used guideline is the Report 3:95 by the Commission on Slope Stability (Skredkommissionen 1995). According to the report, it is in an early stage of a slope investigation, in a clay profile, recommended to measure the groundwater pressure in the lower aquifer. If preliminary slope stability calculations indicate that the drained stability is critical, the pore pressures in the area must be further measured in a reasonable number of points. The measurement period should be at least three months, but preferably up to one year, to facilitate the forecasting of extreme values. If there is a river or a lake at the passive side of the slope, the water level in it should be set to the lowest measured water level (LLW) for undrained stability analysis. For drained and combined analysis considerations must be done regarding the possibilities for low water levels occurring at the same time as high pore pressures, or if some other values should be used instead.

One other important document is the IEG Report 4:2010 (Implementeringskommission för Europastandarder inom Geoteknik (IEG) 2010) that complements Report 3:95 with e.g. the information that the return period for the design water pressure should be 100 years.

In the Göta River Investigation (SGI 2011a) led by the Swedish Geotechnical Institute the pore pressures used in the sensitivity analysis for a future climate change should be increased with 0.25- 0.5 meters for the upper open aquifer (given that the ground surface is not exceeded) and 1-1.5 meters in the lower aquifer. The increase indicated above shall be added to the design values for the present climate.

In Norway the NIFS project, a joint venture between the Jernbaneverket, Norges vassdrags- og energidirektorat og Statens vegvesen, active during 2012- 2015 developed recommendations on how to handle natural disasters in Norway. In their Veileder no 7- Sikkerhet mot kvikkleireskred (Schanche & Davis Haugen 2014) it is recommended that pore pressures should be measured for at least two levels, top and bottom, at each study area. In Report 15- Sikkerhetsfilosofi for vurdering av områdestabilitet i naturlige skråninger (Strand et al. 2016) it is stated that the pore pressure situation is of great importance while using effective stress analysis and the recommendation is that the choice of pore pressure situation should consider extreme precipitation, climate change and also include a prognosis of extreme values. No explicit guidelines were given.

A common statement in the sources above concerns the complexity related to the choice of design pore pressure situation in a slope. But, based on measurements and engineering judgement, it should be possible to make a fair guess of the worst possible scenario in the future.

# 4. FIELD TEST AREAS

This chapter describes the two field test areas studied in this study. The locations of the sites are given in Figure 4-1. Both sites are located in greater Gothenburg area in southwestern Sweden, one in Äsperöd north of Gothenburg city and the other in Linnarhult closer to the city. The sites have soil properties common in southwestern Sweden with mostly lightly overconsolidated clays, the slopes are natural slopes and are situated adjacent to a river. Slope stability calculations show satisfying values for the safety factor, so there are no stability problems due to the field work.


*Figure 4-1. Overview, location of the test sites.*

The selection criteria for the field test sites included e.g. stable slope, “natural”, easy accessible, co-operating landowners, limited 3D effects, available information from earlier studies in or nearby the slopes and vegetation not affecting the stability. The results from the sites should also be representative for a larger area than just the sites so they should not be too special.

## 4.1 Site description Äsperöd

Äsperöd is situated close to Lilla Edet 60 km north of Gothenburg, right along the west shore of the Göta River, see Figure 4-2 and Figure 4-3. The Göta River is 93 km long from Lake Vänern in the north near Trollhättan until it reaches the sea outside Gothenburg. Both in Trollhättan and in Lilla Edet there are canal locks and power stations that regulate the discharge and water level in the river. In one slope in the area geotechnical investigations has been done previously to this study, see (Lind et al. 2010, Rihm 2011 and SGI 2011b), and it was instrumented with piezometers and a precipitation gauge. Calculated factor of safety for the slope is 1.31 for undrained analysis and 1.23 for combined analysis (SGI 2011b).

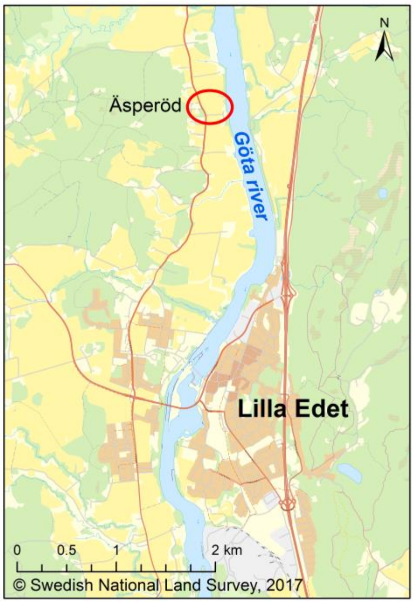


*Figure 4-2. Map of Lilla Edet area with Äsperöd in the north.*

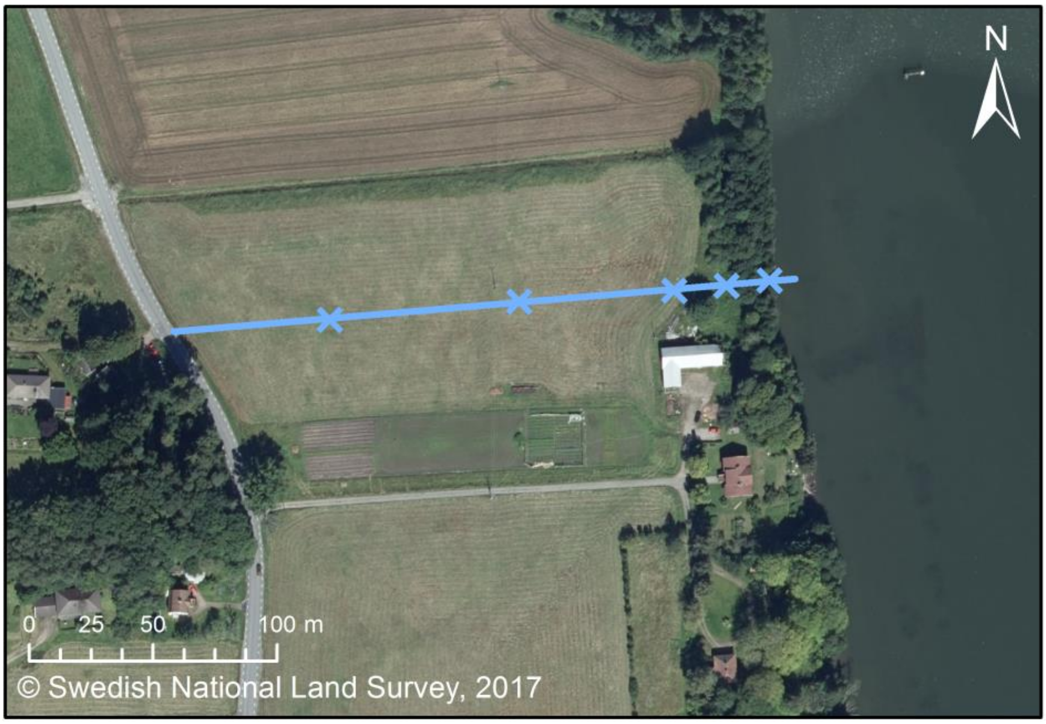


*Figure 4-3. Overview of Äsperöd. Blue line represents the instrumented slope. The X-symbols represent the location of piezometers.*

From the road west of the river, the studied slope is around 280 meters long. The area consists mainly of grassy farmland and the inclination of the area is low, +18 meters in the western part (close to the road) and +14 meters at the crest of the slope. The part from the crest down to the river inclines 1:6 and is partly covered with bushes and smaller trees. The water level in Göta River is around +7 meters and the river is about 15 meter deep outside the studied slope.

### 4.1.1 Soil properties

Geotechnical field tests of the area were performed by Lind et al. (2010) and by the Swedish Geotechnical Institute (SGI 2011b). In the area the soil consists of 1-2 meters of dry crust at the top of the soil profile, followed by clay, with a total thickness less than 10 meters in the western part, and more than 45 meters at the crest of the slope. The clay is silty between 4-10 meters of depth and contains some gyttja. There is also a layer of sand, around 2-2.5 meters thick, at a depth of around 35 meters close to the river and further back at 16 meters of depth. The clay is underlain by approx. 5 meters coarse grained soils (Lind et al. 2010). A quaternary map of the area is shown in Figure 4-4.

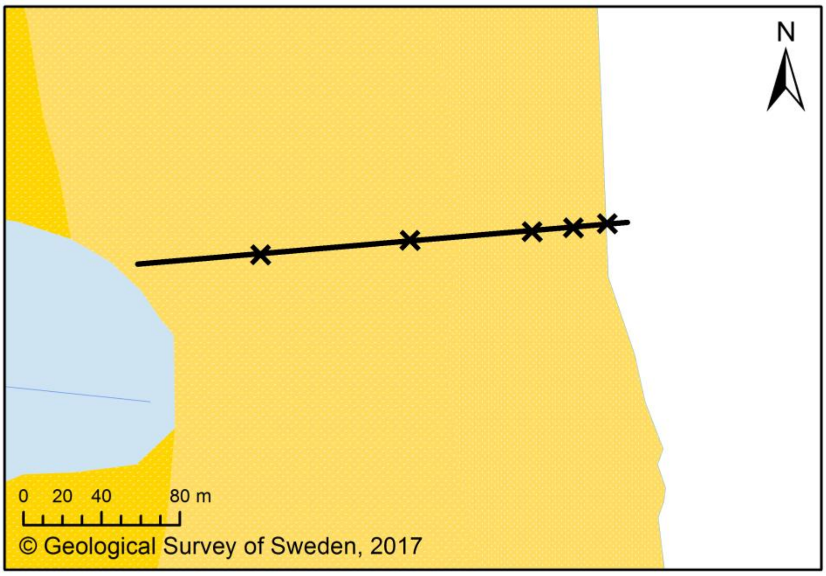


*Figure 4-4. Quaternary map of Äsperöd area. The light yellow areas are postglacial fine deposits, the darker yellow represents glacial clay and the light blue represents sandy till.*

Geotechnical properties for the clay according to laboratory testing of three bore holes performed by SGI (2011b) are presented below and in Figure 4-5 - Figure 4-8:

- The unit weight of the clay in the area varies between 15-17.2 $kN/m^3$.
- The natural water content in the clay varies between 53-85 %.
- The undrained shear strength in the clay (cone and vane) varies from 18 kPa between +17 meters to +4 meters and below that increasing with 1.44 kPa/meter.
- In the western part of the slope the clay has a high sensitivity and it is considered as quick from 6 meters of depth to firm bottom according to Swedish definitions (sensitivity> 50 and a remolded shear strength< 0.4 kPa).
- CRS-tests have been performed in the 3 boreholes at 4 levels each. The results show that the clay is overconsolidated with 30-100 kPa, which corresponds to an OCR of 1.2-2.3.
- The permeability in the clay varies according to the CRS-tests between $7 \cdot 10^{-10}$ -$2 \cdot 10^{-9}$ m/s.

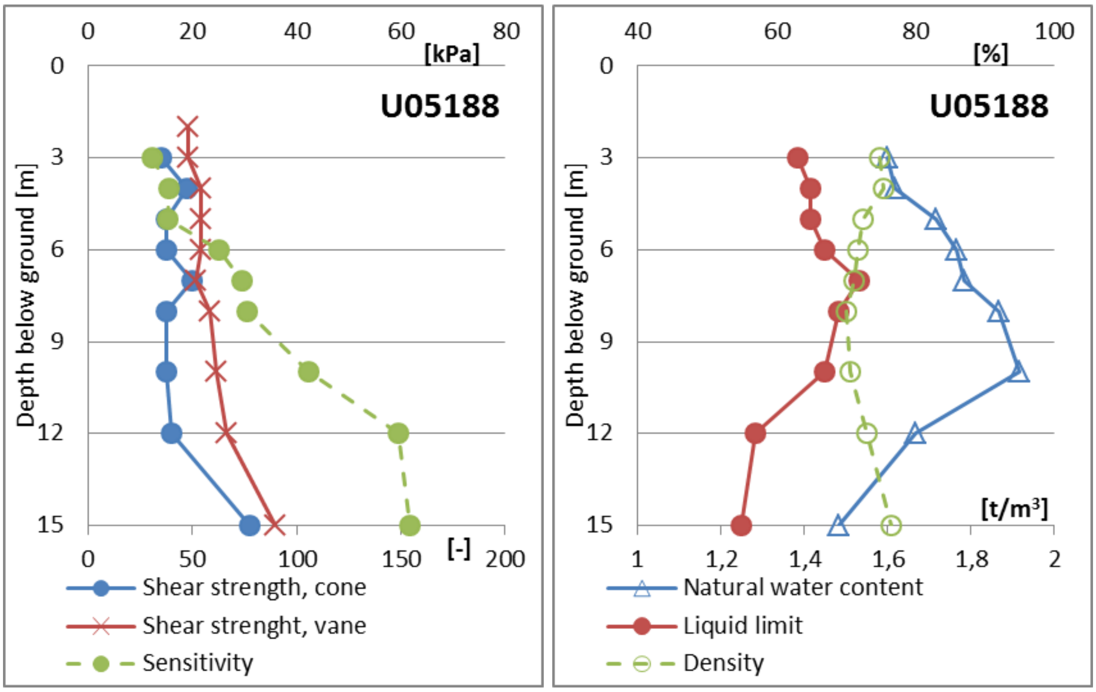


*Figure 4-5. Laboratory test results U05188, situated at the back of the slope.*

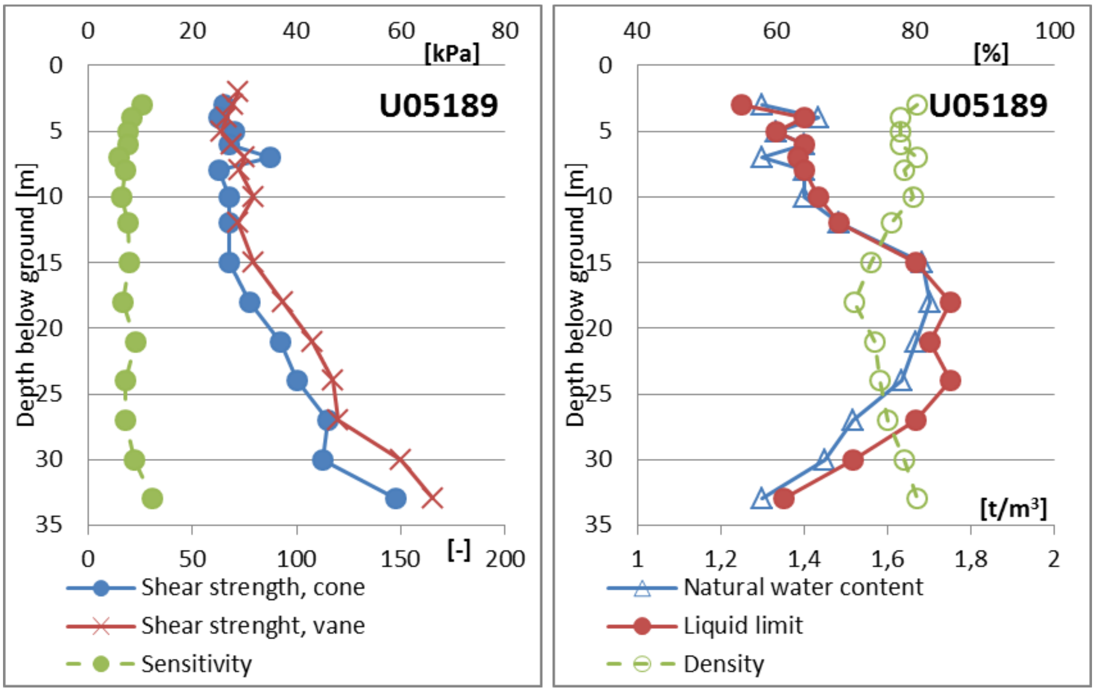


*Figure 4-6. Laboratory test results U05189, situated in the crest of the slope.*

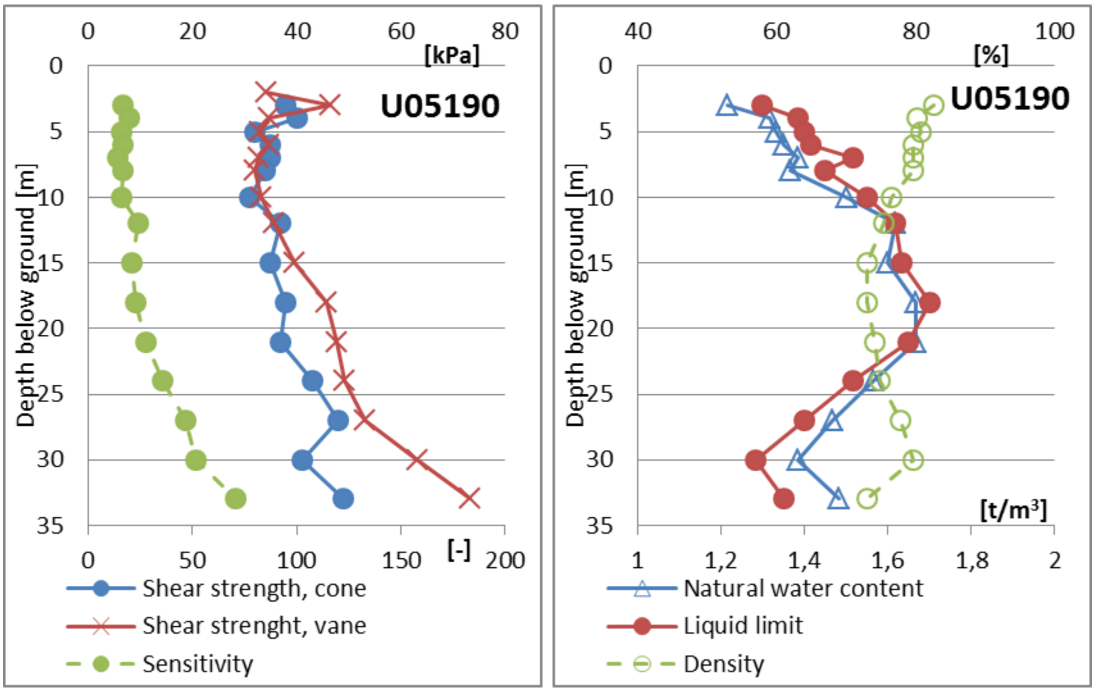


*Figure 4-7. Laboratory test results U05190, situated at the toe of the slope.*

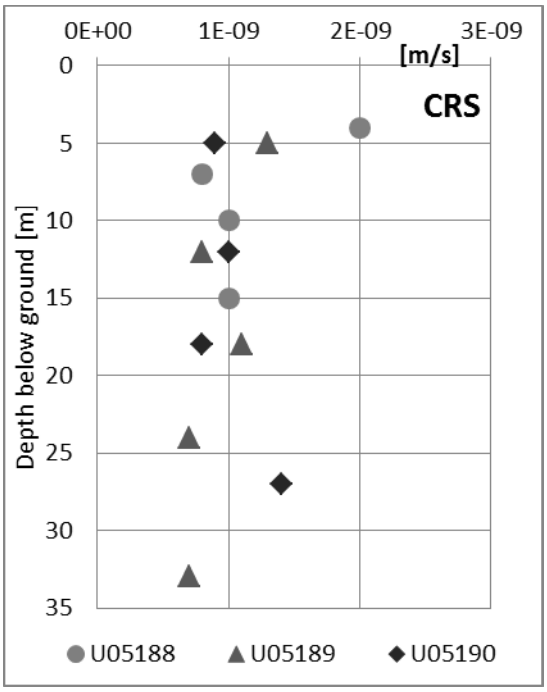


*Figure 4-8. Permeability from CRS-tests in Äsperöd.*

## 4.1.2 Instrumentation

In the Äsperöd test site 19 piezometers have been installed in five different parts of the slope. The first six piezometers where installed in 2007, see

(Lind et al. 2010), two piezometers were installed and monitored in the crest during May to September 2010 (SGI 2011b) and the remaining eleven piezometers were installed in January 2013 for this study. All the piezometers were logging every 4th hour. The piezometers installed 2007 were of the brand BAT, the ones from 2010 were from Geotech and the ones installed in 2013 were of the brand GeoNordic, model Pi30. The position and installation depths of the piezometers are given in Table 4-1 and Figure 4-9. The piezometers installed at the smallest depths are situated in, or just below, the dry crust.

*Table 4-1. Position and installation depths of the piezometers in Äsperöd.*

| Part of slope | Distance from river [meter] | Installation depth [meter] | Year of installation | End of measurement |
|---|---|---|---|---|
| **Back** | 190 | 7.1, 18 | 2007 | January 2016 |
| **Plateau** | 100 | 0.65, 1.2, 5 | 2013 | April 2016 |
| **Crest** | 50 | 0.99, 5 | 2013 | April 2016 |
| | | 8.11, 21.3, 34.4, 49 | 2007 | January 2016 |
| | | 2.5, 5 | May 2010 | September 2010 |
| **Middle** | 30 | 0.8, 1.25, 5 | 2013 | April 2016 |
| **Toe** | 15 | 0.69, 1.49, 5 | 2013 | April 2016 |

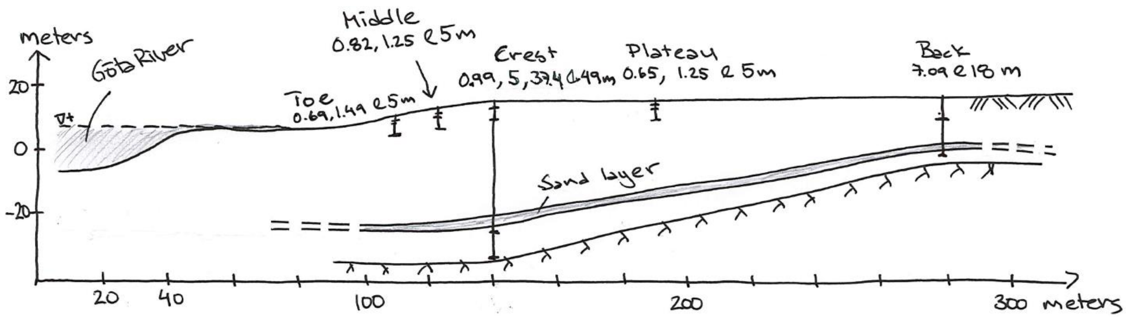


*Figure 4-9. Profile Äsperöd with position and installation depths of piezometers.*

A precipitation gauge was installed in Äsperöd in 2013 for collection of rainfall data. For some periods with problems with the gauge, rainfall data from the municipality of Lilla Edet have been used as a complement. All the 17 piezometers and the precipitation gauge have been monitored until January or April 2016.

Photos taken at the Äsperöd site are shown in Figure 4-10- Figure 4-14.

*Figure 4-10. Piezometers at the toe of the slope. As can be seen the station is placed some meters from the shore due to the vegetation and the coarse erosion protection material placed next to the river.*

*Figure 4-11. Picture from the crest of the slope towards the river. The station in the middle of the slope can be seen in the middle of the picture.*

*Figure 4-12. Piezometers at the crest of the slope, picture taken towards south. An old cowshed in the back.*

*Figure 4-13. Picture taken from the crest of the slope towards west. Station Plateau is situated next to the high powerline mast in the middle of the picture.*

*Figure 4-14. Piezometers and the precipitation gauge at the back of the slope. Picture taken towards east.*

## 4.2 Site description Linnarhult

Linnarhult is situated 15 km northeast of Gothenburg City in the Lärje River valley, see Figure 4-15 and Figure 4-16. The valley is a side valley of Göta River valley and is known for its many small slides and its meandering stream. The test site is situated at the eastern side of the river and consists of farmland. Most of the area is covered with grass but next to the river there are trees. On the top of the slope on the opposite side of the river there is an industrial area with a large houses and paved areas. At the test site there are two instrumented slopes, named Slope 1 and Slope 2, the distance between them is around 350 meters. Both slopes are perpendicular to the Lärje River. The ground elevation in Slope 1 is at +35 meters at the crest of the slope and in Slope 2 the plateau and crest are situated at +30 meters. At both slopes the level on the ground right next to the river is around +20 meters.

Earlier studies of the area has been done by Rankka (1994) who studied a slope situated between the two slopes presented here. The calculated factor of safety for that slope was, for undrained conditions, $F_c$=1.54 and for drained and combined conditions $F_{komb}$=1.2. Another investigation was performed by Sweco Civil (2015) who studied the area on the opposite side of the Lärje River. Their calculated factor of safety for a slope just opposite Slope 2 in this study was, for undrained conditions, $F_c$=1.55 and $F_{komb}$=1.48 for combined conditions. For the other slopes in that study the calculated safety factors for undrained analysis varies between $1.24 < F_c < 2.0$ and for combined analysis $1.20 < F_{komb} < 1.79$.

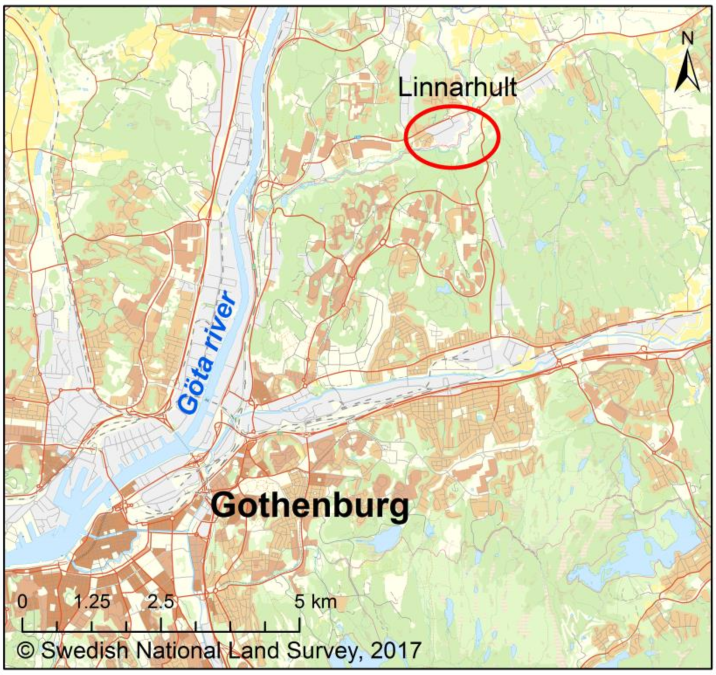


*Figure 4-15. Overview of northeastern Gothenburg area, Linnarhult in the top right corner.*

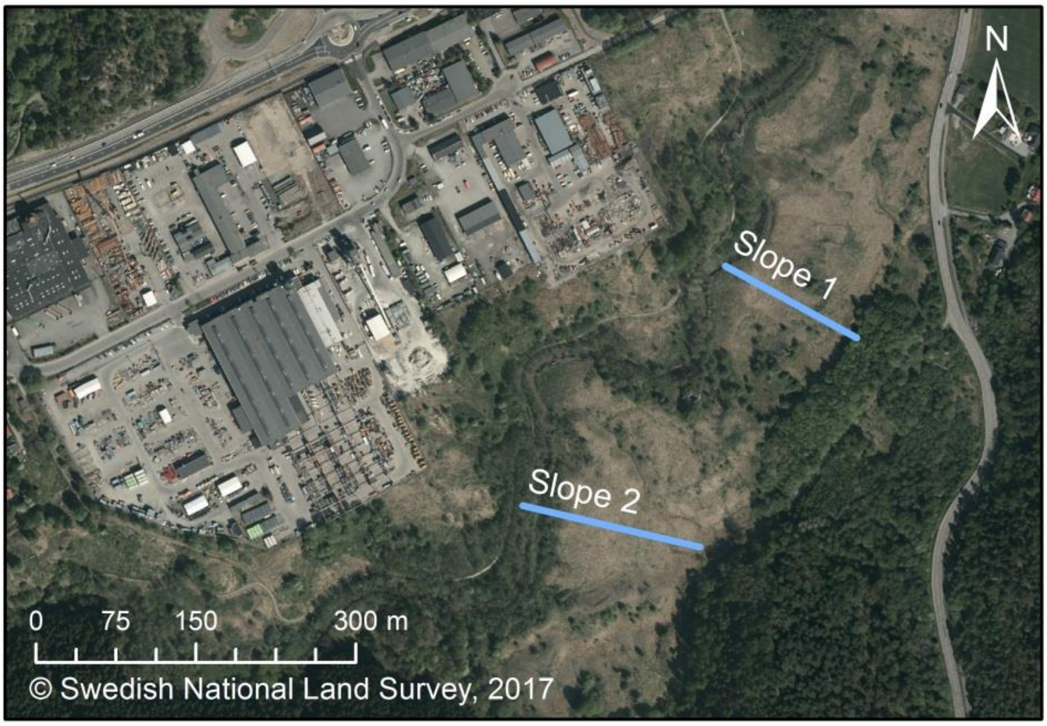


*Figure 4-16. Overview Linnarhult area with the two slopes on the eastern side of the Lärje River.*

### 4.2.1 Soil properties

Site investigations in Linnarhult were performed in December 2014-January 2015. In Slope 1 9 piezometers were installed. In Slope 2 undisturbed samples were taken in one borehole at 9 levels, 3 CPT-soundings were performed and 17 piezometers were installed. The undisturbed samples were sent to the laboratory at Chalmers University of Technology for routine tests and CRS tests at 5 levels.

