# Pore Pressure Response in the Upper Open Aquifer - Field Investigations and Modelling

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ABSTRACT
*For many slopes in clay where the stability is unsatisfactory, high pore pressures is one of the main potential factors triggering a shallow landslide. During rainfall water infiltrates into the soil, which cause a decrease in soil strength, which can be crucial and decisive for whether the slope fails or not. The pore pressure distribution in the slope is part of the data needed for modelling the stability.*
*A question of great importance, and where there is a lack of knowledge today, is regarding the variation of the pressure in the upper 10 meters of the soil profile during different rainfall scenarios, in the short as well as during the long term. The pore pressure in this zone is often crucial for the stability, as the pore pressure to a great extent governs the strength of the soil at these shallow depths. The pore pressure must not be underestimated as the prediction then would be on the unsafe side indicating a fictitiously high factor of safety. When a detailed slope stability analysis is made, including expected climate change, reliable pore pressure predictions are important from an economical point of view.*
*Pore pressure, rainfall and water levels in the nearby rivers have been measured for a long period in two test sites in south-western Sweden. This paper presents an analysis of the measurements and seepage modelling using a commercial seepage modeling software. A better and more reliable prediction of the pore pressure in the entire soil profile, and thereby improving the validity of the stability analysis, can be obtained by using the results presented in this paper together with earlier research.*

**Keywords: slope stability, pore pressure, clay, modelling.**

## 1 INTRODUCTION

One of the main factors causing a landslide in clay (or silt) slopes is high pore pressures. During rainfall water intrudes into the soil, which can cause a decrease in soil strength, which in turn is crucial and decisive for whether the slope fails or not. When modeling the stability, the pore pressure distribution is part of the data needed for the mathematical modeling. The basis for the conceptual model of the pore pressure regime are pore pressure measurements in a few points at a discrete number of depths. These measurements are often supplemented by measurements of the ground water pressure in the underlying confined aquifer. Based on these measurements a model for the pore pressure regime is made and the stability of the slope can be analyzed.
In moderately to steep slopes slides are, if they occur, often rather shallow. However, if a too high pore pressure is used in the analysis, the risk for a slide might be severely overestimated. Pore pressure variations in the Gothenburg region (southwestern Sweden) was studied by Berntson (1983) where a number of sites seemed to have an upper open aquifer of 4 to 6 meters in which the pore pressure distribution was hydrostatic. These findings has been generalized and is used quite extensively by practicing engineers, in spite of the fact that it is based on a limited number of cases. They also form a hypothesis and background for the geotechnical investigations and measurements presented here. Also Persson (2008) studied pore pressure distributions

along the Swedish west coast. He focused on improvements of a method for estimating the maximum pressure in the confined aquifer and a classification system for groundwater level fluctuations.
The pore pressure must not be underestimated as the prediction then would be on the unsafe side indicating a fictitiously high factor of safety. When a slope stability analysis is made, including expected climate change, reliable pore pressure predictions are important from an economical point of view. This paper presents an analysis of measurements from two test sites in southwestern Sweden; Äsperöd and Linnarhult, see Figure 1, and modelling with a seepage modeling software for one of them. The long term gain with the work are the ability of making better and more reliable predictions of the pore pressure in the entire soil profile and thereby improving the validity of the stability analysis.


*Figure 1 Overview Äsperöd and Linnarhult.*

## 2 SITE DESCRIPTION ÄSPERÖD

The test site Äsperöd is situated in southwestern Sweden, 60 km north from Gothenburg, right along the Göta River, see Figure 2. In one slope in the area geotechnical investigations has been done and it has been instrumented with piezometers and a precipitation gauge. The clay slope is, from the river to the outcrop, around 280 meters long. The inclination of the slope is low except from the part next to the river which inclines 1:6. The soil in the area consists mainly of clay.