Since no field work were performed in Slope 1, except for the installation of the piezometers, the possible presence of layers in the clay and depth to firm bottom is not clear. Therefore estimations and knowledge from Slope 2 is used for Slope 1 as well. According to the field tests in Slope 2 the soil in the area consist of 2 meters of dry crust at the top of the soil profile followed by clay, with a total thickness of 20 meters close to the Lärje River and around 30 meters behind the crest of the slope. In Slope 2 there is a layer of sand at 6 to 8 meters of depth below the crest and at 9 to11 meters depth further back in the slope. There is also a more horizontal layer of friction material at the bottom of the soil profile according to the CPT-soundings. A quaternary map of the area is shown in Figure 4-17.

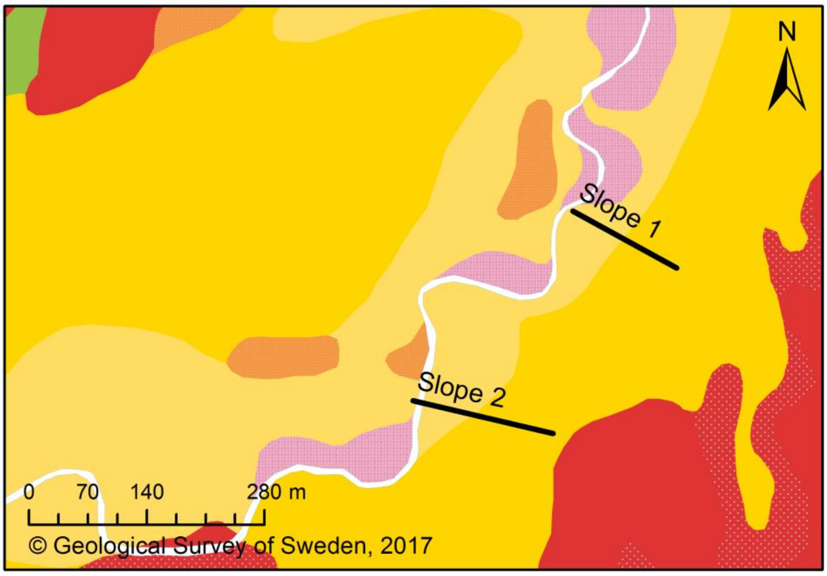


*Figure 4-17. Quaternary map of the Linnarhult area. The red areas are rock, the darker yellow areas represent glacial clay, the bright yellow areas are postglacial clay, orange areas are postglacial fine sand and pink areas are fluvial sediments.*

Geotechnical properties for the clay in the area, according to laboratory testing of the undisturbed samples from a borehole at the crest of Slope 2, are presented below and in Figure 4-18:

- The unit weight of the clay in the area varies between 16.3-17.8 kN/m$^3$. In the layer of sand the density is 20 kN/m$^3$.
- The natural water content in the clay varies between 65 % in the upper part of the clay and 55 % in the deeper parts. The value at 22 % is in the layer of sand.
- The shear strength in the clay (cone, unreduced) varies from 23 kPa at 3 meters below ground level at the crest, to 58 kPa at 18 meters below ground level.
- The sensitivity varies between 23 and 37 [-] and there is no quick clay according to Swedish definitions. In the study by Rankka (1994) sensitivities between 55-123 [-] was found at levels +35- +40m which are at higher levels than tested now. Sweco Civil (2015) indicated that there are layers with quick clay present in the area.
- CRS-tests have been performed at five levels (2, 6, 10, 12 and 18 meters). The result shows an OCR-value of 2.3-3.2 which is

considered as overconsolidated clay. This is in accordance with the values from Sweco Civil (2015) indicating OCR values between 2 and 4 at the crest of their slopes and between 5 and 8 at the toe of their slopes. The oedometer tests by Rankka (1994) indicate OCR values around 1.6-2.6 for the crest of her slope.

- The permeability in the clay varies, according to the CRS-tests, between $1.5 \cdot 10^{-10} – 7.5 \cdot 10^{-10}$ m/s.

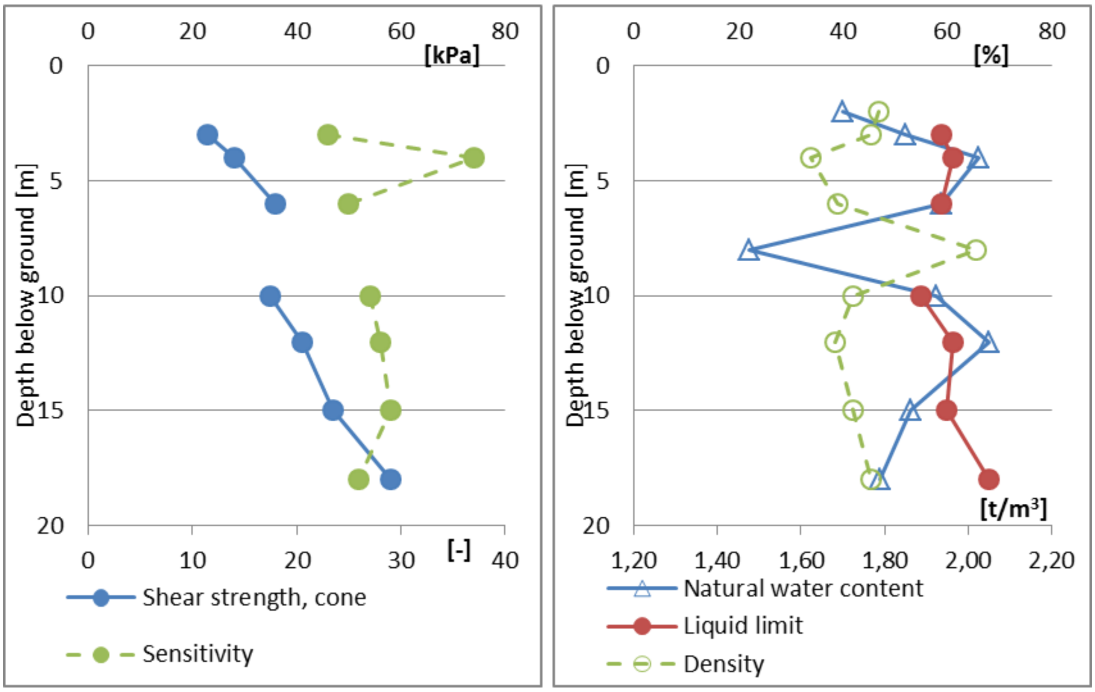


*Figure 4-18. Laboratory test results Linnarhult, crest slope 2.*

### 4.2.2 Instrumentation

In the Linnarhult test site 9 piezometers have been installed in Slope 1 and 17 piezometers in Slope 2. One piezometer was also installed in the Lärje River to measure the water level variation there. All of them where installed between December 2014 and January 2015. The piezometers were logging the pore pressure every 3rd- 4th hour. The position and installation depths of the piezometers are shown in Table 4-2, Figure 4-19, Table 4-3 and Figure 4-20. The piezometers were of the brand GeoNordic, model Pi30. The piezometers installed at the smallest depths are situated in, or just below, the dry crust.

*Table 4-2. Position and installation depths of the piezometers in Linnarhult, Slope 1.*

| Part of slope | Distance from river [meter] | Installation depth [meter] |
|---|---|---|
| **Crest** | ~ 75 | 0.5, 1, 5, 10 |
| **Middle** | ~ 33 | 0.5, 1.4, 6 |
| **Toe** | ~ 7 | 1.3, 5 |

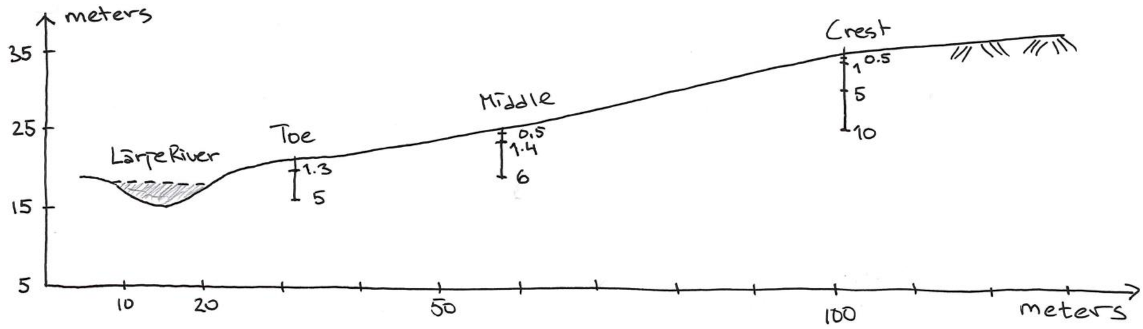


*Figure 4-19. Linnarhult Slope 1, position and installation depths of the piezometers.*

*Table 4-3. Position and installation depths of the piezometers in Linnarhult, Slope 2.*

| Part of slope | Distance from river [meter] | Installation depth [meter] |
|---|---|---|
| **Plateau** | ~55 | 0.5, 1.5, 4.5, 7, 15 |
| **Crest** | ~ 40 | 1, 2, 4, 6.5, 12 |
| **Middle** | ~ 25 | 2.7, 4, 7 |
| **Toe** | ~ 12 | 1.75, 4.75, 9.75, 19 |

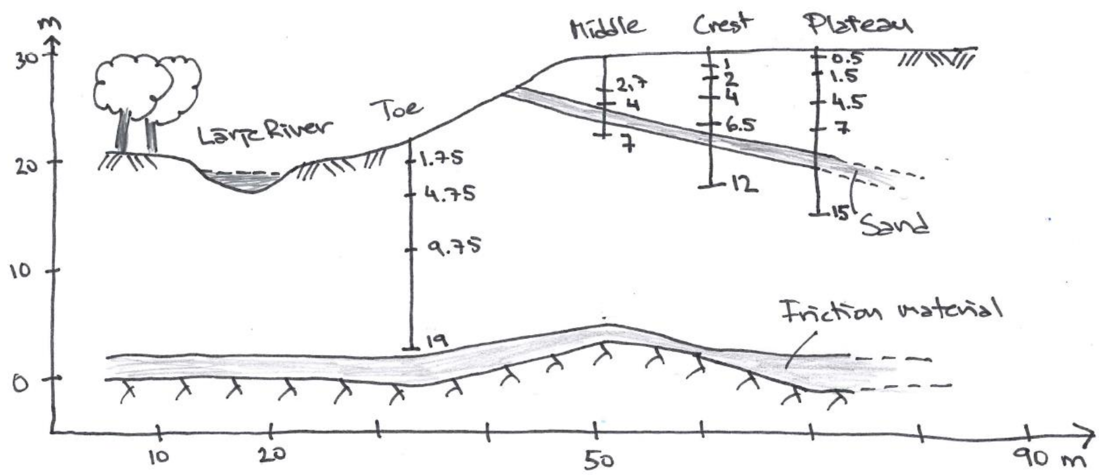


*Figure 4-20. Linnarhult Slope 2, position and installation depths of the piezometers.*

The rainfall measurements used for the Linnarhult area were performed by the City of Gothenburg. Their precipitation gauge is situated in Komettorget, Bergsjön, 2.5 km from Linnarhult.

Photos taken at the Linnarhult site are shown in Figure 4-21- Figure 4-25.

*Figure 4-21. Photo taken next to the piezometers at the crest of Slope 1. The stations in the middle and at the toe of the slope are seen towards the river.*

*Figure 4-22. Photo taken on the Lärje River, direction north from Slope 1. It can be seen that the sides of the river channel are steep, approx. 2 meters high when the water level is as low as in the photo. Erosion protection (coarse material) can be seen near the shore to the right in the photo.*

*Figure 4-23. Slope 2 seen from the height behind the slope. The blue box to the right in the photo is station Plateau. Stations Crest and Middle is situated more to the left.*

*Figure 4-24. Slope 2 seen from the crest and downwards towards south. Station Middle is situated to the left. Station Toe is in the middle of the photo and the station monitoring the Lärje River is seen just next to the river.*

*Figure 4-25. Photo taken from the bottom of Slope 2. Station Toe is closest in the photo and station Middle is seen further up in the slope. Some erosion of material in the slope can also be observed.*

## 5. RESULTS FIELD TEST AREAS

In this chapter the results from the measurements at the test sites in Äsperöd and Linnarhult are described.

After the field tests in Äsperöd and Linnarhult were performed, the results from the piezometer measurements were evaluated and compared. The results can be presented in many different ways. The following sections focus on diagrams with "Date" on the abscissa and the measured "Meters below ground surface" in the specified piezometer shown on the ordinate. All piezometers in the same station are displayed in the same diagram in order to facilitate comparisons. At the ordinate, the ground surface equals "0 meters". In the results presented, positive values equal to a groundwater level below the ground surface and negative values represents artesian pressures, see Figure 5-1. Values that after evaluation are expected to be "true", are shown as solid lines in the diagrams and values that are disregarded are shown as a dotted line. Disregarded values relate to e.g. when the measurements in the piezometer are drifting or when it is an unexpected and/ or inexplicable major change in the results. Also the accumulated precipitation for each month is shown in the diagrams, with its scale on the ordinate on the right hand side of the diagram. The accumulation implies that periods with no precipitation are seen as horizontal lines, and days with high amounts of rain are seen as vertical lines.

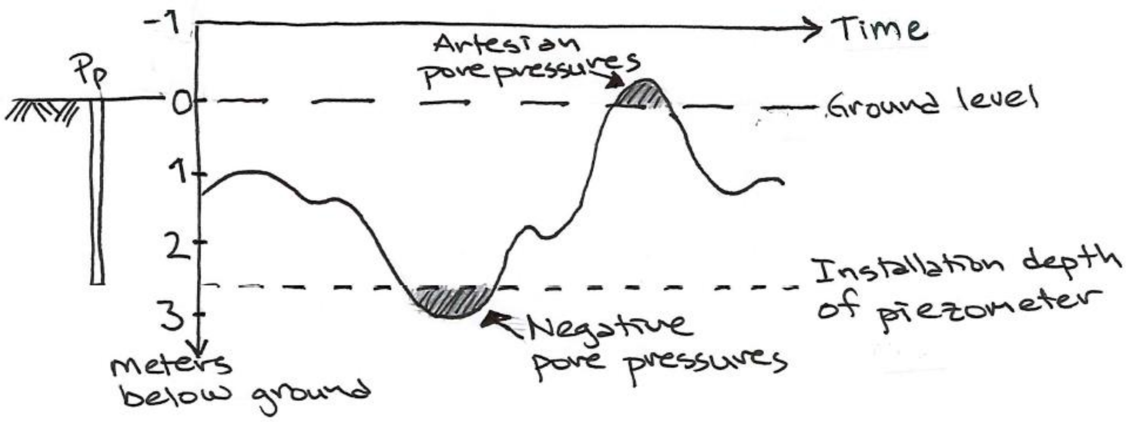


*Figure 5-1. Legend for how to interpret the diagrams with pore pressure fluctuations.*

Also pore pressure profiles are given for the different stations. For each station two figures are shown: The first one displays the minimum and maximum pore pressure value in each piezometer for the entire measurement period (disregarded values are not included). The second figure displays values for the two dates which are expected to represent days with high and low pore pressure values. To facilitate an overview of the pore pressure situation in the entire slope for a given time, the pore pressure distribution for each station is inserted into a sketch of the slope at the end of the Section, see Subsections 5.1.7, 5.2.5 and 5.2.10.

## 5.1 Results from Äsperöd

For the piezometers in Äsperöd measurements were made between the autumn of 2007 until late 2010, and within this study from January 2013 until the spring of 2016. For the period 2007- 2010 just some of the piezometers have been in use at the same time. In January 2013 installations of some new piezometers were done, and after that the piezometers have been logging values every 4$^{th}$ hour (with exceptions from some measurement errors etc.) and the loggers have been emptied roughly every 3$^{rd}$ month. There are also some measurements from two piezometers installed in the crest during May to September 2010 (SGI 2011b). The results presented in this Section focus mainly on the measurements performed during the years 2013- 2016. In general the functionality of the piezometers and loggers has been very good with just some shorter periods with battery failure etc.

### 5.1.1 Precipitation in Äsperöd

In order to relate the pore pressures measured in the slope to the precipitation a rainfall collector with data logger was installed in Äsperöd in 2013. It combines a 20 cm diameter tipping-bucket rain collector with a logger capable of monitoring a value every minute and/ or every 0.2 mm rain. For some periods with problems with the collector or the logger rainfall data from the municipality of Lilla Edet[1] have been used as a complement. The values from Lilla Edet are measured at the waste-water treatment plant 4 km south from Äsperöd. In Table 5-1 the dates of use for each gauge is shown.

[1] Information received from the municipality of Lilla Edet via e-mail during 2016.

*Table 5-1. Dates for use of the precipitation gauges in Äsperöd and Lilla Edet.*

| **Period** | **Used gauge** |
|---|---|
| 2013-01-01 – 2013-03-05 | Lilla Edet |
| 2013-03-06 – 2014-01-11 | Äsperöd |
| 2014-01-12 – 2014-09-10 | Lilla Edet |
| 2014-09-11 – 2015-06-15 | Äsperöd |
| 2015-06-16 – 2015-09-15 | Lilla Edet |
| 2015-09-16 – 2015-12-11 | Äsperöd |
| 2015-12-12 – 2016-04-09 | Lilla Edet |

In Figure 5-2 the accumulated rainfall for each month from January 2013 until April 2016 is shown. It can be seen that the amount of rain in February and March 2013 and in February and October 2015 is very low (<30 mm). August 2014 was the wettest month, with unusually much rain (300 mm), other rainy months (>175 mm) were December 2013, October 2014 and December 2015. According to Alexandersson & Eggertsson Karlström (2001) the normal precipitation (the average of the precipitation values over a 30-year period) for the area is 910 mm/year and the rainiest month is normally October or November with a normal value of 102 mm/month.

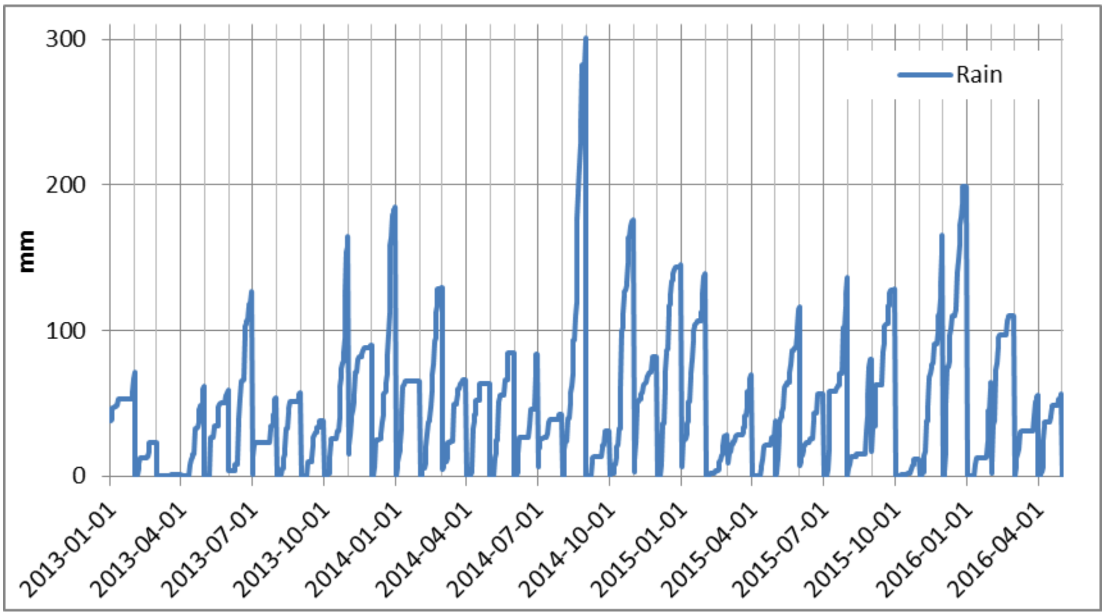


*Figure 5-2. Monthly precipitation in Äsperöd January 2013- April 2016.*

### 5.1.2 Äsperöd, Station Back

The two piezometers in the station at the back of the slope vary very much alike, see Figure 5-3. The piezometer installed at 7.09 meters below ground has a maximum value around 0.5 meters below ground surface. The total soil depth of the clay is around 20 meters so the piezometer at 18.02 meters is placed close to the friction material in the bottom, which can explain why that piezometer reacts so well to precipitation since the friction material is in contact with the ground surface at the very back of the slope and water flows into the layer when it rains. If the friction material did not have any contact with the ground surface it would take very long time for pressure changes due to precipitation to reach that deep into the clay. The amplitude (difference between the minimum and maximum value) is larger for the piezometer at 18.02 meters than for the one at 7.09 meters. As seen in Figure 5-4 the values that was measured in the same piezometers during 2007- 2010 are in the same range as the ones measured 2013- 2016.

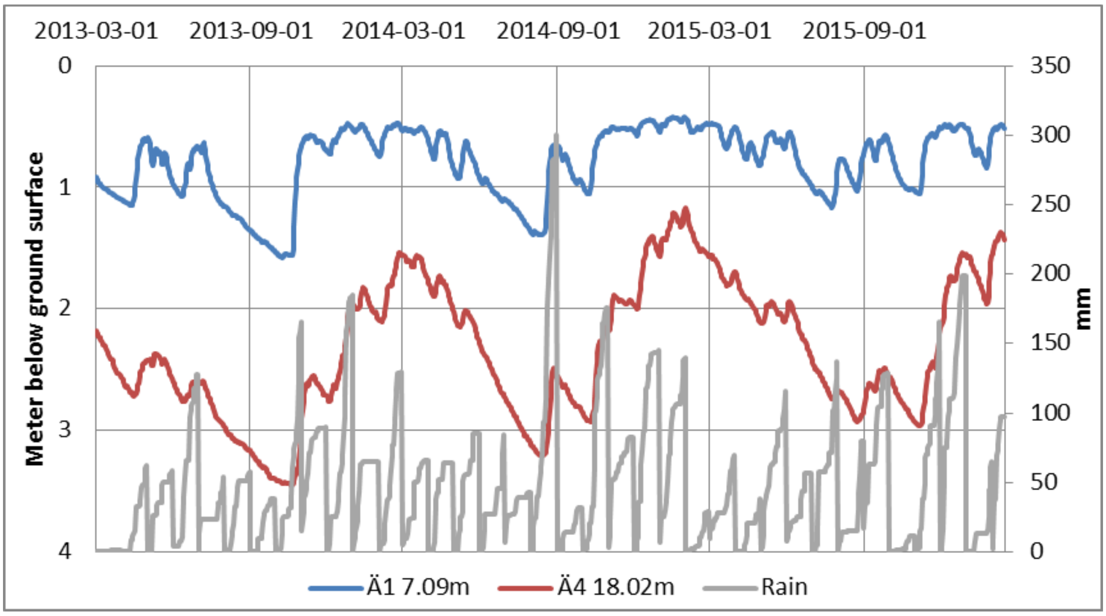


*Figure 5-3. Pore pressure readings and precipitation in Äsperöd station Back 2013-2016.*

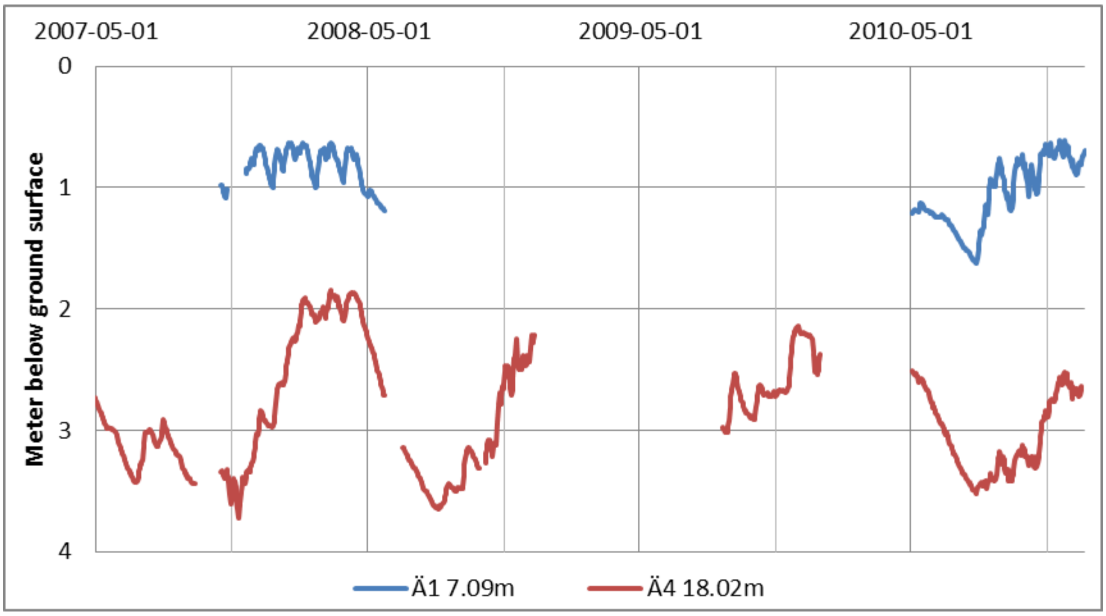


*Figure 5-4. Pore pressure readings in Äsperöd station Back 2007- 2010.*

The variation in pore pressure values in each piezometer is shown in Figure 5-5a and profiles for two different dates representing dates with high and low values respectively are shown in Figure 5-5b. The profiles indicate a groundwater level close to the ground surface and a pore pressure distribution slightly lower than hydrostatic pressure with depth.

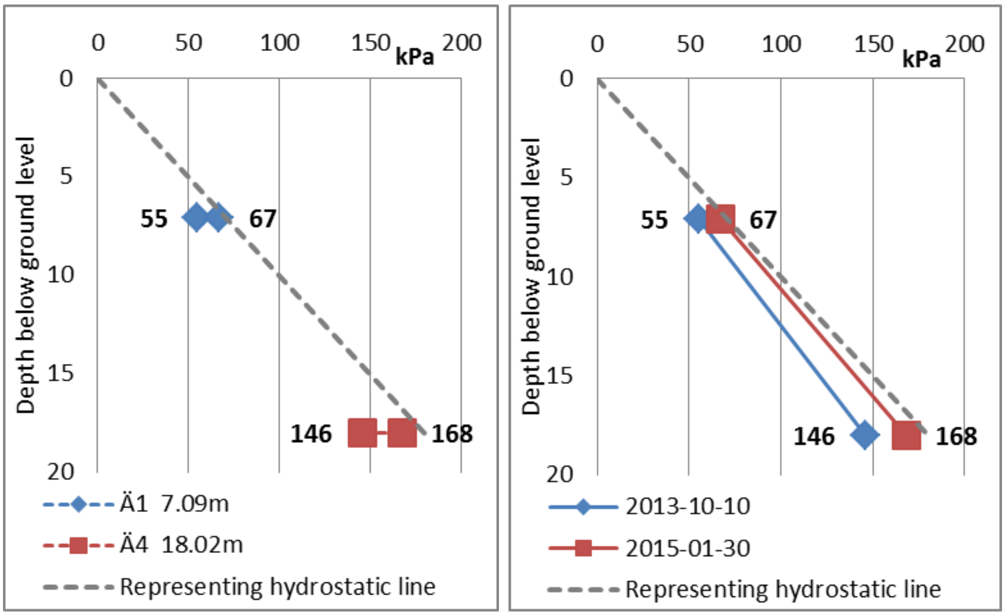


*Figure 5-5* ***a)*** *Pore pressure variations in the two piezometers in Äsperöd station Back 2013- 2016 and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Back.*

### 5.1.3 Äsperöd, Station Plateau

In the station called Plateau, 90 meters from station Back and 50 meters behind the crest of the slope, there are three piezometers installed. During 2013 and the beginning of 2014 they have a very good covariation, see Figure 5-6. In August- October 2013 the shallowest installed piezometer, D1 at 0.65 meters, shows low pore pressure values with a corresponding groundwater level at 1.5-2 meters below the installation depth of the piezometer. This is probably due to just small amounts of precipitation in combination with summer temperatures. Also piezometer D2 at 1.2 meters shows negative pore pressures during some of that period. After problems with the battery and the logger in D1 in the end of February 2014 the piezometer D1 seems to get very erratic and it shows strange results also during the late spring/ summer in both 2014 and 2015. Due to those problems all results after February 22 2014 are disregarded for piezometer D1.

Until April 2015 piezometer D3 shows a groundwater level closer to the ground surface than D2 does, indicating a slightly artesian pore pressure distribution towards depth. In April 2015 the relation between D2 and D3 changes without any obvious reason and D2 then indicates a groundwater level closer to the ground surface. Later in 2015 D2 even shows a groundwater level above the ground level at some occasions which implies a drift in this piezometer. Due to these inconsistencies the pore pressure measurements for D2 during 2015-05-04- 2015-06-12, 2015-08-27- 2015-10-06 and after 2015-11-07 are disregarded. All of the three piezometers in this station show a maximum groundwater level close to the ground surface (to be compared with 0.5 meter under the ground surface in station Back). This correlates with the ground surface being lower here than further back in the slope and the physical impression of it often being wetter in the ground closer to the crest of the slope.

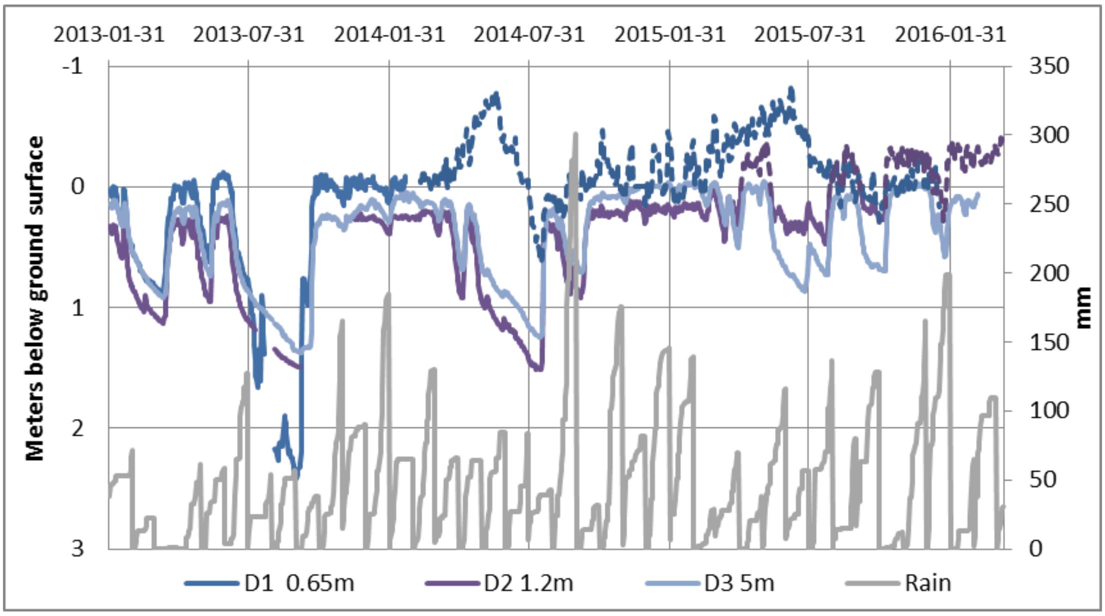


*Figure 5-6. Pore pressure readings and precipitation in Äsperöd station Plateau 2013-2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profiles for this station, Figure 5-7, show a hydrostatical, or slightly artesian, distribution for the two deeper piezometers with a groundwater level varying between 0-1.3 meters below ground surface. Also the maximum value for the shallowest piezometer follows the hydrostatical pressure distribution well whereas it drops to a lower value for dry periods, see Figure 5-7a. The largest variation between the minimum and maximum measured values occurs at the shallowest installed piezometer, in total 26 kPa.

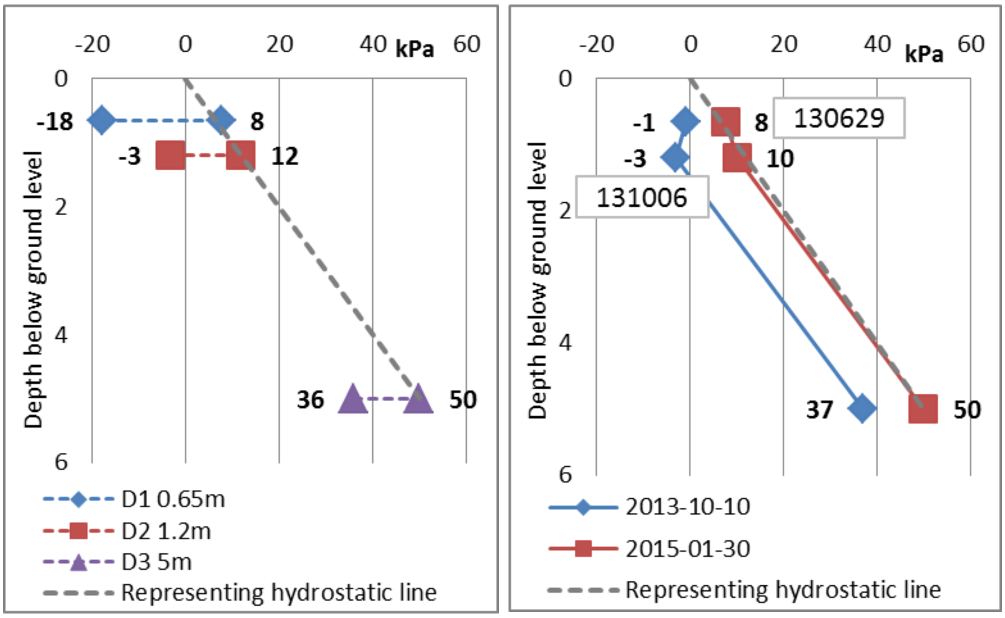


*Figure 5-7* ***a)*** *Pore pressure variations in the three piezometers in Äsperöd station Plateau and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Plateau.*

### 5.1.4 Äsperöd, Station Crest

In the station at the crest of the slope six piezometers were in use 2013-2016 at depths between 1 and 49 meters below ground surface. In Figure 5-8 it can be seen that the covariation between them is not really consistent. Piezometer C1, at 0.99 meter below ground, shows a reasonable fluctuation and a groundwater level varying between 0-2 meters below ground. Piezometer C2 at 5 meters depth follows the same variations over time but with a smaller amplitude and shows a lower groundwater level than C1, which is indicating a downward gradient in the profile. Both those piezometers have a fluctuation pattern that indicates quick reaction to precipitation events.

Piezometer Ä7 at 8.11 meters below ground seemed already from the beginning of 2013 to give inconsistent readings. The earlier registrations from this piezometer during 2007- 2010 show values 0.9-2.3 meters below ground surface, see Figure 5-9, with a trustworthy variation with time, to be compared with the fairly steady curve around 1 meter below ground for most of the time 2013- 2016. In spite of repeated saturation attempts and function control the piezometer did not work well and all the readings 2013- 2016 should be disregarded for Ä7.

The piezometer at 21.27 meters below ground have almost no variations at all for the period 2013-2016, the total difference between the minimum and maximum values are just 2 kPa. Older values from 2010 for this piezometer, see Figure 5-9, shows greater amplitude and a groundwater level 1-1.5 meters closer to the ground surface than the values presented in Figure 5-8, so probably something has happened with the piezometer or the logger. Due to those uncertainties and problems the entire series 2013-2016 from this piezometer is disregarded.

For the two piezometers at greatest depths, 37.43 meters and 49 meters below ground, some covariations can be observed. The one at 49 meters depth shows larger amplitude and a higher groundwater level compared to the one installed at 37.43 meters depth. When observing the soil profile for the slope, see Figure 4-9, it can be seen that there is a layer of 2.5 meter sand at around 34.5-37 meters depth dividing the clay into two parts. The piezometer installed at 37.43 meters depth is placed at the top of the lower clay layer (aquitard 2), just below the sand. The piezometer at 49 meters depth is placed at the bottom of the lower clay layer which is situated on top of the friction material in the very bottom of the soil profile. The piezometer at 49 meters is affected by the pore pressure in the rims of the profile which is reaching this piezometer through the friction material much faster than the reaction in the clay and sand for the one at 37.43 meters. Most likely the friction material will be able to distribute more water compared to the sand and therefore the sand layer will not affect the pore pressures as much. Both the piezometer at 37.43 and at 49 meters depth shows values in the same range during 2007- 2010 as during 2013-2016.

The two piezometers installed and measured at 2.5 and 5 meters depth in May – September 2010 (SGI 2011b) covariate very well indicating a hydrostatical distribution towards depth, see Figure 5-9. The one at 5 meters depth from 2010 indicate a groundwater pressure around 10 kPa higher than the one at 5 meters depth 2013- 2016. Since both of the piezometers used in 2010 were removed after that project was finished the exact location of them related to the newer ones is not clear.

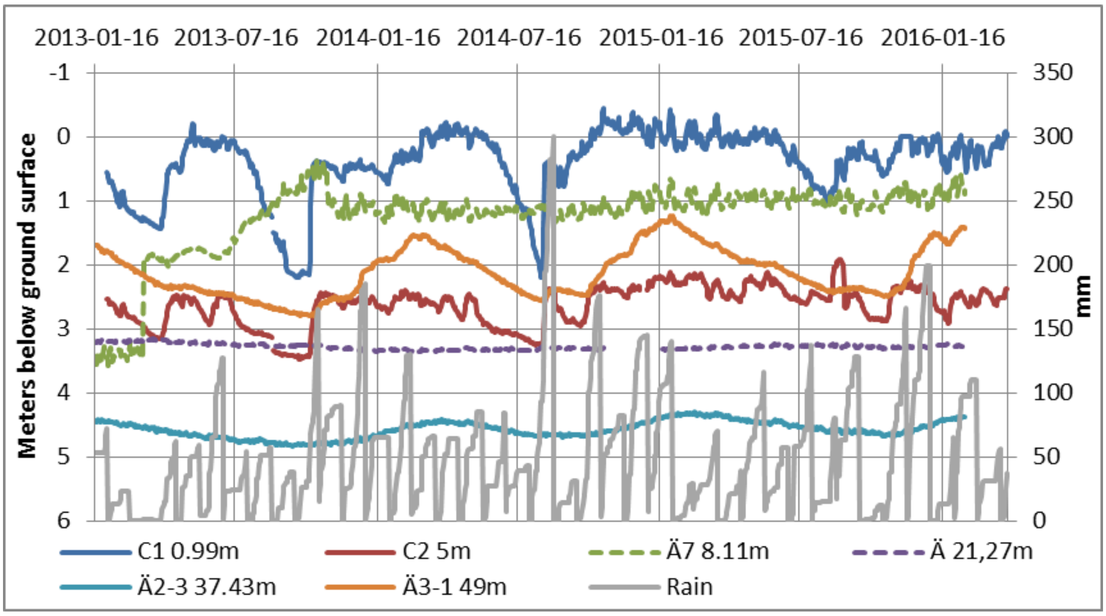


*Figure 5-8. Pore pressure readings and precipitation in Äsperöd station Crest 2013-2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

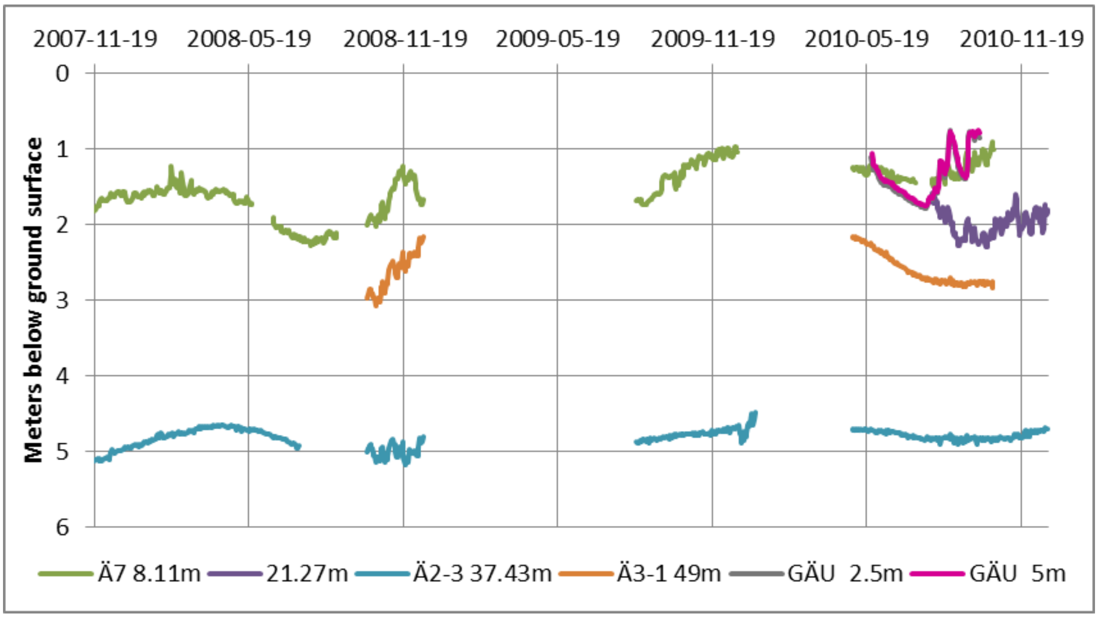


*Figure 5-9. Pore pressure readings in Äsperöd station Crest 2007- 2010.*

In the pore pressure profile for the station at the crest of the slope, see Figure 5-10 and Figure 5-11, the groundwater level is situated 0-2.5 meters below the ground. In the uppermost 6 meters and in the layer of sand (at 34.5-37 meters depth) there is a nearly hydrostatic pore pressure profile during dry to semi-dry periods, but a small downward gradient can be observed. During wetter periods the uppermost piezometer shows a ground water level corresponding to the ground surface and the situation is not hydrostatical. This change does not however have any major effect on the pore pressure further down in the soil profile. The piezometer installed at 49 meters depth is situated, as mentioned, close to the friction material in the bottom of the soil profile and should thus not be expected to be coherent with the rest of the piezometers.

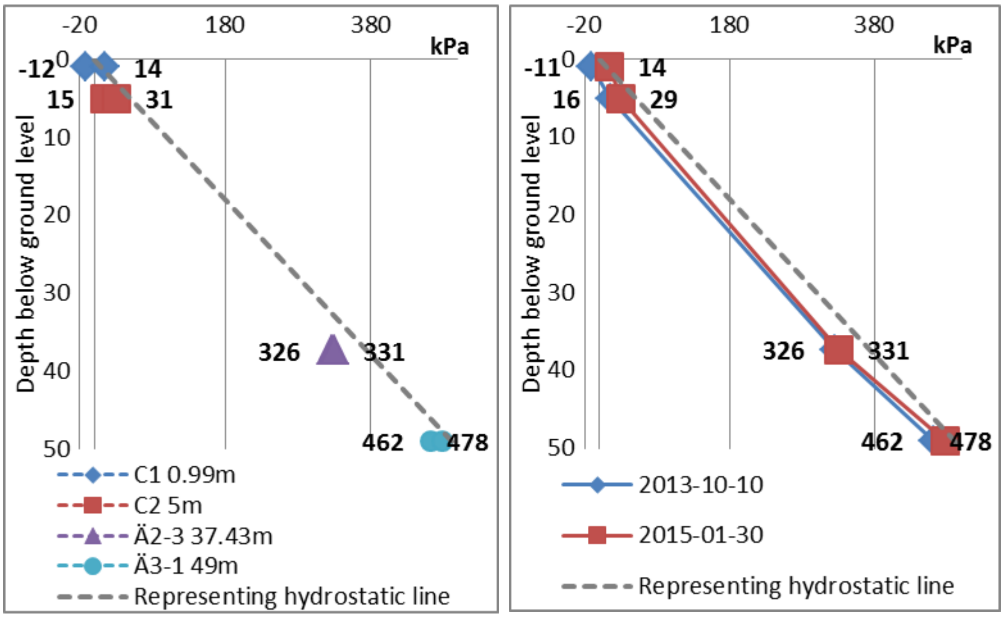


*Figure 5-10* ***a)*** *Pore pressure variations in each piezometer in Äsperöd station Crest 2013-2016 and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Crest. There is a layer with 2.5 meters of sand just above the piezometer at 37.43 meters depth.*

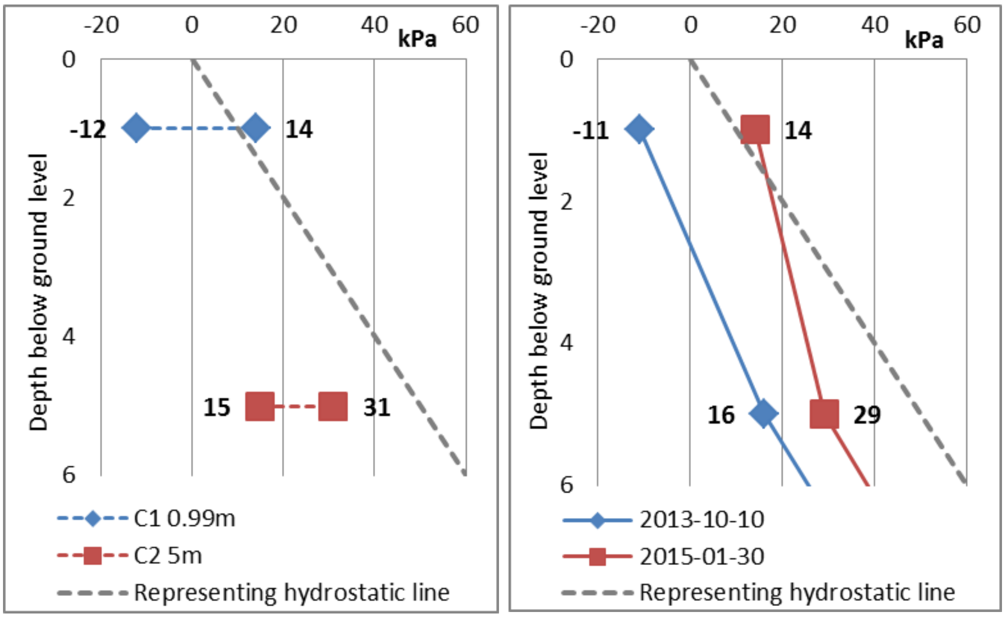


*Figure 5-11 **a)** Pore pressure variations the uppermost 6 meters in Äsperöd station Crest 2013-2016 and **b)** Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Crest, the uppermost 6 meters.*

In Figure 5-12 and Figure 5-13 the pore pressure profile presented above is complemented with the highest and lowest measured values in the piezometers at 8.11 and 21.27 meters depth during the measurement period 2007- 2010 and at 2.5 and 5 meters depth during 2010. It can be concluded that those values fits in fairly well with the rest of the profile. As stated above and seen in Figure 5-13 the piezometer at 5 meters depth 2013- 2016 indicate a lower pore pressure value compared with the piezometer at 5 meters depth 2010. The piezometers at 2.5 and 8.11 meters depth matches the 5 meter values from 2010 better than the ones from 2013- 2016, maybe because of the coherent measurement period.

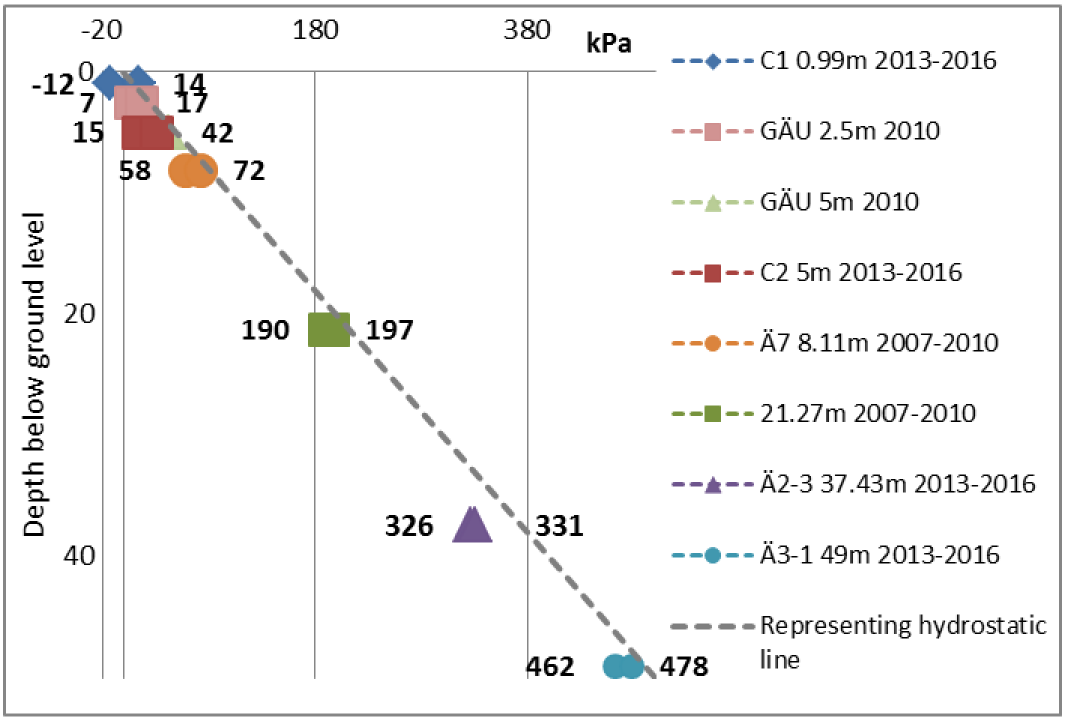


*Figure 5-12. Pore pressure variations in each piezometer in Äsperöd station Crest 2013- 2016 including the piezometers at 8.11 meters during 2007- 2010, at 21.27 meters during 2007- 2010 and at 2.5 and 5 meters during 2010.*

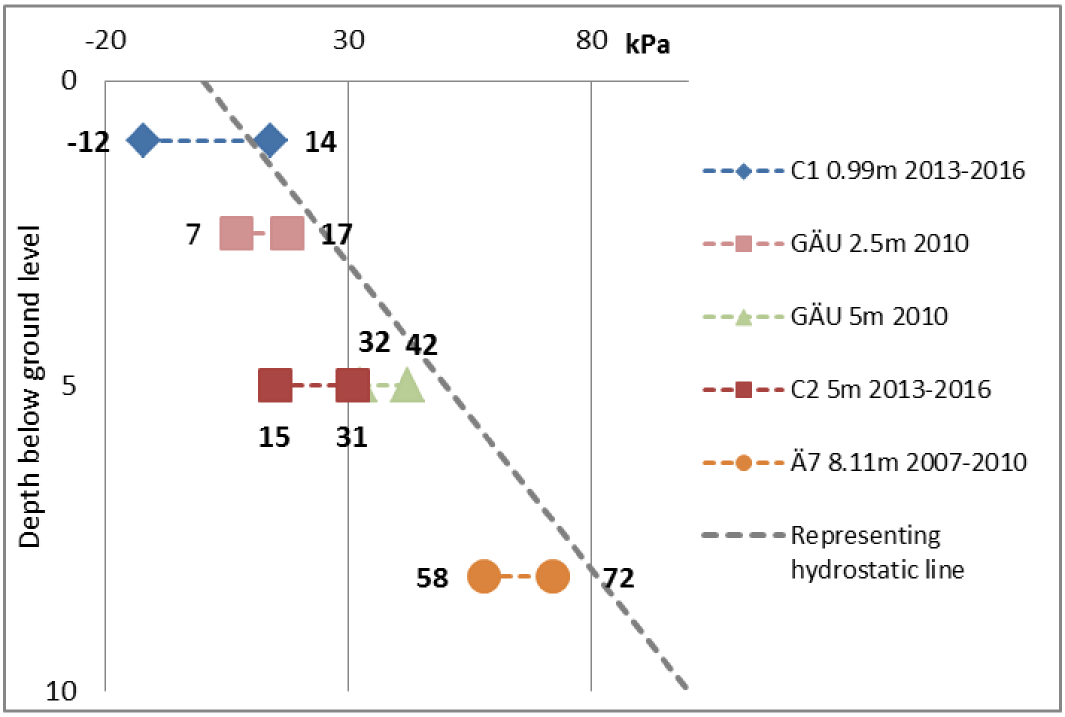


*Figure 5-13. Pore pressure variations of piezometers in the uppermost 10 meters in Äsperöd station Crest 2013-2016 including the piezometers at 8.11 meters during 2007-2010 and at 2.5 and 5 meters during 2010.*

### 5.1.5 Äsperöd, Station Middle

Three piezometers were installed in a station in the middle of the slope. It seems like all three piezometers function well from the installation until the first days of September 2014, see Figure 5-14. After that B2 seems to change from its earlier pattern and from the beginning of 2015 the piezometer shows a higher and higher groundwater level which is not trustworthy so all values after September 3 2014 are excluded. In June 2015 piezometer B1 deviates from its earlier pattern, starting the same day as the logger has been emptied so the change is most likely a problem related to that. Due to this problem all values after June 12 2015 are disregarded for B1. It could be discussed if the values from September/ October 2014 to June 2015 are totally trustworthy, but they are not excluded from the analysis at this point. In December 23 2015 also the deepest installed piezometer, B3, starts to behave in an unexpected way and all values after that are disregarded.