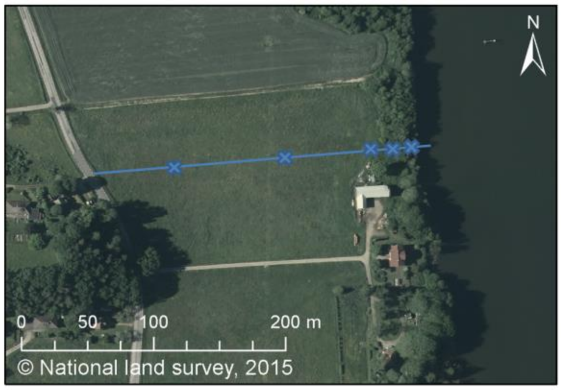


*Figure 2 Overview Äsperöd. Blue line represents the instrumented slope.*

### 2.1 Soil properties

At the site, the ground elevation is at +18 meters in the western part (close to the road) and at +14 meters at the crest of the slope. The steepest part of the slope inclines 1:6 from the crest to the toe. In the area the soil consists of 2 meters of dry crust at the top of the soil profile. Below the dry crust there is clay, with a total thickness less than 10 meters in the western part and more than 40 meters close to the river. Some of the clay is silty between 4-10 meters of depth and some contains gyttja. There is also a layer of sand, around 2 meters thick at a depth of around 35 meters close to the river and further back at 16 meter of depth. The clay is underlain by coarse grained soils. Geotechnical properties for the clay are:

- 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 varies between 12-62 kPa.
- In the western part of the section the clay has a high sensitivity and according to Swedish definitions it is quick (sensitivity>50 kPa and

remolded shear strength <0.4 kPa) from 6 meters of depth to firm bottom.

- CRS-tests have been performed in 3 points 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.

### 2.2 *Instrumentation*

In the Äsperöd test site 17 piezometers have been installed in 5 different parts of the slope. Eleven of the piezometers where installed in January 2013. The other 6 piezometers where installed in 2007. All the piezometers are constantly logging every 4th hour. The position and installation depths of the piezometers are shown in Table 1 and Figure 3.

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

| Part of slope | Distance from river [meter] | Installation depth [meter] |
|---|---|---|
| **Back** | 190 | 7.1, 18 |
| **Plateau** | 100 | 0.65, 1.2, 5 |
| **Crest** | 50 | 0.99, 5, 8.11, 21.3, 34.4, 49 |
| **Middle** | 30 | 0.8, 1.25, 5 |
| **Toe** | 15 | 0.69, 1.49, 5 |

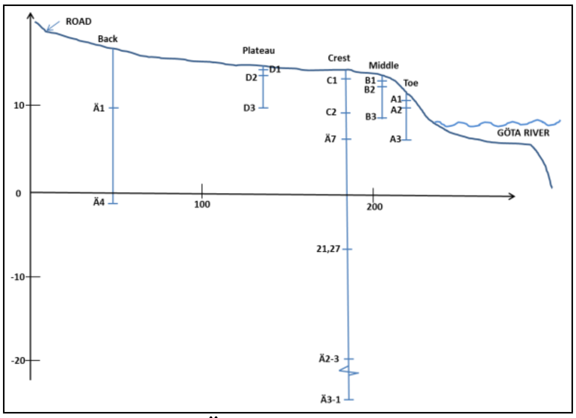


*Figure 3 Profile Äsperöd with position and installation depths of piezometers.*

A precipitation gauge has also been installed in Äsperöd for collection of rainfall data. For some periods with problems with the gauge, rainfall data from the municipality of Lilla Edet have been used. In Figure 4 the monthly rainfall from January 2013 until August 2015 is shown. It can be seen that the amount of rain in February and March 2013 is very low and that August 2014 was the wettest month, with unusually much rain (300 mm). According to Alexandersson (2001) the normal precipitation (the average of the precipitation values over a 30-year period) for the area are 910 mm/year and the rainiest months are normally October or November with a normal value of 102 mm/month.