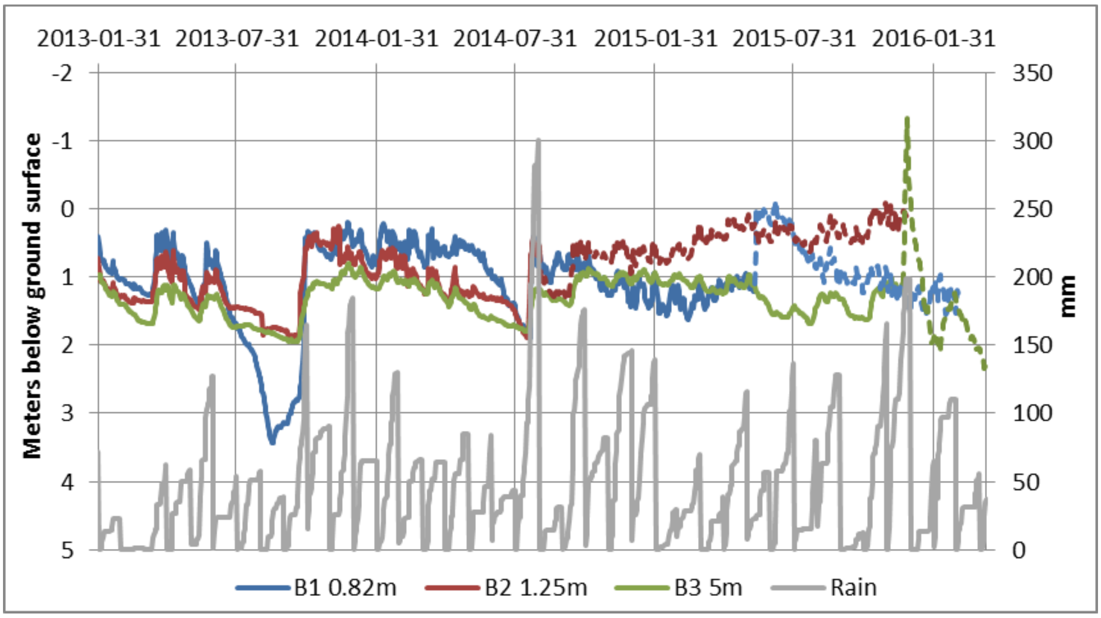


*Figure 5-14. Pore pressure readings and precipitation in Äsperöd station Middle 2013-2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profiles for this station, Figure 5-15, shows larger amplitude for the shallowest piezometer than for the deeper ones which is understandable due to the station being situated at the most inclining part of the slope were the effects from surface runoff etc. is expected to be large. The groundwater level is situated 0-2 meters below the ground and according to the profiles for the dates representing high and low pore pressure values, Figure 5-15b, the distribution seems to be hydrostatic for the middle and deepest piezometer for dry conditions. For wet conditions there might be a downward gradient but since the value for the middle piezometer is from another date the actual distribution is a bit unclear. For both dates the uppermost piezometer shows a lower value than hydrostatic compared to the deeper ones.

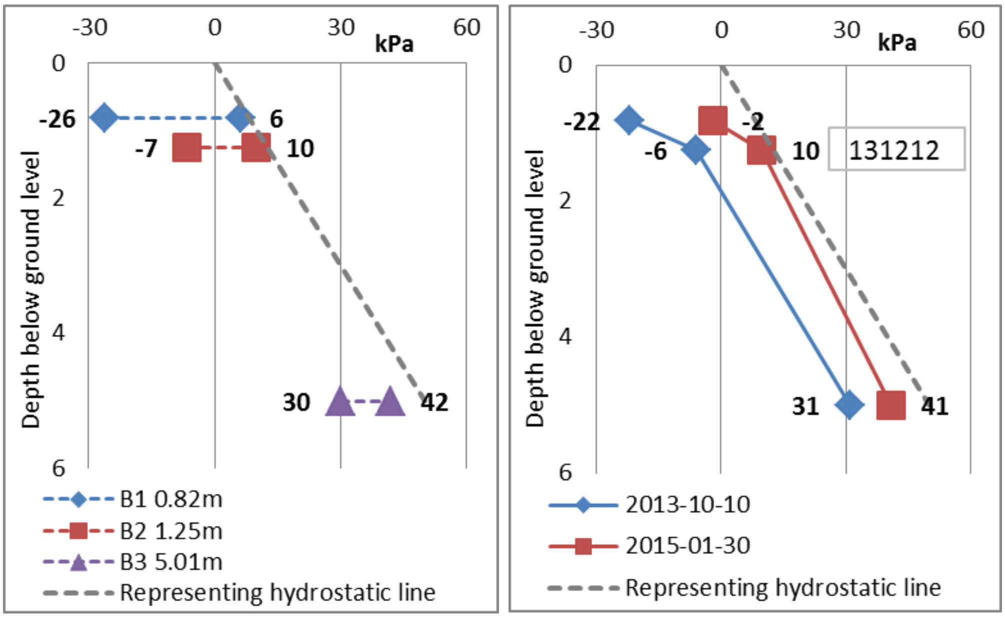


*Figure 5-15* ***a)*** *Pore pressure variations in each piezometer in Äsperöd station Middle and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Middle.*

### 5.1.6 Äsperöd, Station Toe

In the station at the toe of the slope in Äsperöd three piezometers were installed at 0.69, 1.49 and 5.04 meters depth. The shallowest installed piezometer, A1, shows very low groundwater levels during the summer 2013 with a groundwater level more than 7 meters below ground for some days, Figure 5-16. The piezometer seems to recover after that, with first an instantaneous change to a level corresponding to 0 kPa pressure (groundwater level equals the installation depth of the piezometer). In late May 2014 A1 however starts to show divergent values and a lower and lower groundwater level, which does not correlate with the other piezometers in this station, so the piezometer is believed to be out of order after that. This is expected to be related to the heavy dry out and/ or connected to some problems emerging from emptying the logger May 23 2014. At some occasions also A2 shows a very low groundwater level (dries out) and then seems to increase instantly and recover at 0 kPa for a while before showing “normal” results again. Piezometer A3 does never show some extreme values compared to A1 or A2. Both A2 and A3 show a maximum groundwater level 1-1.2 meters below ground level for most of the time.

The ground level where the piezometers at the toe are installed is located around +9 meters above sea level. The elevation of the Göta River varies around +6.6- +7.1 meters above sea level, see further Subsection 5.1.8. This implies that the piezometers A1 and A2 are installed higher than the level of the river and are therefore not directly connected to the fluctuations in the river.

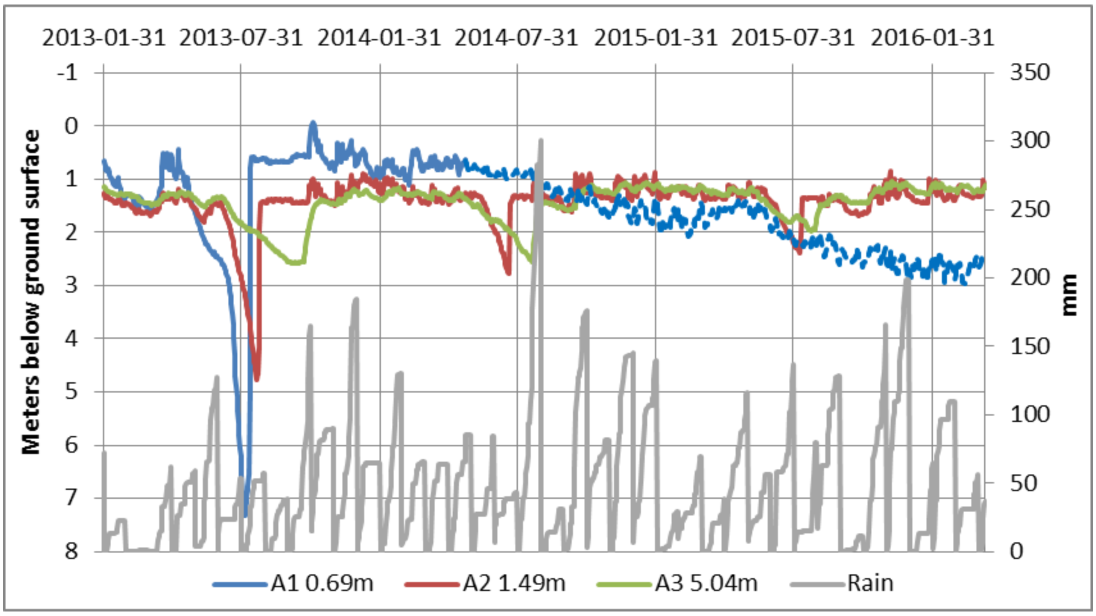


*Figure 5-16. Pore pressure readings and precipitation in Äsperöd station Toe 2013-2016. Values expected to be “true” are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profile based on values for two different dates in this station, Figure 5-17b, shows that the groundwater level is situated 0-1.5 meters below the ground level. When looking at the total minimum values, Figure 5-17a, the groundwater level might be as low as 2.5 meters below ground surface. The inclination of the pore pressure profile is close to hydrostatic between the piezometers installed at 1.5 and 5 meters respectively, but higher in the shallowest piezometer.

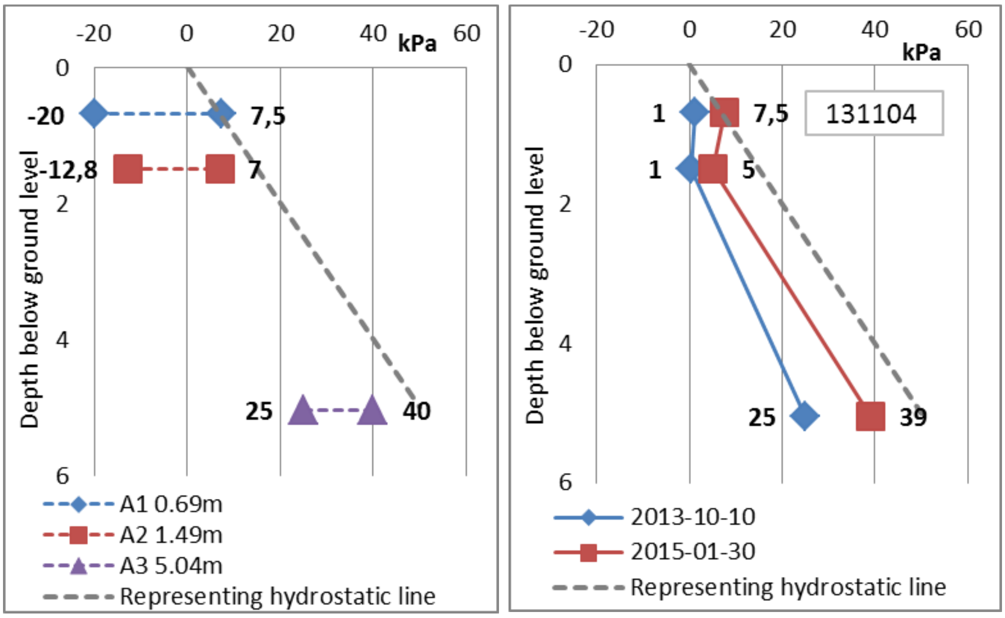


*Figure 5-17* ***a)*** *Pore pressure variations in each piezometer in Äsperöd station Toe and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Äsperöd station Toe.*

### 5.1.7 Pore pressure regime for the slope in Äsperöd

If the pore pressure measurements for each station, presented in the subsections above, are inserted into a profile of the entire slope the total pore pressure distribution in the slope for that day can be studied. A possible location of the groundwater level between the piezometers can also be estimated.

In Figure 5-18 the values for one day, 2013- 01-30, representing periods with high pore pressure values in Äsperöd are shown. It can be seen that the groundwater level is situated at the ground surface behind the crest and at the crest. At station Middle the groundwater level is situated around 1 meter below the ground surface. In the station at the toe of the slope the uppermost piezometer is indicating a higher groundwater level than the deeper ones do, probably related to precipitation that has not reached deeper down in the soil profile yet. Just next to the river there is most likely a groundwater level at the same level as the river, at around +7 meters, in the erosion protection material. For all stations except from the crest there is a hydrostatical pore pressure distribution towards depth in the uppermost meters of clay below the dry crust.

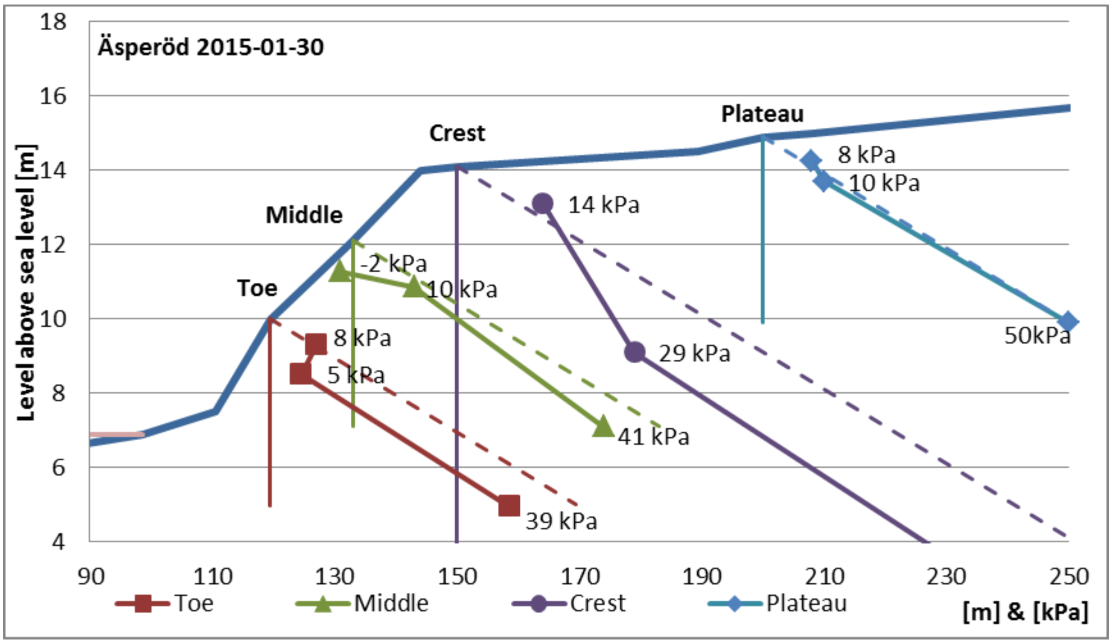


*Figure 5-18. Pore pressure profile for the slope in Äsperöd, date representing high values 2015-01-30. Nb! Different scale at x- and y-axis! The piezometers in station Back and at large depths at station Crest is not shown.*

The situation for a day representing low pore pressure levels, 2013-10-10, is shown in Figure 5-19. It can be seen that the pore pressures at all levels are different from the day with high values. The groundwater level is for this date situated almost 2 meters below ground for the station behind the crest and 2.5 meters below ground at the crest. For the middle of the slope the groundwater level is situated around 1.8 meters below ground and almost the same at the toe.

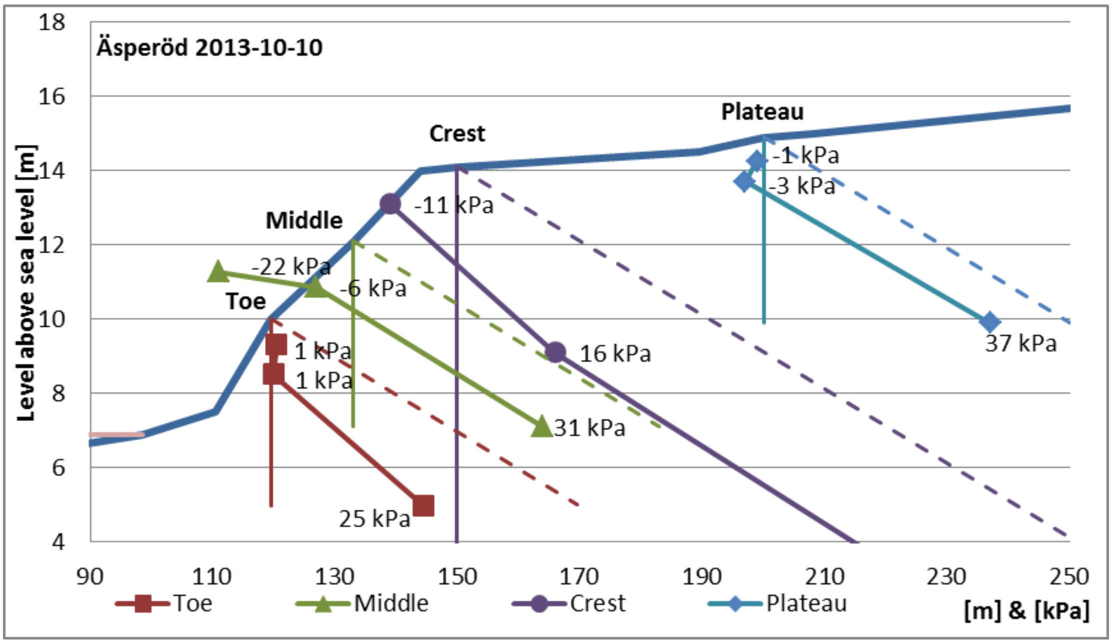


*Figure 5-19. Pore pressure profile for the slope in Äsperöd, date representing low values 2013-10-10. Nb! Different scale at x- and y-axis! The piezometers in station Back and at large depths at station Crest is not shown.*

## 5.1.8 Water level in Göta River

The water level and the discharge in the Göta River are regulated in favor of power production and by the locks in Trollhättan and Lilla Edet. The level is monitored by the power producer Vattenfall. One measuring point is situated in Lilla Edet, 3 km downstream Äsperöd. The water level variations between January 2013 and May 2016 are shown in Table 5-2 and Figure 5-20[2].

*Table 5-2. Water level variation of Göta River, measured in Lilla Edet, January 2013-May 2016.*

| | **Meters above sea level** |
|---|---|
| **Mean** | + 6.90 |
| **Max** | + 7.07 |
| **Min** | + 6.60 |

[2] Information received from Vattenfall Permits & Environment, via e-mail during 2015 & 2016.

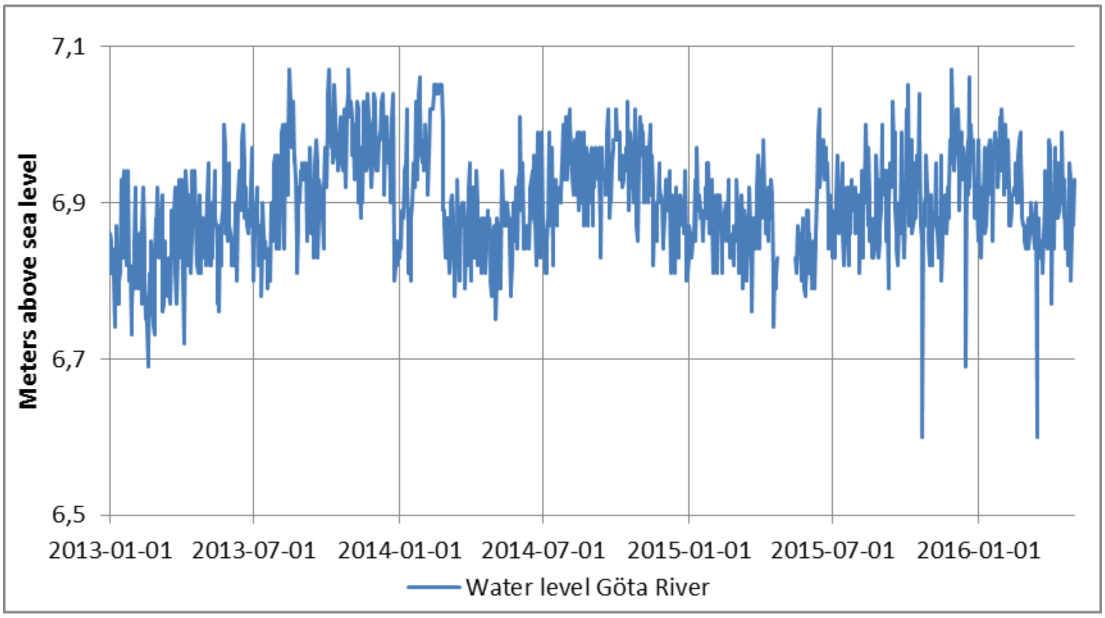


*Figure 5-20. Water level in Göta River, daily mean values January 2013- May 2016, Lilla Edet.*

When studying the correlation between the piezometers installed at the toe of the slope during 2013- 2016 and the variations in the river, Figure 5-21, no correlation between them can be visually seen in that scale. As presented above the piezometers A1 and A2 were installed above the level of the river (at around +8.3 and +7.5 meters) so they “should” not co-variate with the river. Not either the piezometer installed below the level of the river, A3 at +4 meters, indicate any correlation with the water level in the river which is somewhat surprising. This is thus an indication of the piezometer being affected by precipitation and the river being dependent on its regulation.

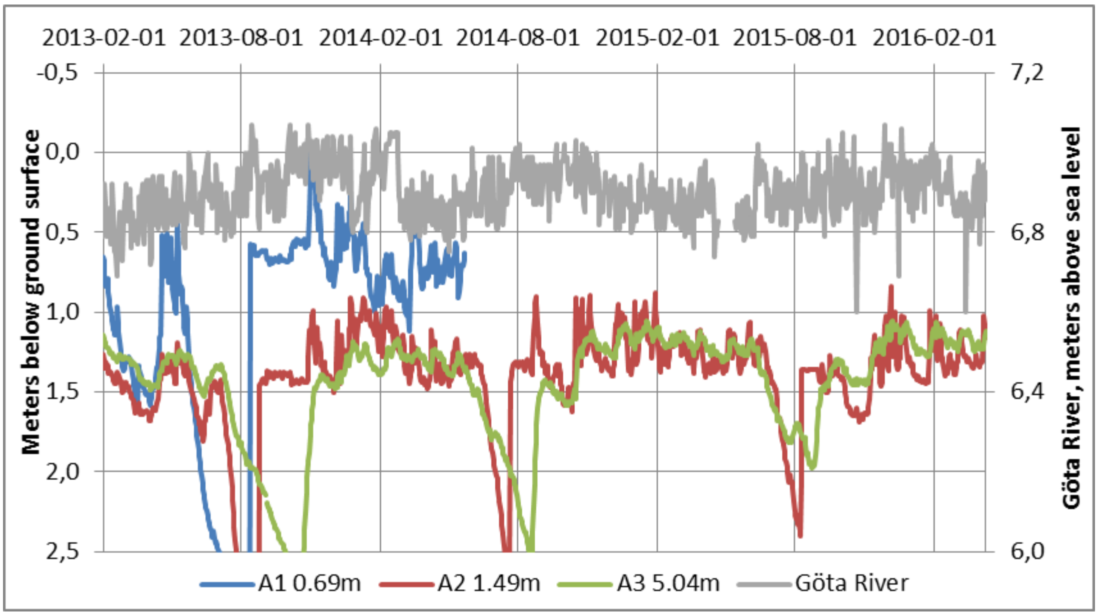


*Figure 5-21. Fluctuation in Äsperöd, daily mean values for the piezometers installed in station Toe and the water level in Göta River February 2013- March 2016.*

Also a statistical analysis was performed, where daily mean values for the piezometers in the toe of the slope (A1, A2 and A3) were compared to the water level in Göta River. A value of 0 % equals no correlation at all and 100 % means total consistency. First the study was performed for a short time, January- March 2014, the computed values of the correlation were then between 9-15 %. For a longer time, January 2014- February 2015, the correlation values ranged between 3-31 %, with the best consistency between the river and the piezometer installed at 5 meters depth at the toe of the slope. So, in conclusion there is no statistical correlation between the piezometer readings in Äsperöd and the water level in the river.

### 5.1.9 Yearly pore pressure fluctuations in Äsperöd

The yearly pore pressure fluctuations for the piezometers in Äsperöd were analyzed. In most of the piezometers a pattern could be observed with high pore pressure values (groundwater level close to the ground surface) during the winter and low values during late summer/ autumn. Those fluctuations are depending on the precipitation but also on the temperature since high temperatures increase the evaporation and less water infiltrates to the soil. When looking at the old measurements from 2007- 2010, the same pattern of yearly variations can be observed even though they are a bit harder to confirm since the continuous measurements periods were shorter for those years. When comparing the measured pore pressure values for the piezometers in Äsperöd with the precipitation during the same time consistency can be concluded. As an example the total annual precipitation is lower 2013 (930 mm) than 2014 (1270 mm) or 2015 (1170 mm) and it can be seen in all stations that the measured pore pressures in general are lower during 2013. A period with low pore pressure values in all piezometers in Äsperöd occurred in the beginning of October 2013. Example of periods with high pore pressure values in the piezometers are in March 2014 and in late January 2015.

In general the results for the piezometers at small depths (<5 meters) show a quick response to precipitation events and the shape of the pore pressure curve with time is therefore "sharp" and "abrupt", Figure 5-22a. The curves for the piezometers at larger depths (>5 meters) have a smoother shape due to the slow reaction to precipitation and the typical yearly groundwater variations is more visible here, Figure 5-22b. The amplitude between the highest and lowest measured pore pressure values in the piezometers varies between different locations, installation depths and between different years. For the piezometers installed in Äsperöd at smaller depths (<5 meters) the amplitude is around 12-28 kPa (1.2-2.8 meters) with some extreme values excluded, and for the ones at larger depths (>5 meters) the amplitude is around 5-23 kPa (0.5-2.3 meters), see Table 5-3.

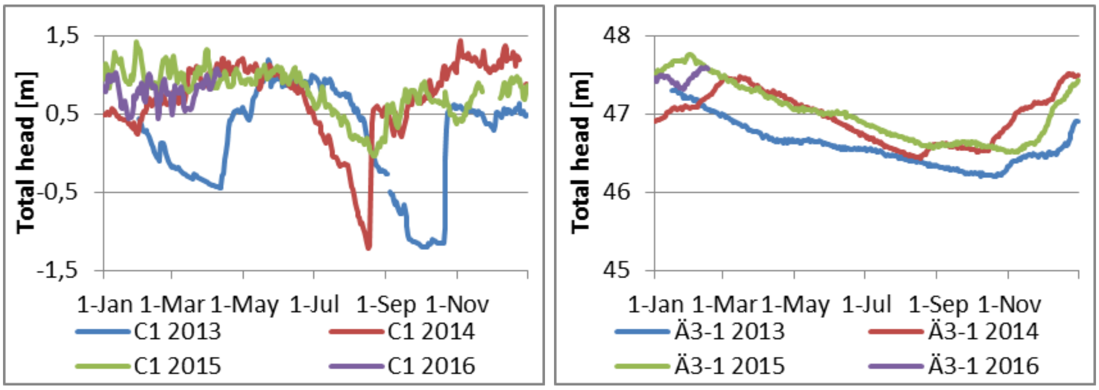


*Figure 5-22 Example of variation pattern in piezometers at* ***a)*** *small depth (<5 meters) and* ***b)*** *larger depth (>5 meters). Both piezometers are installed at the crest of the slope, C1 at 1 meter depth and Ä3-1 at 49 meters depth.*

*Table 5-3. Minimum and maximum values and corresponding dates for piezometers in Äsperöd 2013- 2016.*

| | **Name and installation depth [meters]** | **Min value [kPa]** | **Date min value** | **Max value [kPa]** | **Date max value** | **Amplitude [kPa]** |
|---|---|---|---|---|---|---|
| **Back** | Ä1 7.09 m | 55.1 | 13-10-08 | 66.7 | 15-01-30 | 11.6 |
| | Ä4 18.02 m | 145.7 | 13-10-20 | 168.5 | 15-01-31 | 22.8 |
| **Plateau** | D1 0.65 m | -17.6 | 13-10-02 | 7.7 | 13-06-29 | 25.3 |
| | D2 1.2 m | -3.2 | 14-08-16 | 11.8 | 15-05-04 | 15 |
| | D3 5 m | 36.3 | 13-10-07 | 50.5 | 15-06-02 | 14.2 |
| **Crest** | C1 0.99 m | -12.2 | 14-08-16 | 14.4 | 14-11-04 | 26.6 |
| | C2 5 m | 15.3 | 13-10-07 | 30.8 | 15-09-05 | 15.5 |
| | Ä2-3 37.43 m | 326 | 13-09-28 | 331.3 | 15-03-02 | 5.3 |
| | Ä3-1 49 m | 462 | 13-10-22 | 477.6 | 15-02-01 | 15.6 |
| **Middle** | B1 0.82 m | -11.8 (-26.1) | 13-08-15 (13-09-17) | 6.1 | 14-02-09 | 17.9 (32.2) |
| | B2 1.25 m | -6.5 | 13-10-07 | 9.9 | 13-12-12 | 16.4 |
| | B3 5.01 m | 30.5 | 13-10-07 | 42 | 13-12-25 | 11.5 |
| **Toe** | A1 0.69 m | -20.3 (-66.3) | 13-07-11 (13-08-04) | 7.5 | 13-11-04 | 27.8 (73.8) |
| | A2 1.49 m | -12,8 (-32.9) | 14-07-20 (13-08-21) | 6.5 | 15-12-06 | 19.3 (39.4) |
| | A3 5.04 m | 24.5 | 13-10-07 | 39.9 | 15-12-08 | 15.4 |

## 5.2 Results from Linnarhult

The twenty-seven piezometers in Linnarhult were installed in December 2014 and January 2015. All piezometers have been logging values every 3$^{rd}$ hour during the measurement period which ended in the summer of 2016. For many of the piezometers there have been problems with the loggers, batteries etc. during shorter or longer periods. Due to heavy rainfall with high water levels in the Lärje River the piezometers installed at the toe of Slope 2 and in the river were flooded in November 2015 and could not be used after that. In general it has been more problems with the measurements in Linnarhult than in Äsperöd even though the measurement period was much shorter.