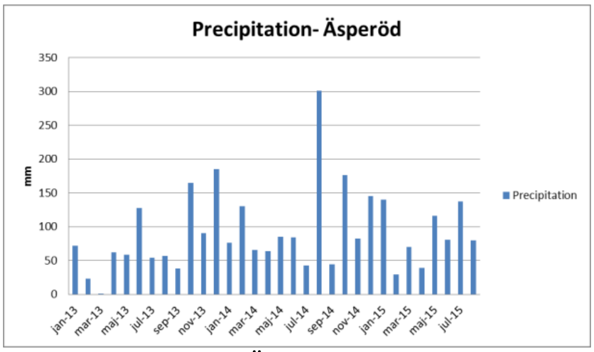


*Figure 4 Rainfall in Äsperöd January 2013-August 2015.*

All the 17 piezometers and the precipitation gauge have been monitored since January 2013 and are still in use (September 2015). The results from the measurements are analyzed in chapter 5.1.

### 2.3 *Water level in the Göta River*

The water level in the Göta River is regulated in favor of power production and the locks, and it 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 April 2015 are shown in Table 2.

*Table 2 Variation in Göta River, January 2013-April 2015 (Vattenfall, 2015).*

| | Meters above sea level |
|---|---|
| **Mean** | 6.9 |
| **Max** | 7.1 |
| **Min** | 6.7 |

## 3 SITE DESCRIPTION LINNARHULT

The test site in Linnarhult is situated 15 km northeast of Gothenburg in the Lärje Stream valley, see Figure 1. The valley is a side valley of the 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 stream and consists of farmland. At the test site there are 2 instrumented slopes, named Section 1 and Section 2, see overview in Figure 5. The distance between the two sections is around 350 meters. Both sections go perpendicular to the Lärje Stream.

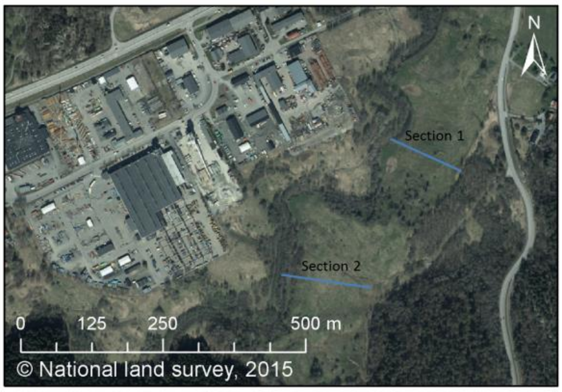


*Figure 5 Overview Linnarhult with the 2 sections.*

## 3.1 Soil properties

Site investigations in Linnarhult were performed in December 2014 - January 2015. The ground elevation in section 1 is at +35 meters at the crest of the slope and in section 2 the plateau and crest are situated at +30 meters. In the Lärje Stream the mean value of the water level is at + 20 meters.
The soil in the area consists of 2 meters of dry crust at the top of the soil profile. Below the dry crust there is clay, with a total thickness of 20 meters close to the Lärje Stream and around 30 meters behind the crest of the slope. There is a layer of silt, approximately 2 meters deep, at 6-8 meters of depth below the crest in section 2. The layer is found at a deeper level further back in the section compared to the level below the crest. There is another layer of silt at 20-30 meters below the ground level with a more horizontal inclination. Geotechnical properties for the clay are:

- The unit weight of the clay in the area varies between 16.3-17.8 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 sensitivity varies between 23-37 kPa and there is no quick clay according to Swedish definitions.
- CRS-tests have been performed in one point at the crest in section 2 at 5 levels. The result shows an OCR of 2.3-3.2.
- The permeability in the clay varies, according to the CRS-tests, between $1.5 \cdot 10^{-10} – 7.5 \cdot 10^{-10}$ m/s.

## 3.2 Instrumentation

In the Linnarhult test site 9 piezometers have been installed in section 1 and 17 piezometers in section 2. All of them where installed between December 2014 and January 2015. The piezometers are constantly logging the pore pressure every 3$^{rd}$- 4$^{th}$ hour. The position and installation depths of the piezometers are shown in Table 3, Figure 6, Table 4 and Figure 7.

*Table 3 Position and installation depths of the piezometers in Linnarhult, section 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 | ~ 6.5 | 1.3, 5 |

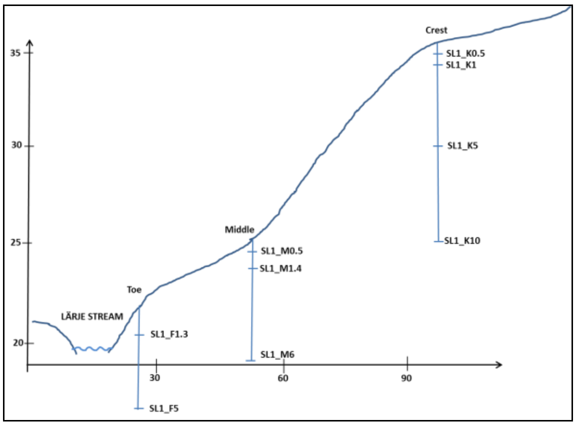


*Figure 6 Linnarhult section 1, position and installation depths of the piezometers.*

*Table 4 Position and installation depths of the piezometers in Linnarhult, section 2.*

| Part of slope | Distance from river [meter] | Installation depth [meter] |
|---|---|---|
| Plateau | ~54 | 0.5, 1.5, 4.5, 7, 15 |
| Crest | ~ 40 | 1, 2, 4, 6.5, 12 |
| Middle | ~ 26 | 2.7, 4, 7 |
| Toe | ~ 12 | 1.75, 4.75, 9.75, 19 |

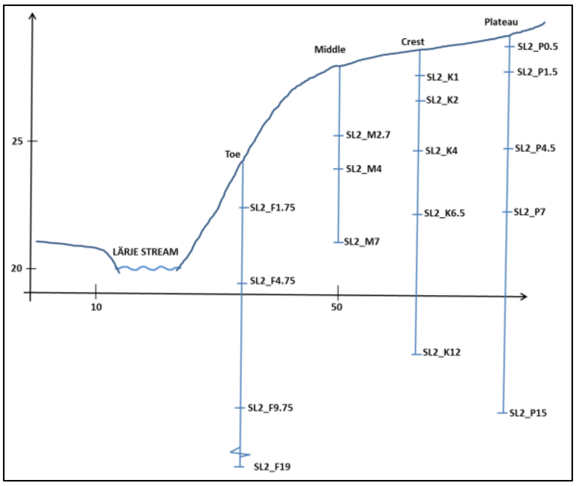


*Figure 7 Linnarhult section 2, position and installation depths of the piezometers.*

The rainfall measurements used for the Linnarhult area is done by the City of Gothenburg. The precipitation gauge is situated in Komettorget, Bergsjön, 2.5 km from Linnarhult. In Figure 8 the monthly rainfall from January-August 2015 is shown. It can there be seen that the amount of rain is smallest in February (40 mm) and largest in January (193 mm). According to Alexandersson (2001) the normal precipitation for the area are 758 mm/year and the rainiest months are normally October or November with a normal value of 82 mm/month.

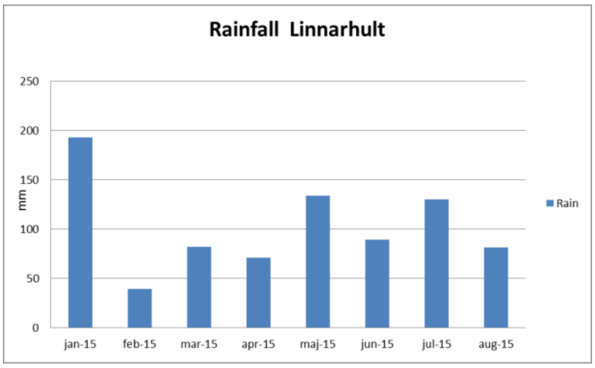


*Figure 8 Rainfall in Linnarhult January- August 2015.*

The results from the piezometers and rain measurements are analyzed in chapter 5.2.