### 5.2.1 Precipitation in Linnarhult

The rainfall measurements used for the Linnarhult area were done by the City of Gothenburg[3]. The precipitation gauge is situated in Bergsjön, 2.5 km from Linnarhult. In Figure 5-23 the accumulated monthly rainfall from January 2015 – June 2016 is shown. It can be seen that the amount of rain is smallest in October 2015 and May 2016 with less than 20 mm per month and largest in January, November and December 2015 with more than 150 mm rain per month. For March and April 2016 the values distributed by the City of Gothenburg were erroneous, and supplementary values from the Swedish Meteorological Institute[4] were used instead. Their measurements were taken in the city center of Gothenburg. According to Alexandersson & Eggertsson Karlström (2001) the typical precipitation for the area is 758 mm/year and the rainiest months are normally October or November with a normal value of 83 mm/month.

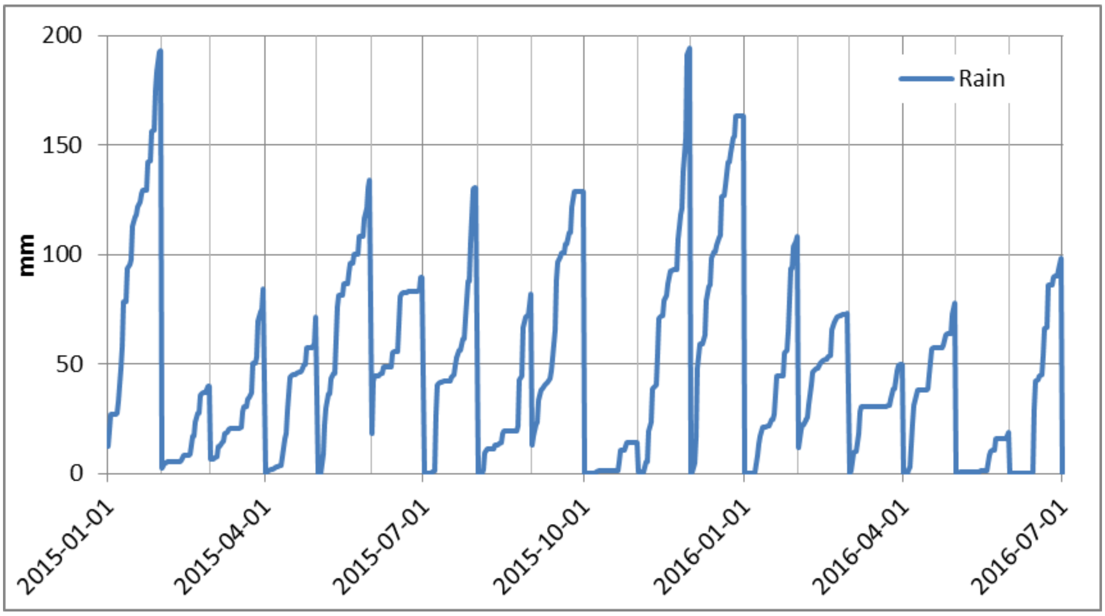


*Figure 5-23. Rainfall in Linnarhult January 2015- June 2016.*

[3] Information received from City of Gothenburg, Kretslopp och vatten, via e-mail during 2015 and 2016.

[4] http://opendata-download-metobs.smhi.se/explore/

### 5.2.2 Linnarhult, Slope 1 Station Crest

In the station at the crest of Slope 1, four piezometers were installed at 0.5-10 meters depth. The two shallowest ones, at 0.5 and 1 meter depth, have a good covariation indicating hydrostatical conditions in the uppermost part of the soil profile, see Figure 5-24. The values recorded for the piezometer at 0.5 meters depth in January- March 2016 seem a bit strange with a groundwater level half a meter closer to the ground compared to the same months 2015, since the values are questionable they were disregarded from further analyze. The piezometer at 5 meters depth does covariate well with the two more shallow ones but with a slower response and smother shape, which is natural due to the dampening effects from the soil etc. The deepest installed piezometer, at 10 meters depth, is drifting during the entire measurement period and does not show any trustworthy values at all and is therefore disregarded.

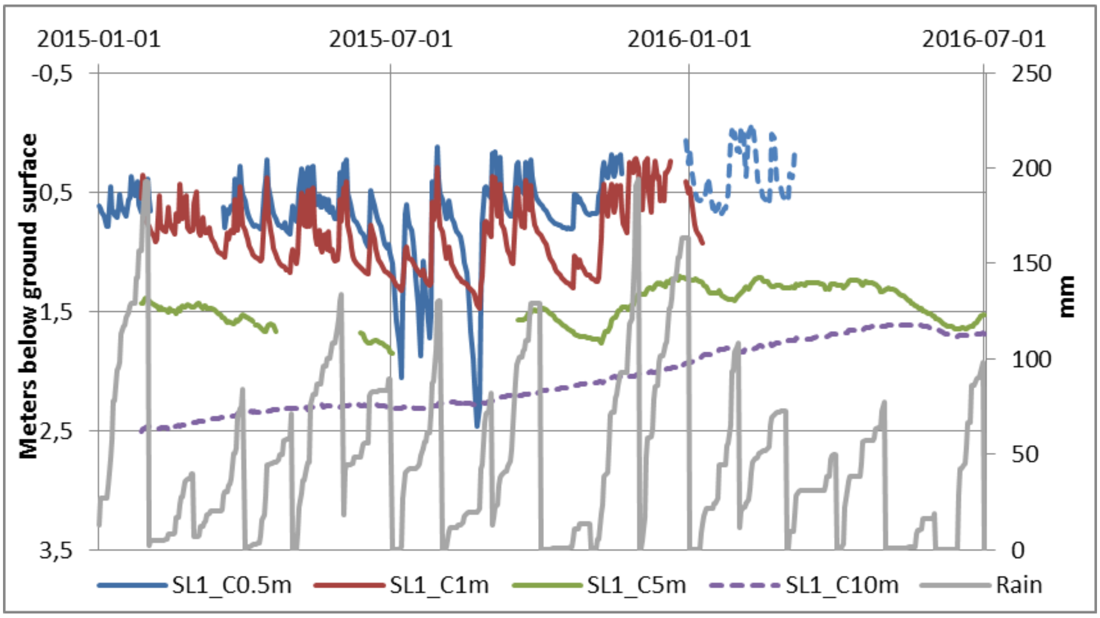


*Figure 5-24. Pore pressure readings and precipitation in Linnarhult Slope 1 Station Crest January 2015- June 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profiles in Figure 5-25a indicate larger variations in the two shallow piezometers, at 0.5 and 1 meters depth, than in the one at 5 meters depth. The groundwater level is situated 0-1.5 meter below the ground surface and the pressure distribution indicates hydrostatical pressures between the piezometers at 1 and 5 meters depth for periods with low pore pressure values, see Figure 5-25b. For wetter periods a slight downward gradient and a higher groundwater level is indicated.

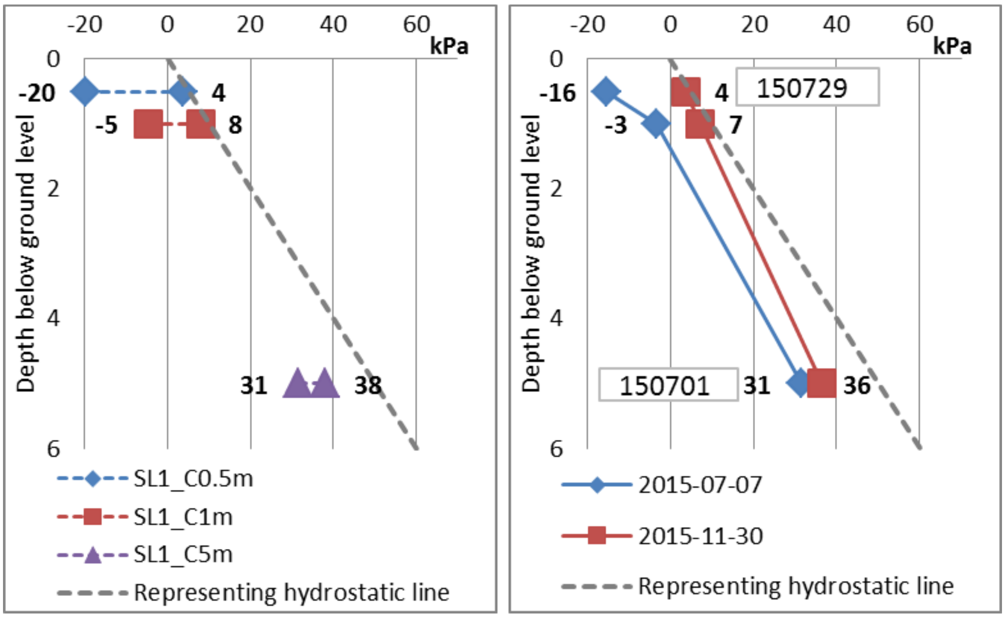


*Figure 5-25 **a)** Pore pressure variations in each piezometer in Linnarhult Slope 1 Station Crest and **b)** Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 1 Station Crest.*

### 5.2.3 Linnarhult, Slope 1 Station Middle

In the middle of Slope 1, three piezometers were installed, at 0.5-6 meters depth, and their results correlates very well for most of the measurement period, see Figure 5-26. The curves for the two shallowest installed piezometers, at 0.5 and 1.4 meters, are almost identical during February to November 2015 indicating a hydrostatical pore pressure profile. Values are missing for the piezometer at 1.4 meters for the last weeks of 2015, probably due to battery problems. When the logging starts again in December 30 2015 it shows a groundwater level some decimeters higher than before the interruption and also higher than the same period one year earlier and these values are disregarded from further analyze. The same difference cannot be seen in the piezometers at 0.5 or 6 meters depth, but in the shallowest one at the crest (see Figure 5-24). The piezometer installed at the greatest depth, 6 meters, indicates artesian values with a groundwater level 0- 0.5 meters above the ground level from the start until May 2016. Then something happens with this piezometer and the measured values suddenly drop for no obvious reason, those values are therefore disregarded.

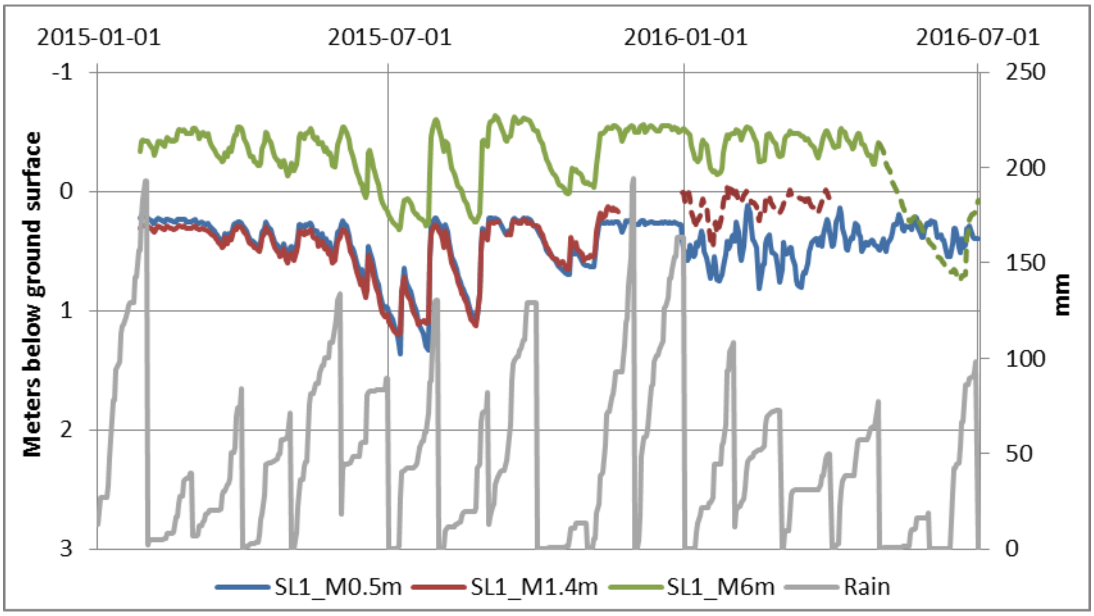


*Figure 5-26. Pore pressure readings and precipitation in Linnarhult Slope 1 Station Middle January 2015- June 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

For the station in the middle of Slope 1 the pore pressure amplitudes are in the same range for the three piezometers, see Figure 5-27a. The pore pressure distribution towards depth, Figure 5-27b, shows a hydrostatical distribution with the groundwater level 0-1m below ground level for the two uppermost piezometers. Towards depth there is a slight artesian value for the deepest installed piezometer at 6 meters.

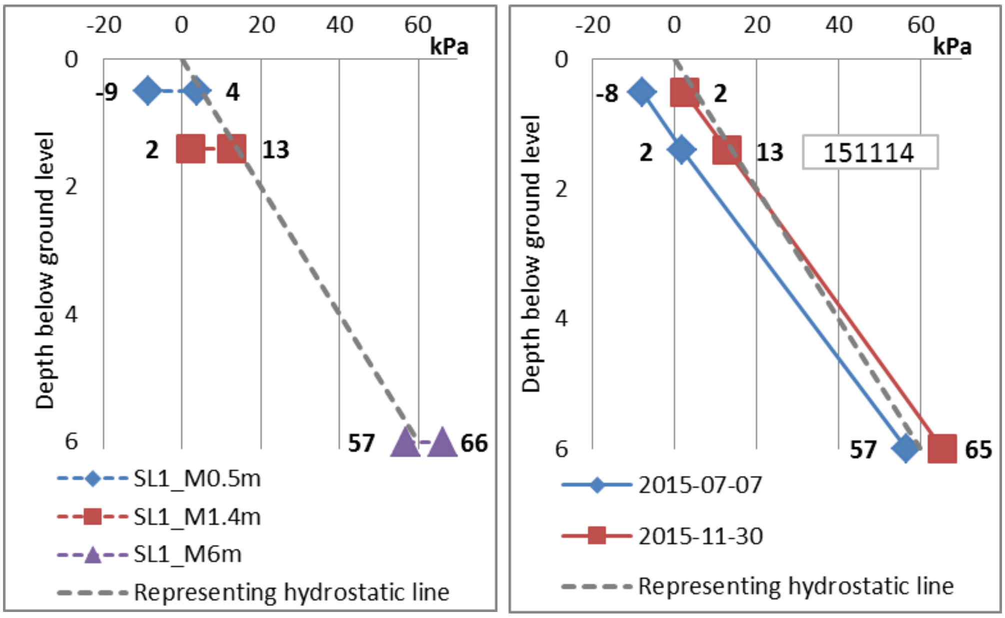


*Figure 5-27* ***a)*** *Pore pressure variations in each piezometer in Linnarhult Slope 1 Station Middle and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 1 Station Middle.*

## 5.2.4 Linnarhult, Slope 1 Station Toe

In the station at the toe of Slope 1 in Linnarhult two piezometers were installed at 1.3 and 5 meters depth. The shallow one was situated above the estimated mean water level in the Lärje River. At first glance the two piezometers seem to covariate well from the installation until late in July 2015, see Figure 5-28, even though the amplitudes differed. The one at 1.3 meters depth however show negative values (groundwater level deeper than the installation depth of the piezometer) which are not trustworthy. This can be concluded when studying the variation with time, which is very small, in spite of the heavy rain. In July 29 2015 the measures for the piezometer at 1.3 meters suddenly increases without any obvious reason and shows a groundwater level corresponding to the installation level (approx. 0 kPa pore pressure) and stays so for 4 months. Finally the period, December 2015- August 2016, has reasonable amplitudes and positive measurement values (groundwater level higher than the installation depth of piezometer), so this is the only period with trustworthy pore pressure measurements in this piezometer, even though it during the period is some shorter periods with measurements around 0 kPa again.

The piezometer installed at 5 meters depth below ground seems to correlate well to precipitation events. The heavy rain in late November 2015 can be viewed as a quick and large change in the groundwater level. Due to problems with the batteries in the logger no values were registered after February 10 2016 so there is just a short period with accurate measurements in both piezometers in this station at the same time.

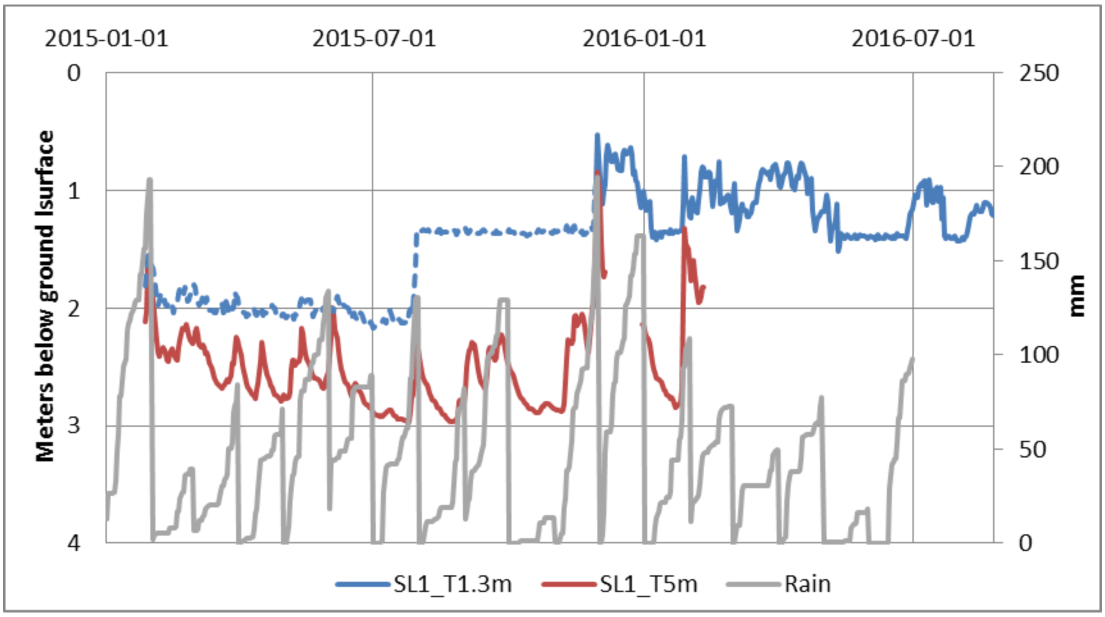


*Figure 5-28. Pore pressure readings and precipitation in Linnarhult Slope 1 Station Toe January 2015- August 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profile for the station at the Toe of Slope 1, Figure 5-29, indicates a groundwater level 0.5-1.5 meters below ground level. For periods with high pore pressure levels, the distribution towards depth is hydrostatic. For periods with dryer conditions, the pore pressure distribution is lower than hydrostatic towards depth.

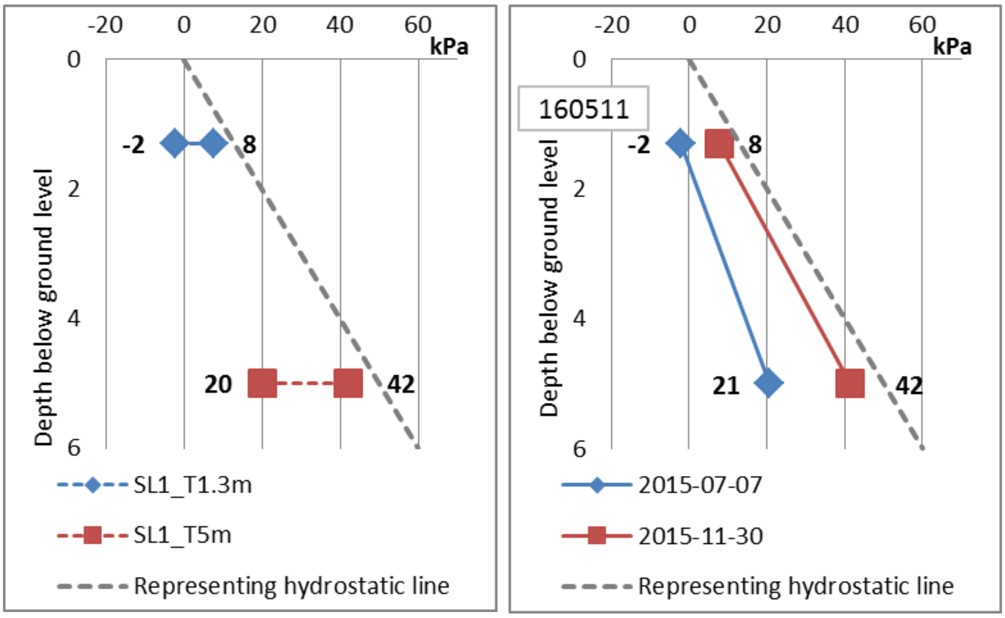


*Figure 5-29 **a)** Pore pressure variations in each piezometer in Linnarhult Slope 1 Station Toe and **b)** Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 1 Station Toe.*

### 5.2.5 Pore pressure regime for Linnarhult Slope 1

In Figure 5-30 the values for one day representing a period with high pore pressure values, 2015-11-30, for all stations in Slope 1 are shown. At that day the groundwater level was situated at or close to the ground surface at all three stations. Since the level of the water surface in the Lärje river was not monitored at all times, the level is somewhat uncertain. Thus, for the end of November 2015 it is known that there were heavy rains with very high levels in the river as a consequence. It is also known that some of the ground next to the river was flooded due to this rain so the water level in the river was at least as high as the bank of the river, around +20- +21 meters, at that time.

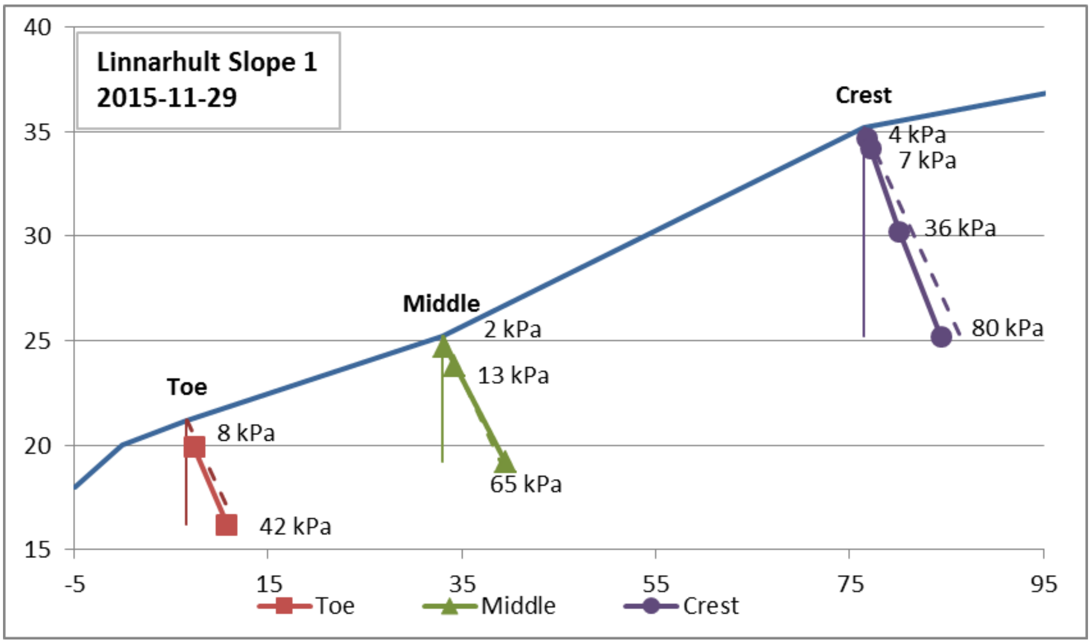


*Figure 5-30. Pore pressure profile for Slope 1 in Linnarhult, date representing high values, 2015-11-29. Nb! Different scale at x- and y-axis!*

The situation for a date with a low groundwater level, 2015-07-07, is shown in Figure 5-31. It can be seen that the pore pressures in the station at the crest and in the middle of the slope is situated around 1.1-1.3 meters below the ground. Also for the station at the toe of the slope the groundwater level is around 1 meter below the ground surface. The water level in the Lärje River is not measured for this date but is expected to be low and situated at around +19 meters.

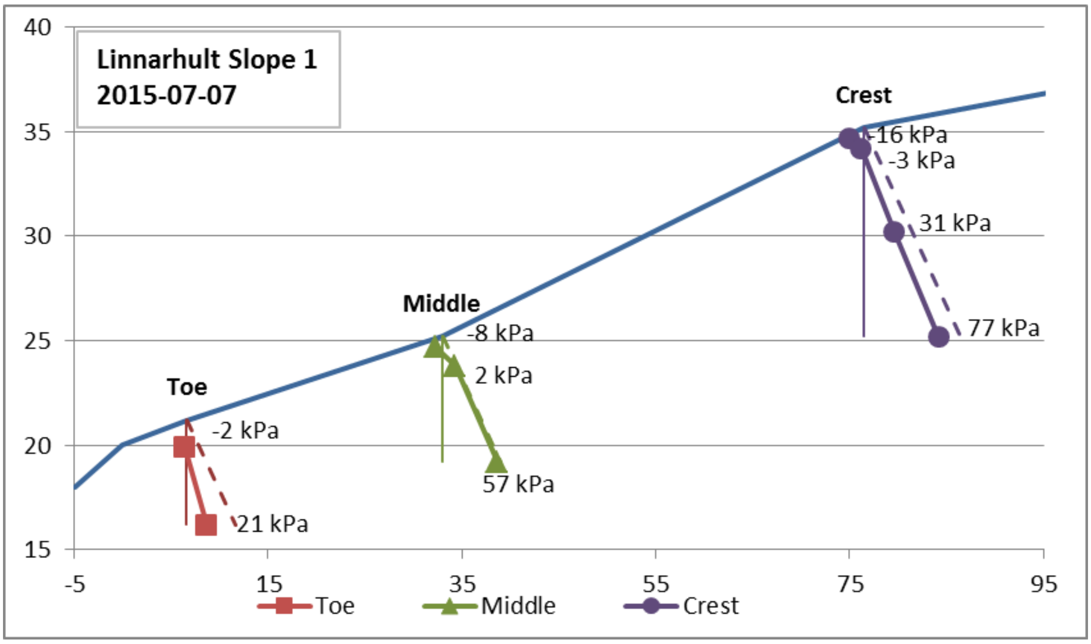


*Figure 5-31. Pore pressure profile for Slope 1 in Linnarhult, date representing low values, 2015-07-07. Nb! Different scale at x- and y-axis!*

### 5.2.6 Linnarhult, Slope 2 Station Plateau

In Linnarhult Slope 2 the station called Plateau is placed 15 meters behind the crest of the slope and five piezometers were installed there at 0.5-15 meters depth. There is a layer of sand at approx. 9-11 meters depth dividing the clay into two aquitards. In Figure 5-32 the fluctuation in readings from the piezometers at this station are shown. It can be seen that the two deepest installed piezometers showed unrealistic values at first but then settled at reasonable values after 1-3 weeks. The reason for those values is probably related to the effect of the installation.

The three shallower piezometers at 0.5, 1.5 and 4.5 meters depth have a good covariation from the installation until late November 2015. After the heavy rain event November 29 the piezometer at 4.5 meters depth shows artesian values for 4 months, which differs from the other piezometers. Since nothing similar happens in the other piezometers the pore pressures in the piezometer at 4.5 meters depth are disregarded after November 27 2015.

The piezometer at 7 meters depth has smaller amplitude than the more shallow installed piezometers but varies in a similar pattern. The deepest installed piezometer, at 15 meters depth, is installed in the middle of the lower clay layer (aquitard 2), some meters from both the layer of silt (at 9-11 meters depth) and from the friction material in the bottom (at around 28 meters depth). It is therefore natural that the pore pressure shows small variations and slow response to precipitation. Anyhow, at some occasions it looks like the pore pressure responds almost instantly to heavy precipitation events when looking in a detailed scale. The groundwater level indicated by the piezometer at 15 meters depth is situated 1.5-2.5 meters deeper than for the other piezometers.

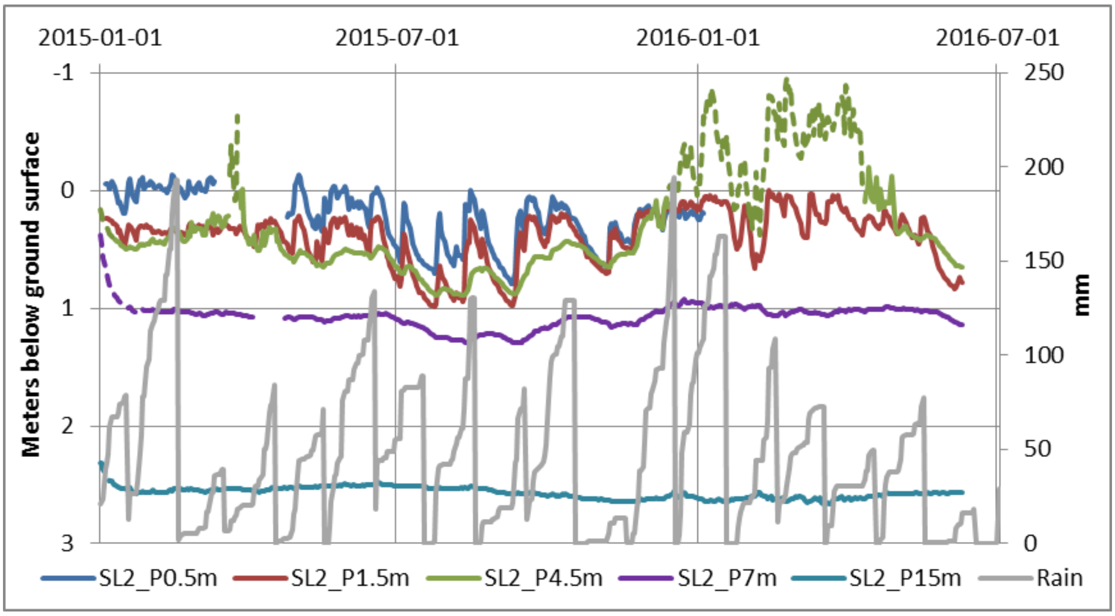


*Figure 5-32. Pore pressure readings and precipitation in Linnarhult Slope 2 Station Plateau January 2015- May 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profile for the station at the plateau indicates a hydrostatic pore pressure situation for the uppermost 4.5 meters followed by a downward gradient in the two deepest piezometers, see Figure 5-33 and Figure 5-34. There is a "drop" in the pore pressures between the piezometers at 4.5 and 7 meters depth. The pore pressure distribution in the sand layer at 9-11 meters depth is most likely hydrostatic. This implies that the pressure between the piezometers at 7 and 15 meters depth are not evenly distributed and that the piezometer at 7 meters depth is affected from below by the sand layer, see Figure 5-35. The sand might have draining capacity at some times and it will increase the pore pressures in its vicinities at other times depending on the attributes at the rims of the profile.

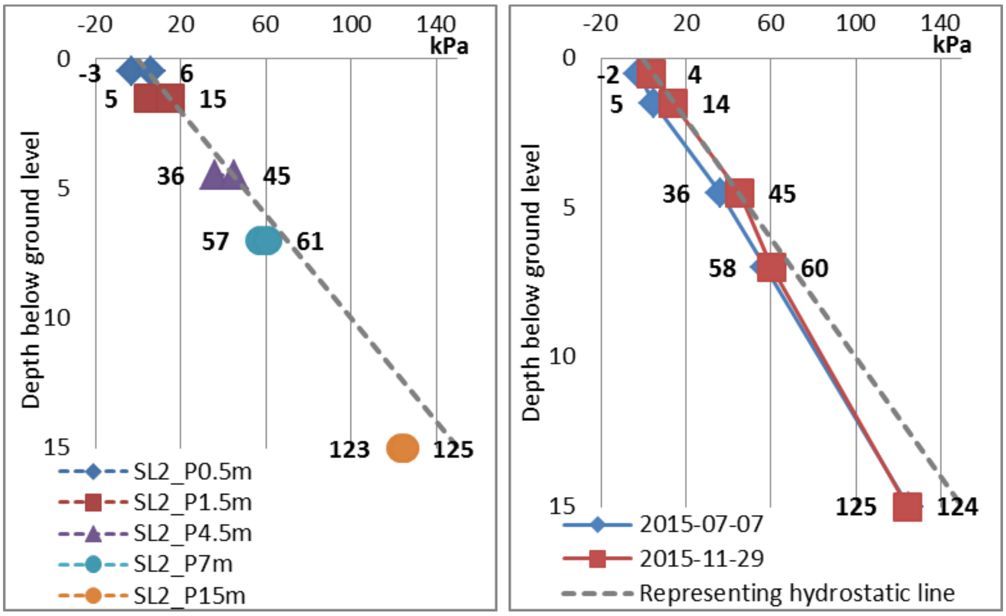


*Figure 5-33* ***a)*** *Pore pressure variations in each piezometer in Linnarhult Slope 2 Station Plateau and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Plateau.*

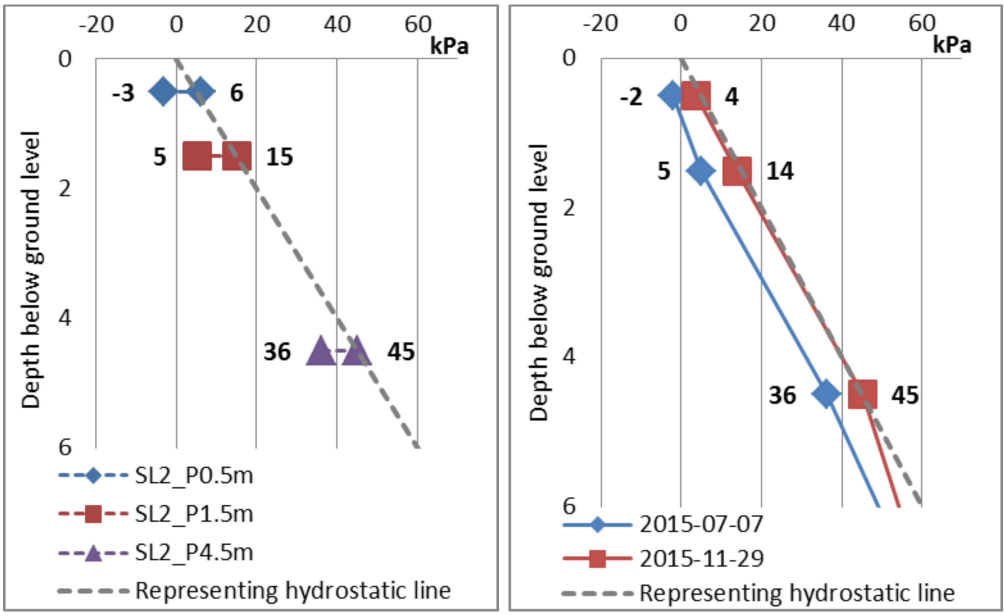


*Figure 5-34* ***a)*** *Pore pressure variations the uppermost 6 meters in Linnarhult Slope 2 Station Plateau and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Plateau, the uppermost 6 meters.*

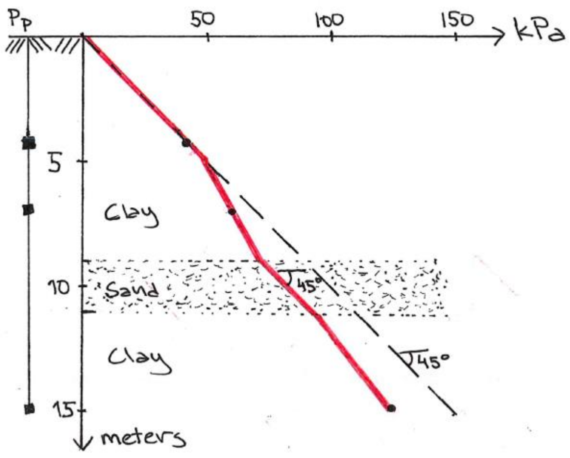


*Figure 5-35. The red line represents the possible pore pressure distribution in clay divided into two aquifers by a layer of sand.*

## 5.2.7 Linnarhult, Slope 2 Station Crest

Five piezometers were installed in the station at the crest of Slope 2 between 1-12 meters depth below ground. The layer of sand present in the station at the plateau is at the crest situated at approx. 7-9 meters depth according to the CPT-soundings, and divides the clay into two aquitards. The piezometers at 1 and 4 meters depth correlate well, except for the first 2 months where the one at 4 meters indicates a low groundwater level drifting upwards, see Figure 5-36, which is probably related to the installation. There are also strange values for the piezometer at 2 meters depth the first months but it seems to work well between March and August 2015. After that the piezometer shows a higher and higher groundwater level so values should be excluded due to drifting. Also the piezometer at 6.5 meters depth behaves strange the first months but from mid-March 2015 it looks stable. It is installed just above the layer of sand and is therefore affected by the pore pressure situation there which can be seen as a lower ground water level indicated by this piezometer than in the ones further up in the profile. The deepest installed piezometer in the station, at 12 meters depth, seems to have a moderate response to precipitation in spite of it being situated in the clay and some meters below the water bearing sand layer.

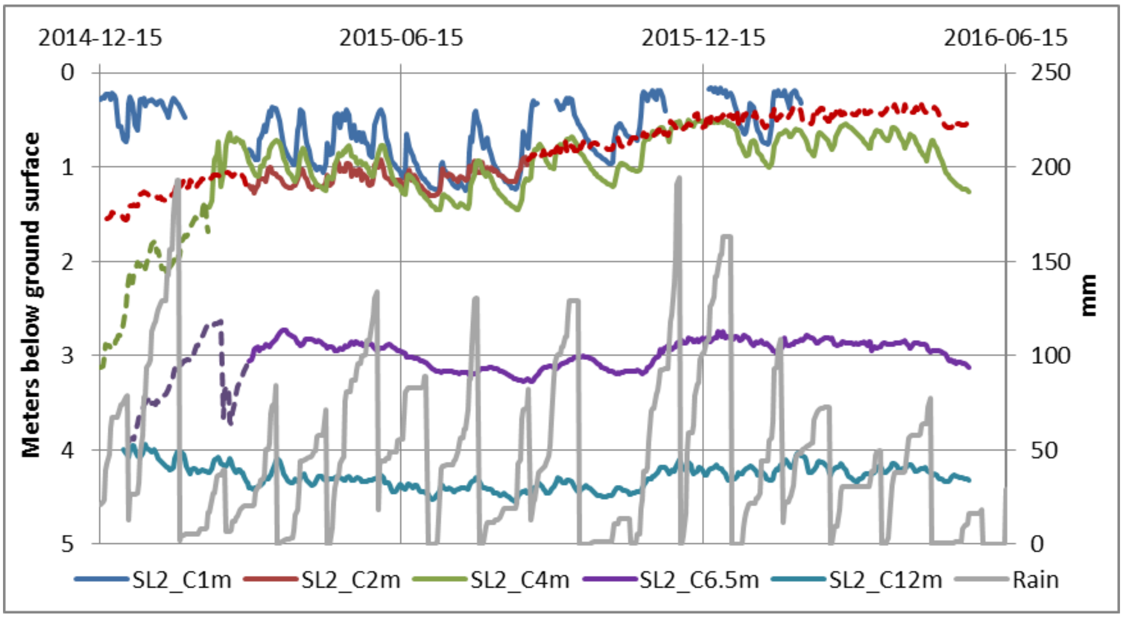


*Figure 5-36. Pore pressure readings and precipitation in Linnarhult Slope 2 Station Crest December 2015- May 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profile for the station at the crest shows almost hydrostatical values for the three uppermost piezometers, indicating a groundwater level 0-1 meter below ground, Figure 5-37 and Figure 5-38. Between the piezometers at 4 and 6.5 meters the pore pressure profile is nearly vertical, this is due to the influence of the sand layer (at 7-9 meters depth) as explained in Subsection 5.2.6. According to observations done at field visits, there might also be some outflow of water into the slope near the crest which will contribute to the lowering of the pore pressure at those depths. The pressure distribution indicates a downward gradient for the piezometer at 12 meters depth.

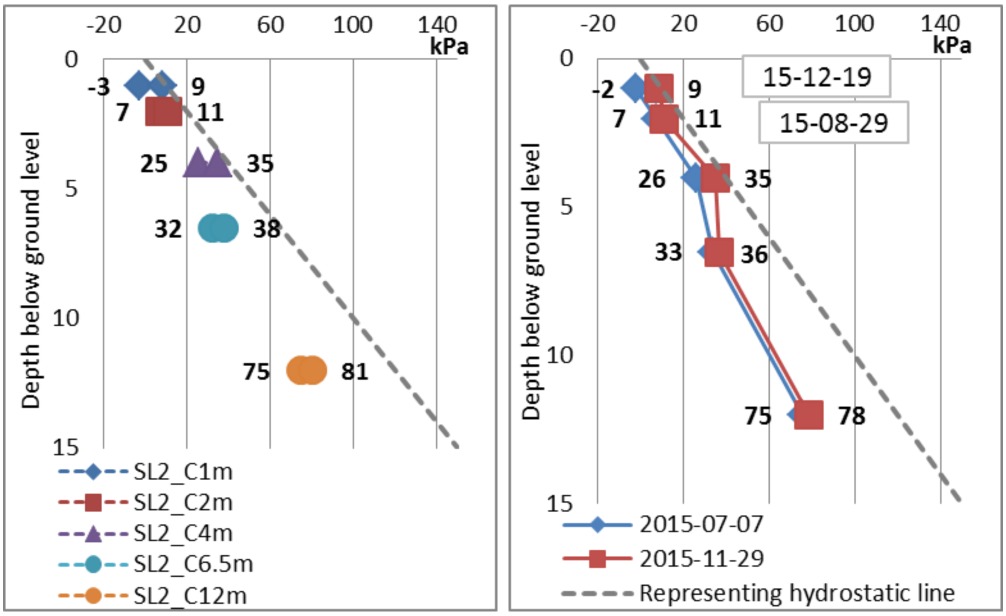


*Figure 5-37* ***a)*** *Pore pressure variations in each piezometer in Linnarhult Slope 2 Station Crest and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Crest.*

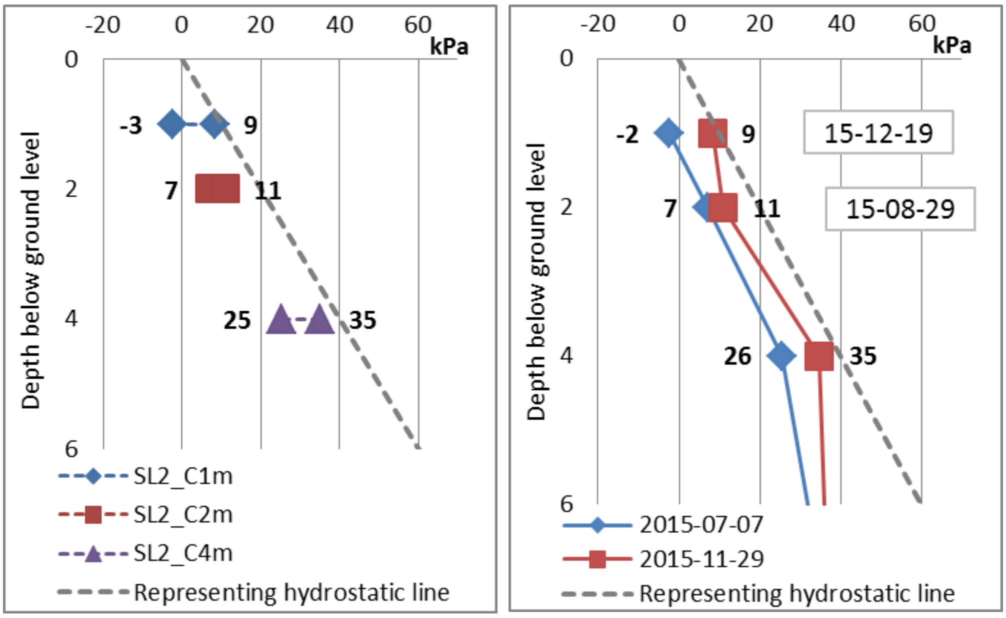


*Figure 5-38* ***a)*** *Pore pressure variations the uppermost 6 meters in Linnarhult Slope 2 Station Crest and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Crest, the uppermost 6 meters.*

### 5.2.8 Linnarhult, Slope 2 Station Middle

In the station at the middle of Slope 2 three piezometers were installed at 2.7-7 meters depth and they covariate well, see Figure 5-39. There is a layer of sand approx. 4-6 meters below ground, which is just below the middle piezometer and above the deepest one. For unknown reasons, according to the field technicians, the loggers in the piezometers at 2.7 and 7 meters depth did not work after they were emptied December 18 2015 and no pore pressure values were recorded after that. The piezometer at 4 meters depth does indicate a higher groundwater level compared to the other two piezometers October 2015 but no values are disregarded.

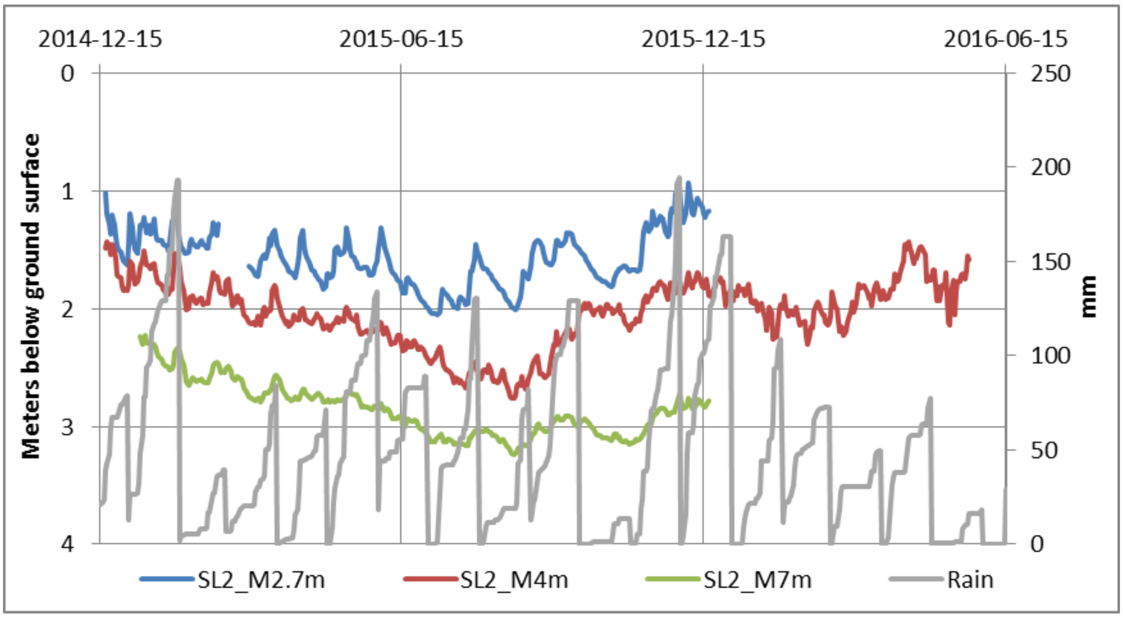


*Figure 5-39. Pore pressure readings and precipitation in Linnarhult Slope 2 Station Middle December 2015- May 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

For the station in the middle of Slope 2, the pore pressure profile shows a pressure distribution lower than hydrostatic towards depth, see Figure 5-40. The groundwater level in this station is situated 0-2 meters below the ground surface. The layer of sand at 4-6 meters depth below ground level influences the pressure distribution between the piezometers at 4 and 7 meters depth the same way as explained in station Plateau and Crest above. There is likely influence from surface runoff to the piezometers, and the ground water level might not be able to reach as high due to that compared to the stations installed at flatter parts of the slope.

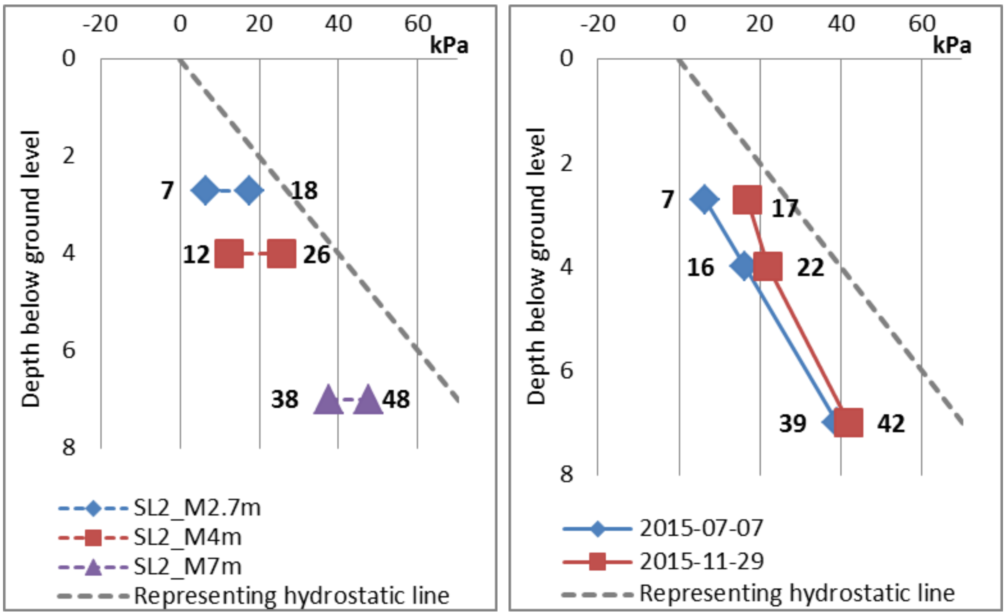


*Figure 5-40* ***a)*** *Pore pressure variations in each piezometer in Linnarhult Slope 2 Station Middle and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Middle.*

### 5.2.9 Linnarhult, Slope 2 Station Toe

In the station at the toe of Slope 2, four piezometers were installed between 1.75-19 meters depth. The deepest installed piezometer is installed just above the layer of friction material (approx. 2 meters thick) on top of the bedrock. The station is placed about 12 meters behind the shore of the Lärje River and the shallowest piezometer is installed at a level just above the estimated mean water level in the river. The layer of sand present in the stations further back in this slope is not present at the toe of the slope, since this station is situated at a lower level. However, it seems as if some coarser material is present under the dry crust according to the CPT-soundings and the shallowest piezometer at 1.75 meters depth is situated just under this layer.

In Figure 5-41 the fluctuation for all the piezometers in the station can be seen. The two deepest installed piezometers in the station have a good covariation and both of them show artesian values corresponding to around 2.2 and 5.5 meters higher than the ground level respectively. It looks like they both might drift a bit, but it is hard to assess since the measurement period ended abrupt due to the flooding in the end of November 2015. Due to the flood, two of the piezometers, at 1.75 meters and 19 meters depth, lost values measured before the flood, and none of them functioned after that, so no more values were recorded after that event.

In Figure 5-42 the two shallowest installed piezometers at 1.75 and 4.75 meters depth are shown in more detail. There it can be seen that they do not vary with really the same pattern and that the one at 4.75 meters indicates a groundwater level slightly closer to the ground level compared to the one at 1.75 meters. The amplitudes in those two piezometers are smaller compared to the corresponding piezometers in the toe at Slope 1, possibly due to the layer of friction material on top of the clay here.

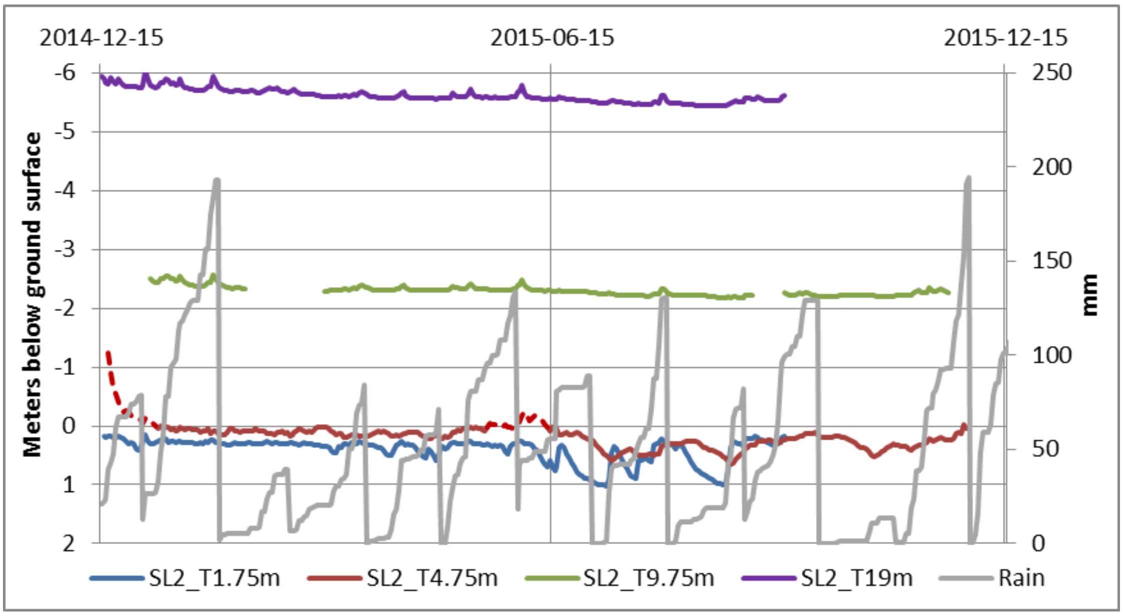


*Figure 5-41. Pore pressure readings and precipitation in Linnarhult Slope 2 Station Toe December 2015- December 2016. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

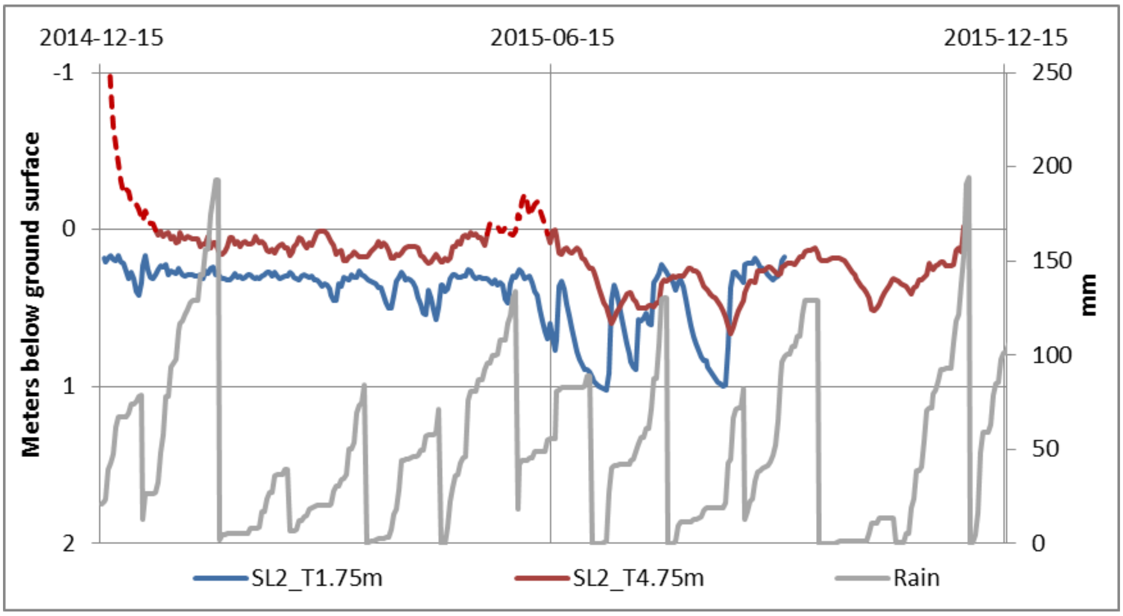


*Figure 5-42. Pore pressure readings and precipitation in Linnarhult Slope 2 Station Toe December 2015- December 2016, detailed figure of piezometers installed <5 meters below ground level. Values expected to be "true" are shown as solid lines in the diagram and values that are disregarded are shown as dotted lines.*

The pore pressure profile for the station at the toe of the slope, see Figure 5-43 and Figure 5-44, shows hydrostatical values in the uppermost 5 meters and artesian values in the piezometers at larger depths. The groundwater level is situated 0-1 meter below ground level.