## *3.3 Water level in the Lärje Stream*

The water level in the Lärje Stream is monitored with a piezometer installed in the stream in section 2. The total head varies between 0.7-2.7 with a mean value of 1.1 for the period January- June 2015.

# 4 SIMULATION WITH A SEEPAGE MODELING SOFTWARE

In order to simulate different scenarios with various pore pressures and rainfall data, a model of the Äsperöd area has been set up using a commercial seepage modeling software. To validate the model a simulation has been done for a shorter period of time, one month. The selection of time period is based on a combination of pore pressure measurements and rainfall. The simulation started after a period with just a small amount of rain, followed by a large amount of rain in a short period of time. This was done in order to see how the infiltrated rainwater percolates in the soil profile. After data comparison of different periods the start date was chosen to April 1st 2013 and the end date one month later, April 30th 2013.
Before April 1st there was only 4 mm of rain the last month (March 2013). Between April 1st and 30th it rained 62 mm. It is shown in Figure 9 that the piezometers reacted quickly to the rainfall, especially the ones installed at shallow depths (less than 5 meters).

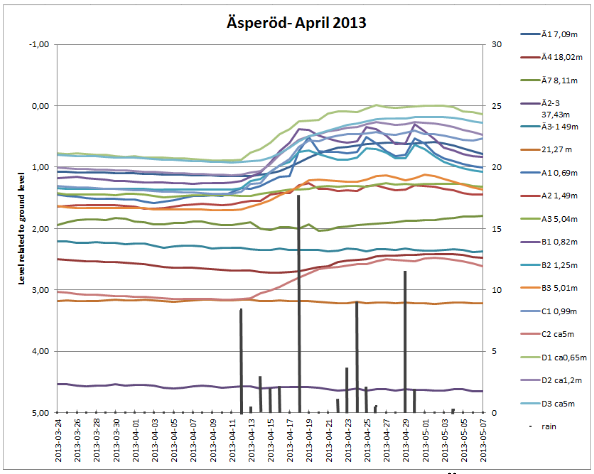


*Figure 9 Piezometers and rainfall in Äsperöd April 2013.*

The simulations with the seepage modeling software are done in order to simulate the pore pressure situation in the area in April 2013 and to validate the soil properties. The first simulation was a steady state simulation with the values for April 1st 2013. After that a transient analysis was made for the rest of the month (April 1st -30th 2013). In this analysis the rainfall during the period was included as a hydraulic function with the rainfall for each day added as a constant rain. The sensitivity of the model to changes in the permeability in the clay and in the dry crust has also been studied.

# 5 RESULTS

The data collected from Äsperöd and Linnarhult has been analyzed and some of the results are presented here. Since there are values for several years from the piezometers in Äsperöd comparisons between the years can be done. Pore pressure profiles with high and low values for the areas are also assembled. Also the results from the simulations with the seepage modeling software are presented and discussed.

## *5.1 Measurements in Äsperöd*

For the piezometers in Äsperöd there are measured values of the pore pressure from the autumn 2007 until September 2015. For the period 2007-2010 there are just values for some periods and not all the piezometers at the same time. In January 2013 another 11 piezometers were installed and since then there are registered values every 4th hour. A fluctuation pattern can be seen for the yearly variations for the piezometers. The difference between the highest and lowest registered values (min- and max-values) in the piezometers varies with installation depth and between different years. The ones that were installed in 2013 at shallow depths (in or close to the dry crust) are the ones with the greatest difference between the extreme values (negative values included). The majority of the piezometers have variations between 10-20 kPa.
When it comes to the response time for the rain in the piezometers it can be seen that the ones at shallow depths have a faster response time and also a more irregular shape, see Figure 10, compared to the ones at larger depths which are slower in their response and the curves have a smother shape, see Figure 11. Persson (2008) describes different types of fluctuation patterns based on observation series such as "quick responding stations", "medium-slow responding stations with rather pronounced maximum levels" and "slow responding stations".