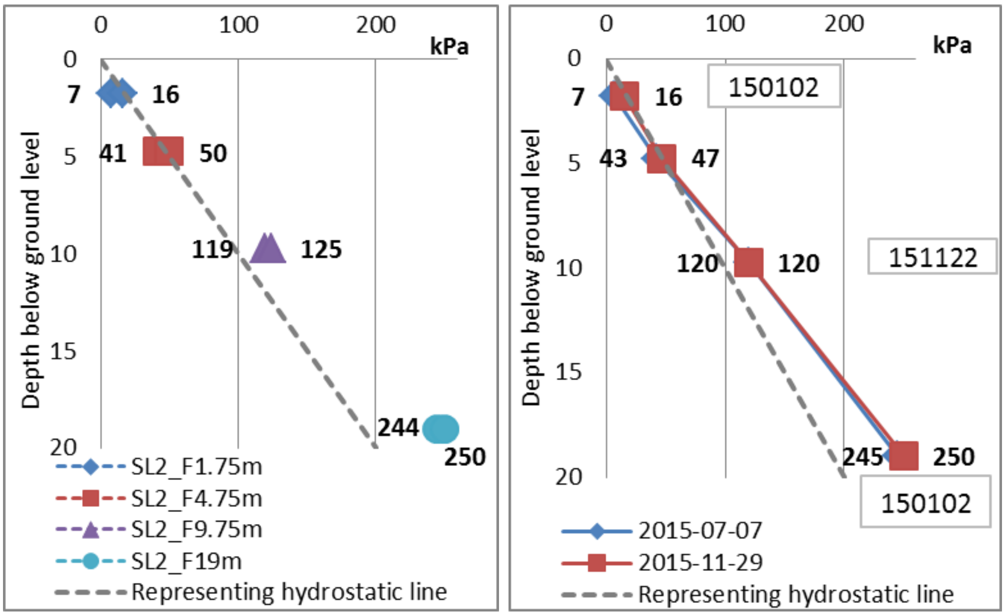


*Figure 5-43* ***a)*** *Pore pressure variations in each piezometer in Linnarhult Slope 2 Station Toe and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Toe.*

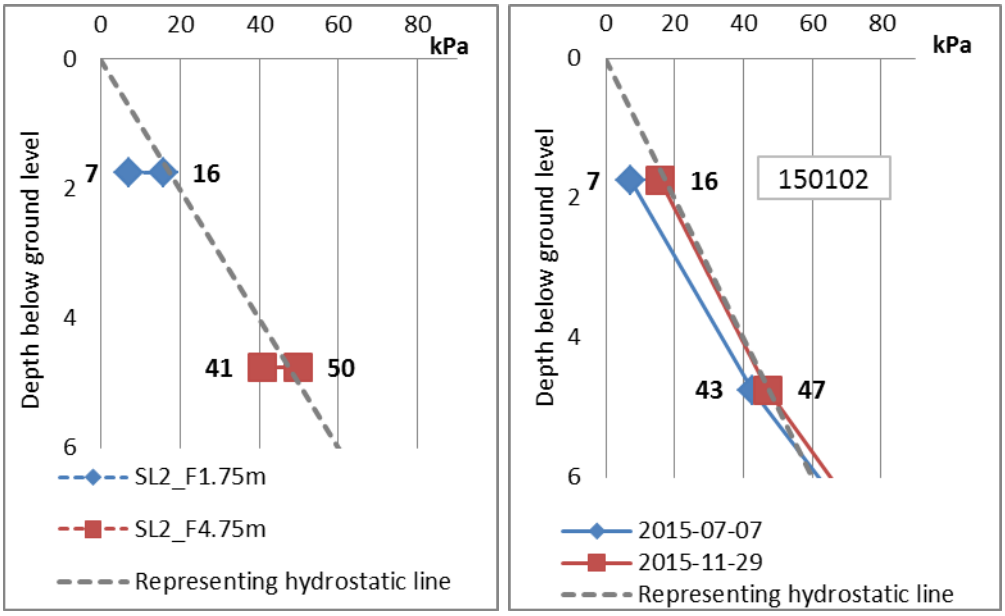


*Figure 5-44* ***a)*** *Pore pressure variations the uppermost 6 meters in Linnarhult Slope 2 Station Toe and* ***b)*** *Pore pressure profile for two dates representing high and low pore pressure values at Linnarhult Slope 2 Station Toe, the uppermost 6 meters.*

### 5.2.10 Pore pressure regime for Linnarhult Slope 2

In Figure 5-45 a profile of Slope 2 representative for a date with high pore pressure values, 2015-11-29, is shown. The groundwater level at that day is situated in or just below the ground surface in all stations at the slope. As mentioned in Subsection 5.2.5 the water level in the Lärje River was very high at this time, most probably at least at +21 meters.

The firm lines in the figure represent a pore pressure distribution corresponding to the split pressure profile, presented in Subsection 2.6, with hydrostatical pore pressure distribution at 0 to 5 meters below ground level. Below this the pore pressure change is expected to be evenly distributed down to the sand layer. In the layer of sand the pore pressures are assumed to be hydrostatical, and that pore pressure distribution also continues in the clay further down. For station Middle the distribution is not as clear as in the other stations, possibly related to influence from surface runoff etc.

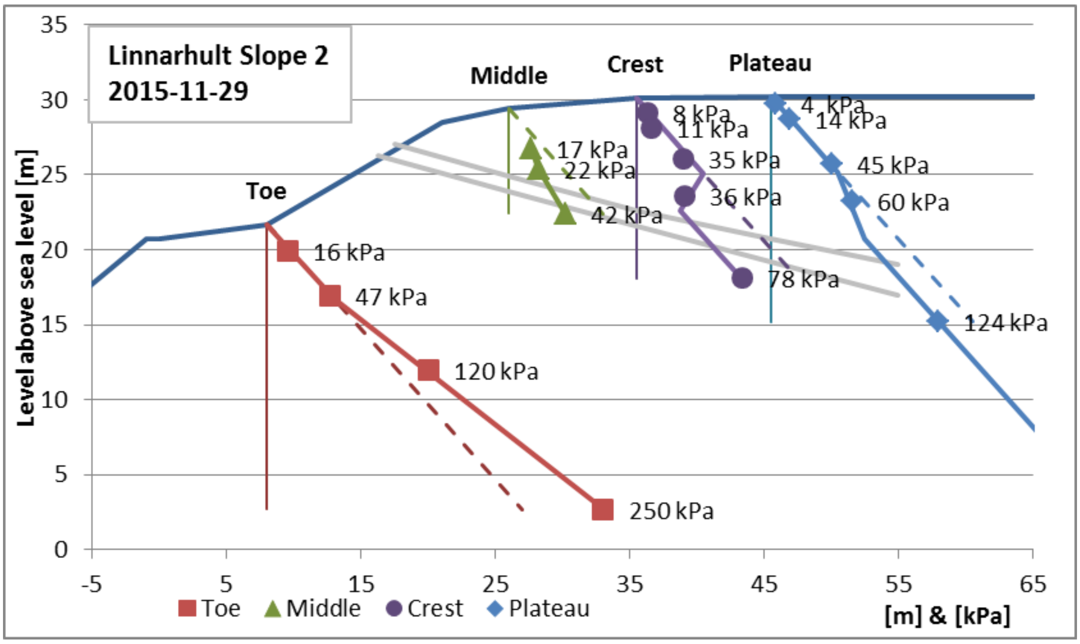


*Figure 5-45. Pore pressure profile for Slope 2 in Linnarhult, date representing high values, 2015-11-29. Nb! Different scale at x- and y-axis!*

For the situation with low pore pressure values in the slope, from 2015-07-07, a profile is shown in Figure 5-46. Also here are the lines representing the split pressure profile. It can be seen that the measured values indicates a groundwater level situated around 1 meter below the ground surface in the stations at the plateau and at the crest. In the middle of the slope it has dropped to around 2.5 meters below the ground surface. At the toe of the slope the groundwater level is situated less than 1 meter below ground. The same problems with determining the pressure distribution consist for station middle during those conditions as for the high values. The water level in the Lärje River is not known for this date but is expected to be low and situated at around +19 meters.

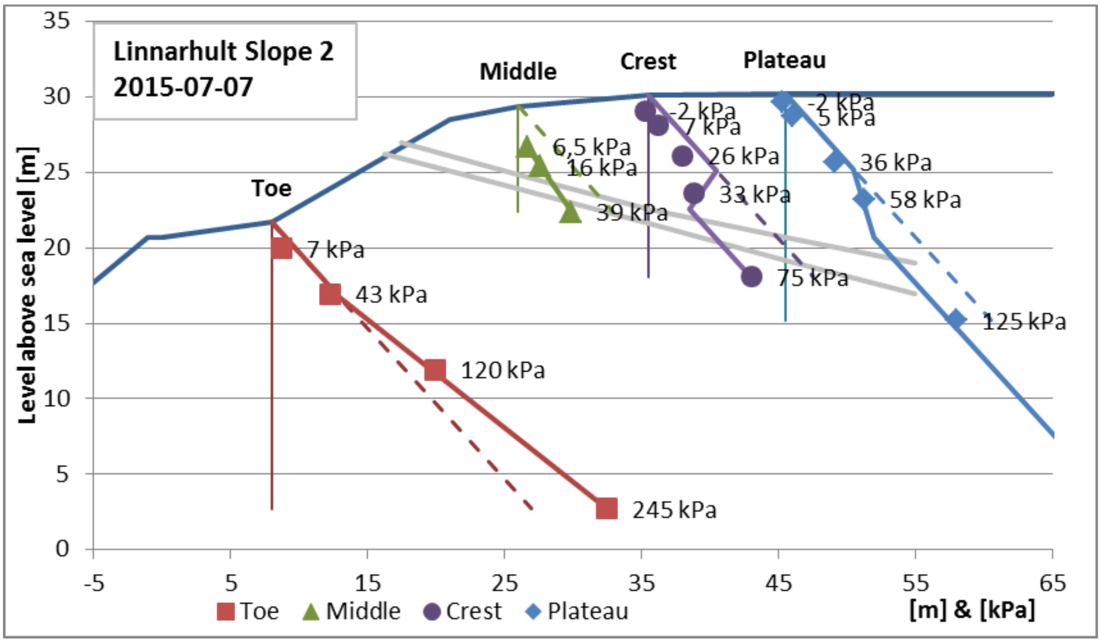


*Figure 5-46. Pore pressure profile for Slope 2 in Linnarhult, date representing low values, 2015-07-07. Nb! Different scale at x- and y-axis!*

### 5.2.11 Water level in Lärje River

The Lärje River is unregulated and the water level is not measured on a regular basis. In this study an attempt was done to monitor the water level with a piezometer installed in the river in Slope 2. The piezometer were placed at the bottom of the river close to the shore, see Figure 5-47. Unfortunately the exact installation level of the piezometer is not known but it can anyhow be concluded that the level in the river vary a lot over the year. The measured total head varies between +0.6- +3.4 meters from the installation depth with a mean value of +1.0 meter for the period January-June and October- December 2015, see Table 5-4. As seen in Figure 5-48 the measured water level in the river fluctuates very much with the rain (each bar in the diagram represents one day).

*Figure 5-47. Piezometer installed in Lärje River, the blue box contains the logger.*

*Table 5-4. Water level variation in Lärje River, January- December 2015.*

| | **Meters above installation depth** |
|---|---|
| **Mean** | + 1.04 |
| **Max** | + 3.41 |
| **Min** | + 0.57 |

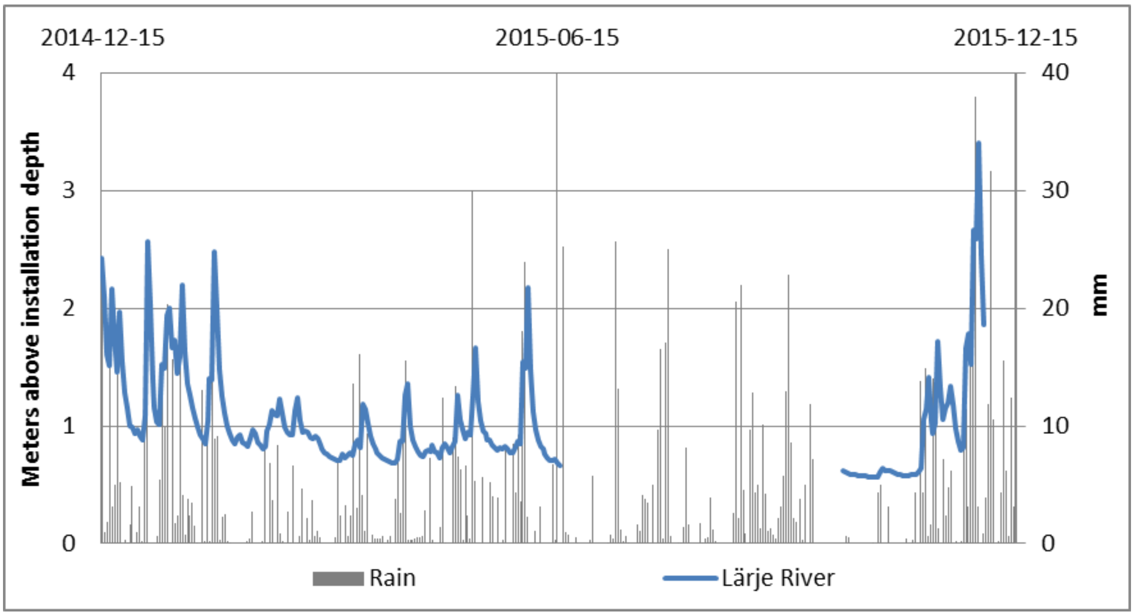


*Figure 5-48. Water level in the Lärje River and rain, December 2014- December 2015.*

### 5.2.12 Yearly pore pressure fluctuations in Linnarhult

The yearly pore pressure variations for the two slopes in Linnarhult are analyzed. Since the total measurement period is just around 1.5 years and there have been problems with many of the piezometers and loggers comparisons for longer periods could not be performed. Only eight of the piezometers in Linnarhult have continuous measurement periods longer than 3 months for the same months both in 2015 and 2016. Attempts to evaluate the yearly fluctuations were despite this done. In general it is harder to see the expected yearly variations (high pore pressure values during the winter and low values during late summer/ autumn) in Linnarhult than it was for Äsperöd. It can thus be seen that the piezometers at small depths (<5 meters) in general show a quicker response to precipitation events than the ones at larger depths (>5 meters), see example in Figure 5-49 and Figure 5-50.

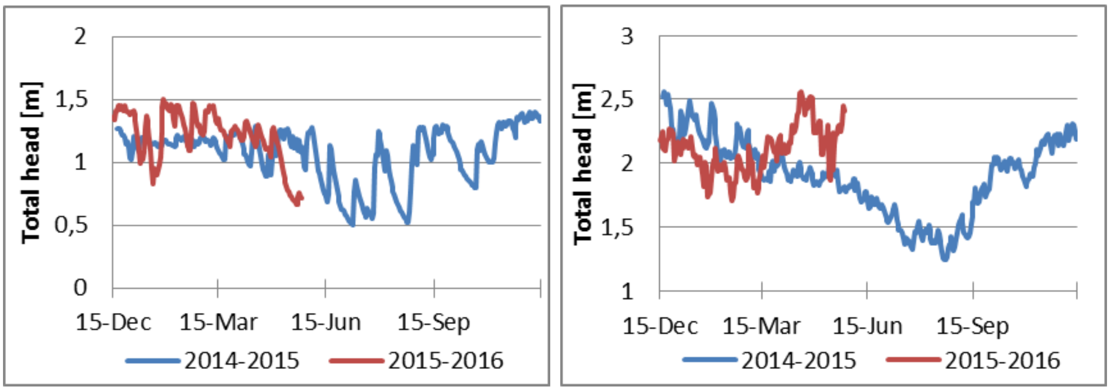


*Figure 5-49 Example of variation pattern in piezometers at small depth (<5 meters)* ***a)*** *Linnarhult Slope 2 Station Plateau 1.5 meters and* ***b)*** *Linnarhult Slope 2 Station Middle 4 meters.*

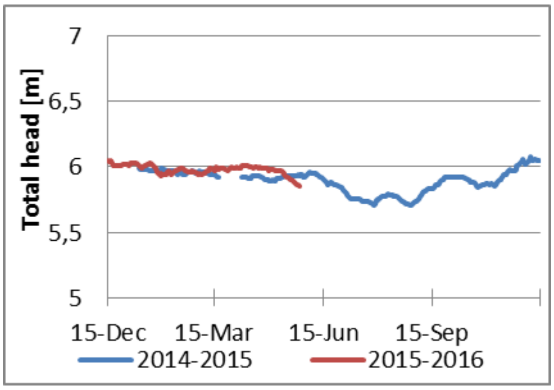


*Figure 5-50. Example of variation pattern in piezometers at larger depth (>5 meters) Linnarhult Slope 2 Station Plateau 7 meters.*

The amplitudes between the highest and lowest measured pore pressure values in the piezometers vary, see Table 5-5 and Table 5-6. For the piezometers installed at 0-5 meters below ground surface the amplitude is around 4-24 kPa (0.4-2.4 meters) and for the deeper ones the amplitude is smaller, around 2-10 kPa (0.2-1 meter). When studying differences between Slope 1 and Slope 2 it could be seen that the amplitudes are slightly higher for the piezometers installed at shallow depths in Slope 1 compared to Slope 2.

*Table 5-5. Minimum and maximum values and corresponding dates for piezometers in Linnarhult Slope 1, 2015- 2016.*

| | **Installation depth [m]** | **Min value [kPa]** | **Date min value** | **Max value [kPa]** | **Date max value** | **Amplitude [kPa]** |
|---|---|---|---|---|---|---|
| **Slope 1 Crest** | 0.5 m | -19.7 | 15-08-23 | 3.8 | 15-07-29 | 23.5 |
| | 1 m | -4.8 | 15-08-24 | 7.9 | 15-12-06 | 12.7 |
| | 5m | 31.4 | 15-07-01 | 37.9 | 15-12-26 | 6.5 |
| **Slope 1 Middle** | 0.5 m | -8.7 | 15-17-18 | 3.9 | 15-02-09 | 12.6 |
| | 1.4 m | 2 | 15-07-08 | 12.7 | 15-11-17 | 10.7 |
| | 6 m | 56.8 | 15-07-07 | 66.4 | 15-09-05 | 9.6 |
| **Slope 1 Toe** | 1.3 m | -2.2 | 16-05-11 | 7.7 | 15-11-30 | 9.9 |
| | 5 m | 20 | 15-07-24 | 42 | 15-11-30 | 22 |

*Table 5-6. Minimum and maximum values and corresponding dates for piezometers in Linnarhult Slope 2, 2015- 2016.*

| | **Installation depth [meters]** | **Min value [kPa]** | **Date min value** | **Max value [kPa]** | **Date max value** | **Amplitude [kPa]** |
|---|---|---|---|---|---|---|
| **Slope 2 Plateau** | 0.5 m | -3 | 15-08-27 | 6.3 | 15-01-28 | 9.3 |
| | 1.5 m | 5.1 | 15-07-07 | 15 | 16-01-27 | 9.9 |
| | 4.5 m | 36.1 | 15-07-25 | 45.2 | 15-11-29 | 9.1 |
| | 7 m | 57 | 15-08-28 | 60.8 | 15-12-06 | 3.8 |
| | 15 m | 123.4 | 16-02-29 | 125.2 | 15-06-03 | 1.8 |
| **Slope 2 Crest** | 1 m | -2.5 | 15-07-24 | 8.5 | 15-12-19 | 11 |
| | 2 m | 7 | 15-07-03 | 11 | 15-08-29 | 4 |
| | 4 m | 25.4 | 15-07-08 | 35 | 15-12-06 | 9.6 |
| | 6.5 m | 32.2 | 15-09-02 | 37.7 | 15-04-04 | 5.5 |
| | 12 m | 74.5 | 15-08-23 | 80.6 | 15-01-11 | 6.1 |
| **Slope 2 Middle** | 2.7 m | 6.5 | 12-07-07 | 17.6 | 15-12-06 | 11.1 |
| | 4 m | 12.4 | 15-08-22 | 25.6 | 16-04-17 | 13.2 |
| | 7 m | 37.7 | 15-08-22 | 47.7 | 15-01-11 | 10 |
| **Slope 2 Toe** | 1.75 m | 7.3 | 15-07-07 | 15.9 | 15-01-02 | 8.6 |
| | 4.75 m | 40.9 | 15-08-26 | 49.8 | 15-06-04 | 8.9 |
| | 9.75 m | 119.2 | 15-08-26 | 124.5 | 15-01-02 | 5.3 |
| | 19 m | 422.4 | 15-08-19 | 250.2 | 15-01-02 | 5.8 |

# 6. SIMULATIONS- RESULTS AND ANALYSIS

As described in earlier chapters, the pore pressure distribution is part of the data needed for modeling the stability of a slope. A question of great importance, also connected to future climate changes, is uncertainties on how the stability will change due to a heavy rainfall. Therefore it would be beneficial to be able to model seepage, using a software, in order to predict the changes in pore pressures occurring in the upper part of the slope when subjected to heavy rain. Here two classes of simulations are dealt with, 1-dimensional and 2-dimensional. There is also software available for 3-dimensional analyses, but then more data are needed than available within this study. Therefore 3-dimensional analyses are not included in this thesis.

## 6.1 Types of predictions depending on available information

When trying to predict the pore pressure situation in a slope, the available information can vary in type and quantity. The goal with the simulation is thus often the same: to achieve a better knowledge about the pore pressure situation in the slope. Depending on the available information three different types of predictions can be identified.

A Type A prediction of the pore pressure situation implies that basically only soil data is available, including the stratigraphy and the permeability of the different soil layers. Apart from that the boundary conditions, such as the groundwater pressure in the bottom layer or aquifer is needed for the simulation, along with the prevailing pore pressure conditions at the far left and far right boundaries. The pore pressures predicted by the simulation, including also infiltration from rain, would then be a true Type A prediction.

Rarely is so much information available that a Type A prediction can be made with any high degree of confidence. A Type B prediction could then, apart from available soil data, include some measurements of pore pressures. The hydraulic data for the soil (e.g. permeability) are then adjusted so that the model will generate the given pore pressure regime. Based on this modified soil data, the prediction of pore pressures for other boundary conditions and/ or precipitation cases could then be classified as a Type B prediction.

Also a Type B prediction requires a fair amount of information, and often there are anomalies in the soil hard to detect, which can influence the results to a great extent. A more pragmatic approach could be to use the adjusted hydraulic data available for a given situation, in combination with measured pore pressures, only to predict the pore pressures in the areas where there are no measurements available. This would be a Type C prediction. The model obtained could then be used for the prediction of a slightly different scenario, where the boundary conditions and pore pressures are only marginally changed or adjusted to represent a future design situation. Thereby a set of design pore pressures would be obtained.

## 6.2 1-dimensional finite difference analysis

Simulation of pore pressure changes for the 1-dimensional case requires knowledge of the variation of the permeability ($k$) as well as the variation of the modulus ($M$) with depth. Also the boundary conditions, the change in groundwater pressure in the lower confined aquifer as well as in the upper open aquifer with time, must be known or assumed. Then the change of the total pore pressure profile with time can be calculated. Berntson (1983) developed and used a program called POR-82 for handling pore pressure changes for 1-dimensional cases, but no version of that program is available today.

For this study the focus is natural changes in slightly overconsolidated clays, and thereby problems related to settlements are not included. Here the constraint modulus ($M$) during loading and unloading in the overconsolidated state is of great importance. When the modulus is high, moderate changes at the boundaries will affect the rest of the profile very quickly as the resulting strains are small, and thus also the volume of water which shall flow is extremely small.

In a soil with constant permeability with depth in the entire profile, the pore pressure distribution is evenly distributed between the lower limit of the upper open aquifer and the upper limit of the lower aquifer. Most real cases are, however, not that simple and soil with different permeability's are often present within the same profile. In more permeable layers the pore pressure changes will occur faster than in parts with lower permeability. Often a hydrostatical pressure distribution will then be present in layers with friction material such as sand. As seen in Figure 2-8 the more permeable layers may affect the pore pressure distribution above and below the actual layer.

## 6.3 2-dimensional finite element analysis

The need for input data for a 2-dimensional analysis is the same as for the 1-dimensional state but with the addition of the relation between the permeability in the horizontal and vertical directions, and the boundary conditions at the right and left borders of the model.

A number of 2-dimensional seepage simulations were made within this study primarily using the software SEEP/W. This program is very potent and can handle different types of boundary conditions, saturated and unsaturated flow, layers with different permeability and also different permeability in the horizontal and vertical directions. Furthermore, the code can account for rain and how it will affect the pore pressure change throughout the soil profile, depending on the intensity of the rain. Simulations have been performed for a fictive test slope and for the slope in Äsperöd.

### 6.3.1 Fictive test slope

To achieve a better understanding of how pore pressures were handled in SEEP/W and how the program handles boundary conditions, the first step in the simulation process was to model a comparatively simple fictive test slope. This slope had a simple geometry and the same clay material in the entire slope. Analytical solutions are available for such a problem and it can also be solved by means of sketching a flow net. A simple flow net indicates that the groundwater level should be horizontal from the boundary at the right hand side of the model and from that form a smooth transition below the crest of the slope and connect to the free water surface. This has earlier been described by Harr (1991). The simulations with the computer codes were initially performed for Steady state conditions, which mean that no time dependent processes were included.

In Figure 6-1 the geometry of the fictive test slope can be seen. The inclination of the slope is 1:3 and applied boundary conditions are a free water surface (lake, river etc.) with 2 meters depth at the left hand side. At the boundary at the right hand side hydrostatic pore pressures from 1 meters depth below the ground surface (Head= 6 meter) were assumed. The pressure at the bottom of the profile is constant along the whole boundary (Pressure head = 31 meter) which results in an artesian pressure distribution at the left hand side (under the lake/ river). In the inclining part of the slope a boundary condition called Potential seepage face review (with Total flux= 0 $m^3/s$) is applied to avoid ponding on the surface. The material properties used in the analysis were chosen to represent typical conditions for western Sweden. Originally the soil model *Saturated only* was chosen with: Saturated x-conductivity=$10^{-9}$ m/s and $K'_y/K'_x$= 1 (the same hydraulic conductivity in x- and y-directions), Saturated volumetric water content= 0.3 $m^3/m^3$ and the Coefficient of volume compressibility $m_v=1/M$= 0.001/kPa.

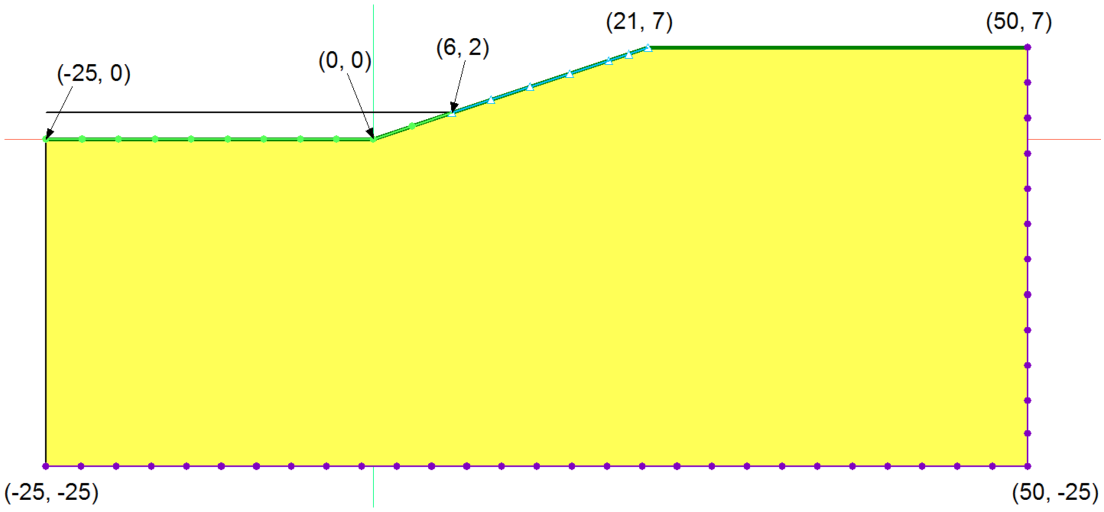


*Figure 6-1. Geometry and coordinates of the fictive slope.*

The result from the first simulation with SEEP/W did not give reasonable results, instead the simulation resulted in a groundwater level that was almost a straight line, see Figure 6-2. This means that the result from the simulation imply lower pore pressures in the upper part of the slope than a traditional flow net would indicate.

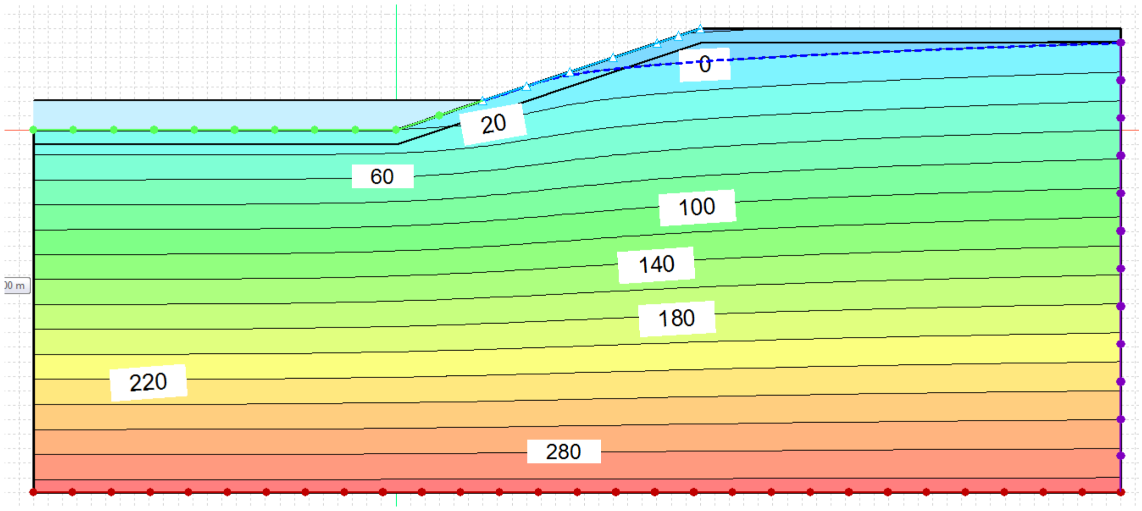


*Figure 6-2. Result SEEP/W simulation 1. Material model: "Saturated only", clay with permeability $k=10^{-9}$.*

The SEEP/W Support team[5] suggested adjustment of the input data by applying a small amount of precipitation, around 1 % of the daily mean precipitation, on the ground surface at all times. When this was applied in a model with the same soil properties as in the former simulation the result gave a somewhat higher groundwater level at the right hand side of the model but almost no change around the crest, see Figure 6-3. Applying precipitation like this does not seem like a very good alternative since it is hard to estimate the intensity.

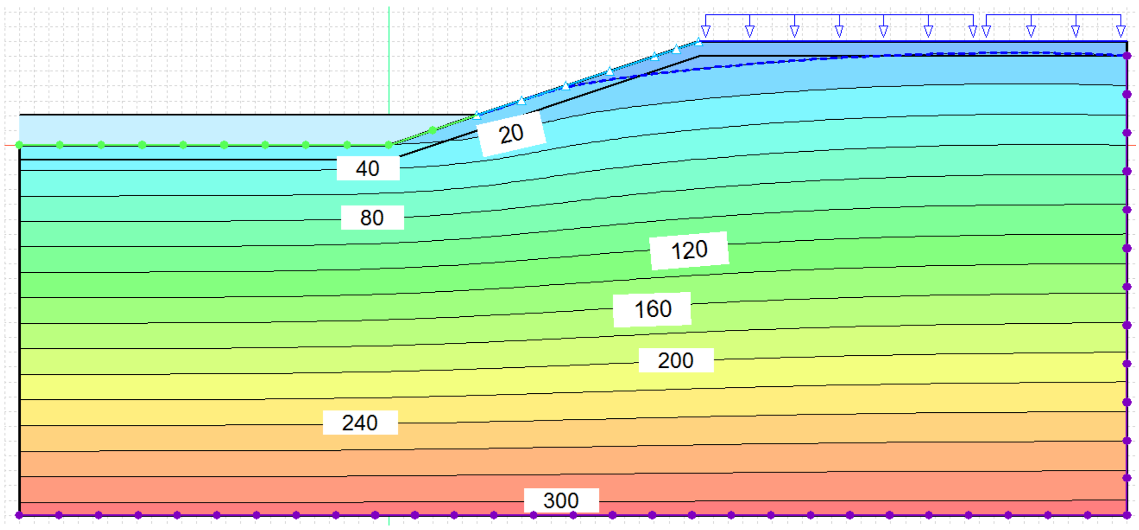


*Figure 6-3. Result SEEP/W simulation 2. Same input parameters as in simulation 1 but with an added precipitation $q=5 \cdot 10^{-11}$ m/s.*

[5] Information received from GEO-SLOPE Support via e-mail during May 2016.

To check the result from the SEEP/W simulation a complimentary simulation was done with the software MODFLOW[6]. The same geometry and soil parameters as in the SEEP/W simulations were used but no precipitation. The result given by MODFLOW did comply much better with the expectations, see Figure 6-4.

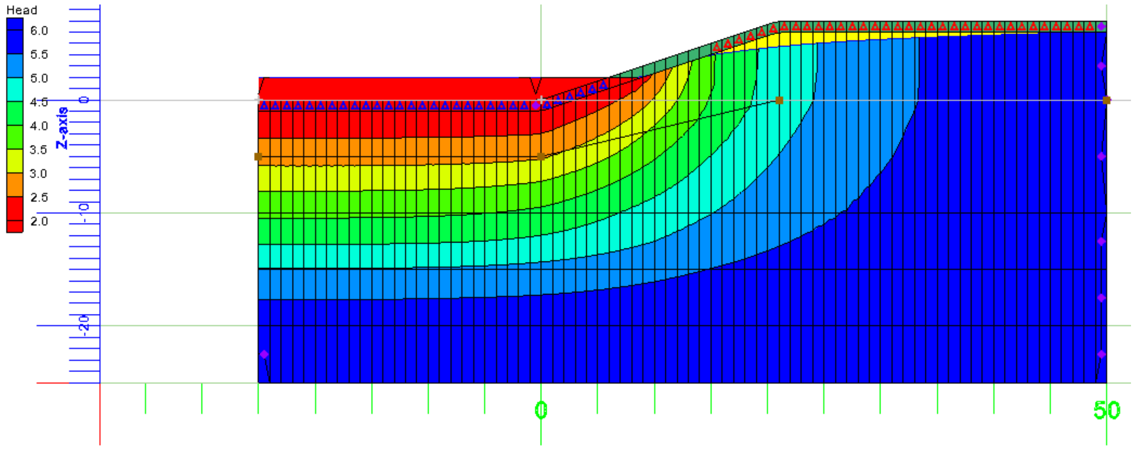


*Figure 6-4. Result MODFLOW simulation.*

The SEEP/W model was then updated again and a different soil model, called *Saturated/ unsaturated*, was now used. This model is more advanced than *Saturated only* and demands more knowledge about the soil properties since more parameters are used e.g. curves for the ”Hydraulic conductivity function” and ”Volumetric water content function”. There are some example curves provided in SEEP/W but some parameters are added by the user. The results with *Saturated/ unsaturated* complied much better with the expected results and the MODFLOW analysis compared to the *Saturated only* simulations, see Figure 6-5. A conclusion from this is that *Saturated only* is a too simple model for this problem and *Saturated/ unsaturated* should be used instead.

[6] Personal communication with Jonas Sundell, Chalmers University of Technology, November 2016.

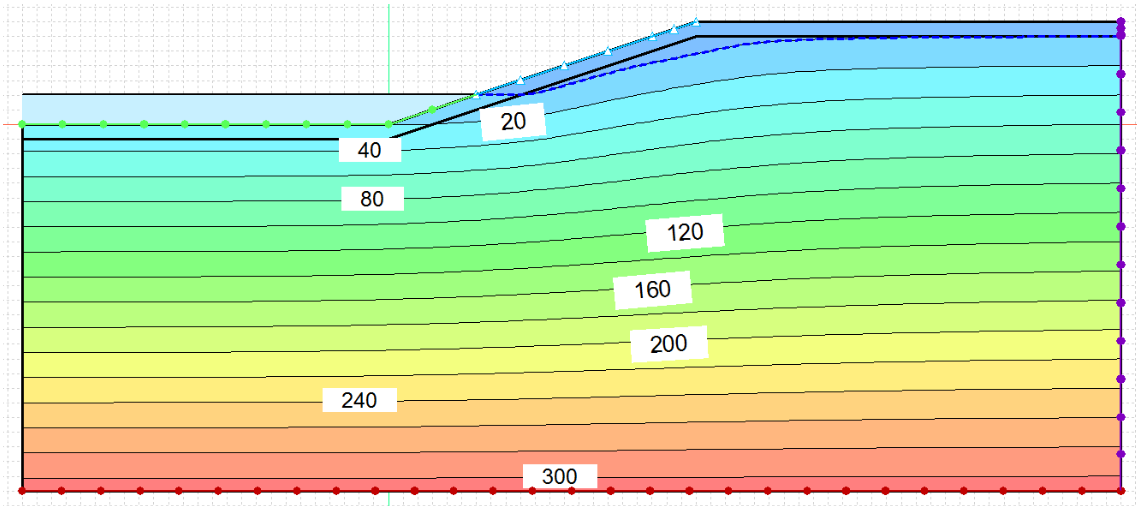


*Figure 6-5. Result SEEP/W simulation 3. Material model: Saturated/ unsaturated.*

### 6.3.2 Äsperöd

After the initial simulations of the fictive test slope the next step was to model one of the test sites in the study and Äsperöd was chosen. The geometry and the soil profile were fairly well known, although the values for the permeability were known only at a limited number of discrete points. After preparing the SEEP/W model with the geometry and soil parameters, the intention was to use pore pressure data for a given date as start values and then add the real precipitation for e.g. the next month and end up with simulated pore pressure values which then could be compared with the measured values. When the simulation is performed as a *Steady state analysis* the initial pore pressures are added to the model as boundary conditions and in a *Transient analysis* the pore pressures are added as a Spatial function. The precipitation for the chosen time span is then added as a time dependent boundary condition, where the precipitation can be different for different hours or days. The results from different time steps of the simulation and for different parts of the slope can be extracted from the SEEP/W simulation and exported to e.g. Microsoft Excel for further data handling and evaluation.

Before the simulation with an added real precipitation could be performed for the slope in Äsperöd, several simulations were made to find the stationary solution using rather stable measured pore pressures along the boundaries. The real challenge was to find a plausible pore pressure distribution for the entire slope, based on results from only a limited number of piezometer measurements. The problem was further complicated by the fact that values for the permeability were only available for a number of CRS-tests, which in turn did not capture the macro structure of the soil.

From observations it is known that the uppermost five meters of the soil profile usually show a hydrostatic pore pressure distribution, but with a ground water table varying with the intensity of rainfall. It is also known that even limited anomalies can have a great influence on the pore pressures in the soil profile. Given these difficulties, still a large number of simulations have been performed where a wide variety in the span of the parameters have been tested. The results are, however, somewhat discouraging. It is possible to obtain pore pressure profiles from simulations that are rather similar to those measured for a given time, when systematically altering the permeability. However, the set of parameters, mainly permeability as a function of space, is necessarily not reflecting values which were obtained in the laboratory. Furthermore, when using that set of parameters for a different time series, including rainfall etc. it did not necessarily give reasonable results. The general trend might be reasonable, but not the actual values.

As earlier presented by Blomén (2016), a simulation was done in order to simulate the pore pressure situation in the Äsperöd area in April 2013. The simulation consisted of a steady state analysis for the conditions April 1 followed by a transient analysis for the rest of the month. The rainfall during the period was included as a hydraulic boundary condition. Results from the simulation were evaluated for two of the stations in the slope, the toe and behind the crest, and the values were compared with the measured values from the site. In general, the results from the simulation gave a larger reaction of the pore pressures to the rainfall than the measurements did. This might depend on the dry crust and clay being simulated as *Saturated only* at that time, which is a simplification of the reality. The agreement between the measured values and the simulated ones is better for the station behind the crest than for the toe of the slope.

### 6.3.3 Linnarhult

The pore pressure situations in the two slopes in Linnarhult were not modelled in SEEP/W during this study. The main reasons for this were that the sloping layer of clayey sand in Linnarhult did complicate the simulation, and since the results from Äsperöd with less complicated soil profile did not show satisfying results, it was not likely to get satisfying results for Linnarhult either. Another complication was that the variation of the pore pressure in the clayey sand layer was not known, except for in a very limited number of points.

## 6.4 Conclusions

A number of simulations have been done in order to investigate how the pore pressure regime in a slope can be predicted. Unfortunately it does not seem possible, based on only laboratory test results and knowledge of the soil profile and stratigraphy, to predict the pore pressure distribution with any degree of accuracy, especially not for the upper part of the soil profile.

The performed simulations for a fictive test slope revealed that SEEP/W gave most realistic results when using the *Saturated/ Unsaturated* material model compared with the material model *Saturated only*. It was also obvious that the face elements of the slope should be assigned as Potential seepage face to simulate realistic pore water pressures along the part of the slope where seepage may be occurring, otherwise unreasonably large pore pressures would be obtained for the surface elements. A lot of input data is needed in order to simulate a given slope in a satisfying way. The permeability in the clay may vary with depth and in different directions and it is difficult to get comprehensive values of it from field and/ or laboratory tests. Element testing in the laboratory results in values representative for a small sample and the field test methods for determining the permeability will not always give representative values.

However, SEEP/W can be used as a tool to increase the understanding of the hydraulic properties of a slope, provided that extensive measurements of the pore pressures in the slope are available along with laboratory measurements of the permeability and knowledge about the soil profile. But, as mentioned above, SEEP/W cannot be used as a tool for prediction of the pore pressure in the entire slope, based on limited measurements of pore pressures along with laboratory test results. Results will be obtained, but not to the degree of accuracy normally required. It is, therefore, concluded that probably the only reasonable way of predicting the pore pressures in the upper say 10 meters of soil in a clay slope is to base it on a combination of earlier experience and empiricism, the understanding gained through the measurements performed within this study, and earlier observations, complemented with measurements in the slope at hand.

A simplified procedure for estimating the pore pressures in the upper 10 meters of a clay slope would then be:

1. Assume that the pore pressure down to 5 meters below the ground surface or below the water table is hydrostatic.
2. The worst case for the groundwater table is that it coincides with the ground surface. However, if the slope is steep, or if measurements during wet periods have indicated that the groundwater level is situated deeper than the ground surface, use that value.
3. Make a prediction of the maximum groundwater pressure in the underlying confined aquifer as suggested in e.g. Report 3:95 (Skredkommissionen 1995).
4. Sketch a flow net for the clay slope, assuming constant permeability for all the clay situated deeper than 5 meters below the ground surface. Here a code like SEEP/W can be beneficial.
5. Extract pore pressure profiles for a number of points to be used in the following stability analysis.
6. If it is obvious that the clay profile hydraulically consists of more than one soil layer, adjust the flow net accordingly.

# 7. CONCLUSIONS AND RECOMMENDATIONS

This chapter contains conclusions based on the findings from this project. Recommendations for how to measure and predict the pore pressures in a clay slope are also given, as well as some recommendations for future research.

## 7.1 Typical pore pressure regime

Several measurements from different parts of Sweden, including the measurements performed within this project, suggests that a typical clay soil profile can be considered as consisting of an upper open aquifer (dry crust clay) followed by aquitard 1, of approximately 5 meter thickness together in which the pore pressures are basically hydrostatic. It is underlain by aquitard 2, usually consisting of clay with a low permeability. Finally on top of the bedrock a confined aquifer of frictional material is situated. The pore pressures in the upper and lower aquifers vary with the season, precipitation, frost etc. The amplitude depends on topography in the area and the geographical location. A schematic figure of the pore pressure profile for a clay profile <u>without</u> any layers of frictional material is shown in Figure 7-1 and <u>with</u> a layer of frictional material in the clay in Figure 7-2.

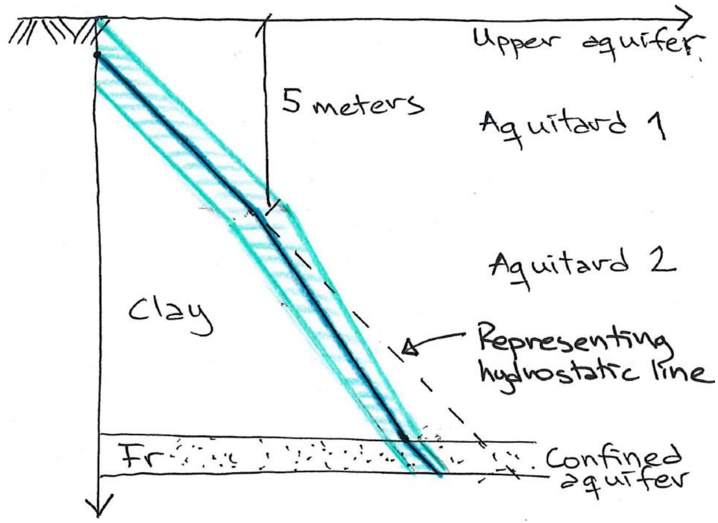


*Figure 7-1. Typical pore pressure profile and its variation in clay <u>without</u> any layers.*

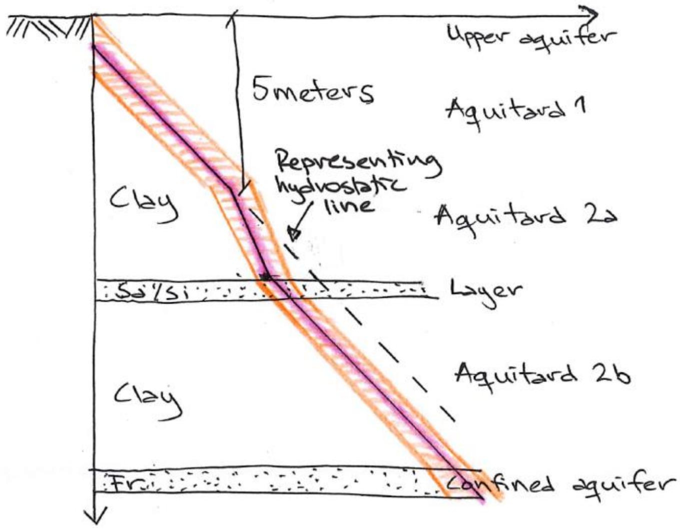


*Figure 7-2. Typical pore pressure profile and variation in clay with an embedded layer of friction material.*

In both cases in the figures above, the pore pressures in aquitard 1 are hydrostatical. The pore pressures in aquitard 2 change with the variation at the boundaries, it does vary almost linearly with depth given that the permeability is constant within this aquitard. The time delay is very small and the pore pressures adjust to the new boundary values within a very short period of time, usually a matter of days, or a few weeks. This is due to a number of reasons; the stress change is rather small, often less than 15 or 20 kPa, stress changes occur within the overconsolidated region, the clay has been exposed to a great number of stress cycles, and finally stress path changes direction. Thus, the necessary strain due to loading or unloading is very small and so is the volume of water needed to flow.

The situations in both cases above are valid where the ground surface is close to horizontal or only has a moderate slope. Closer to the crest of the slope, the groundwater table can be expected to drop a little and then connect to the water table at the bottom of the valley, or the ground surface if no river or watercourse is present. How large the drop of the ground water table at the crest is, if any, varies with local conditions.

## 7.2 Conditions at the watersides and under rivers or lakes

The measurements at the Äsperöd and Linnarhult sites indicate the existence of an open aquifer of about 5 meter thickness also close to the river. To what extent this zone also exists under the river is not known. However, a reasonable assumption for rivers, lakes or other watercourses less than 5 meters deep could be to assume that the pore pressures are hydrostatic to a depth of about 5 meters below the ground surface at the waterside and at that level also under the river or lake, see Figure 7-3.

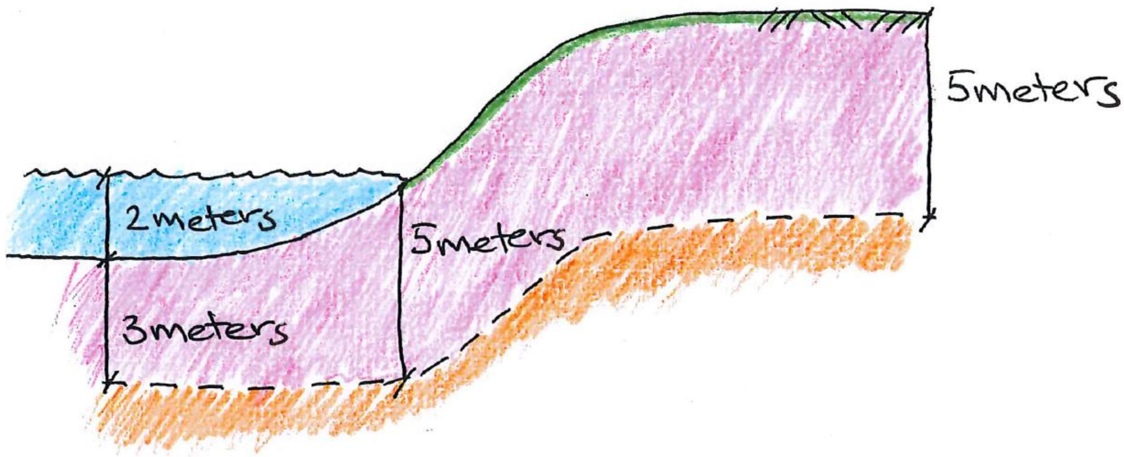


*Figure 7-3. Example with water depth less than 5 meters, here exemplified with 2 meters. The hydrostatical zone (purple) is situated down to 5 meters under the ground surface and 3 meters under the bottom of the river or lake (mean water level).*

In case the river or lake is deeper than 5 meters the pore pressure can be assumed to be hydrostatic in the area between 0 to 1 meter under the bottom of the river or lake, to 5 meters under the ground surface at the waterside, see Figure 7-4.

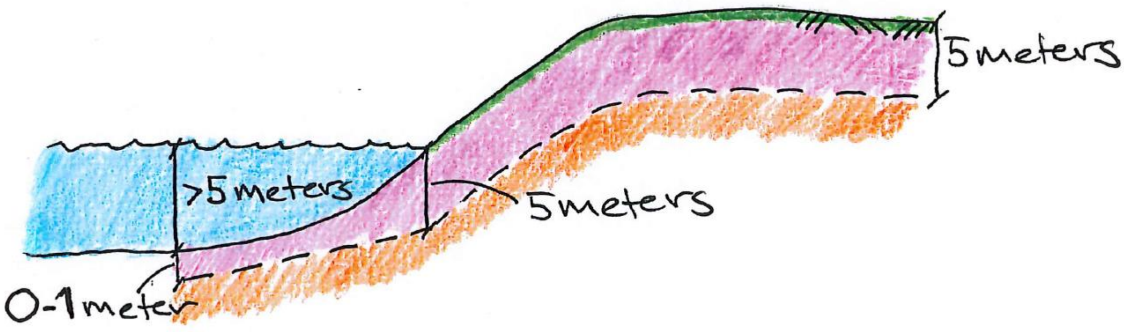


*Figure 7-4. Example water depth more than 5 meters. Here the hydrostatical zone (purple) is situated between a point 0 to 1 meter under the bottom of the river or lake, to a point 5 meters under the ground surface at the waterline.*

Most clay deposits in western Sweden are fairly homogenous, also with respect to permeability. It is therefore reasonable to assume that the pore pressures vary approximately linearly with depth from the bottom of the hydrostatic zone discussed above to the confined aquifer at the bottom of the total soil profile. In case the soil contains layers of other, more permeable, materials, the pore pressure profile will change according to that.

## 7.3 Water level in the river or lake

It is obvious that in an undrained stability analysis, the lowest measured water level, LLW, should be used, since that case gives the smallest resisting moment, and thereby also the lowest safety factor.

However, when performing an effective stress stability analysis the design pore pressures are very high, and the question of which water level to use in the river or lake requires some consideration. An assumption on the safe side would be to assume LLW also for this case. However, in that situation the pore pressures under the river or lake should be assumed to comply with that low water level, rather than pore pressures corresponding to any higher water level, even if the water level in the river or lake drops rather suddenly. The reason for this is the high modulus during unloading. Also a drop in water level results in a drop in total stress, and thus also a certain drop in pore pressures.

Often the design value for the water level in a river or lake, LLW, only lasts for a short period of time, a matter of hours, and it does not seem reasonable to use that value as a design value. Further research regarding a cautious value of the water level in combination with design values for the pore pressures needs to be investigated.

## 7.4 Recommendations for pore pressure measurements and choice of design pore pressures

In a stability analysis for a slope it is important to investigate whether the pore pressures are critical for the stability or not. If not, very few measurements of pore pressures need to be done. As presented in Section 6.4 a suggestion for a simplified procedure for estimating the pore pressures in the upper 10 meters of a clay slope could be:

1. Assume that the pore pressure down to 5 meters below the ground surface or below the water table is hydrostatic.
2. The worst case for the groundwater table is that it coincides with the ground surface. However, if the slope is steep, or if measurements during wet periods have indicated that the groundwater level is situated deeper than the ground surface, use that value.
3. Make a prediction of the maximum groundwater pressure in the underlying confined aquifer as suggested in e.g. Report 3:95 (Skredkommissionen 1995).
4. Sketch a flow net for the clay slope, assuming constant permeability for all the clay situated deeper than 5 meters below the ground surface. Here a code like SEEP/W can be beneficial.
5. Extract pore pressure profiles for a number of points to be used in the following stability analysis.
6. If it is obvious that the clay profile hydraulically consists of more than one soil layer, adjust the flow net accordingly.

Regarding the pore pressure condition at the waterside and under the river or lake, these should be adjusted according to Section 7.2 and 7.3.

## 7.5 Suggestions for future research

Some ideas are identified as suggestions for future research work:

- Perform long term pore pressure measurements at more places outside western Sweden. If those results comply well with the results presented in this study, the stated recommendations regarding pore pressure measurements and design pore pressures values can be validated.
- Measure the pore pressures in the clay material under the bottom of rivers and watercourses to increase the knowledge of the conditions there and to validate the assumptions made within this thesis.

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