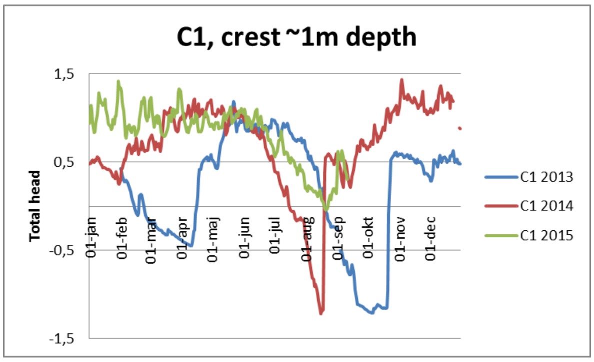


*Figure 10 Fluctuation pattern in quick responding station in Äsperöd.*

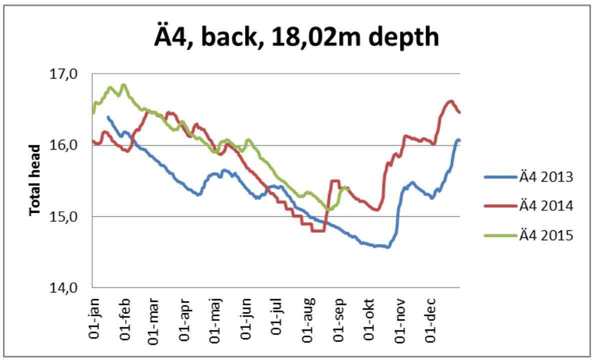


*Figure 11 Fluctuation pattern in medium-slow responding station in Äsperöd.*

The pore pressure profile for the stations in Äsperöd has been evaluated using measurements representing one period with low values, October 10th 2013, and one representing high values, January 30th 2015. The situation in different parts of the slope is shown in Figure 12- Figure 15. The results show a situation with pore pressures close to hydrostatical values for all stations except for the station at the crest. For the piezometers installed at the crest of the slope (Figure 13) the pore pressure does not follow the same pattern as the other stations. The situation here is diverged from the hydrostatical values and gives instead a lower pressure at 5 meters depth compared to a hydrostatic line starting from the ground surface. One explanation to this may be the distinct crest of the slope that makes the isolines for the pore pressure incline more than the hydrostatical line.

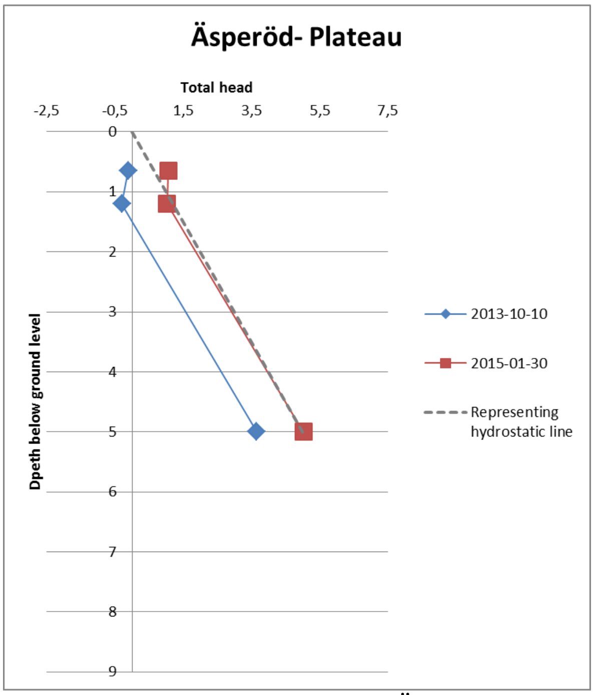


Figure 12 Pore pressure profile, Äsperöd-Plateau.

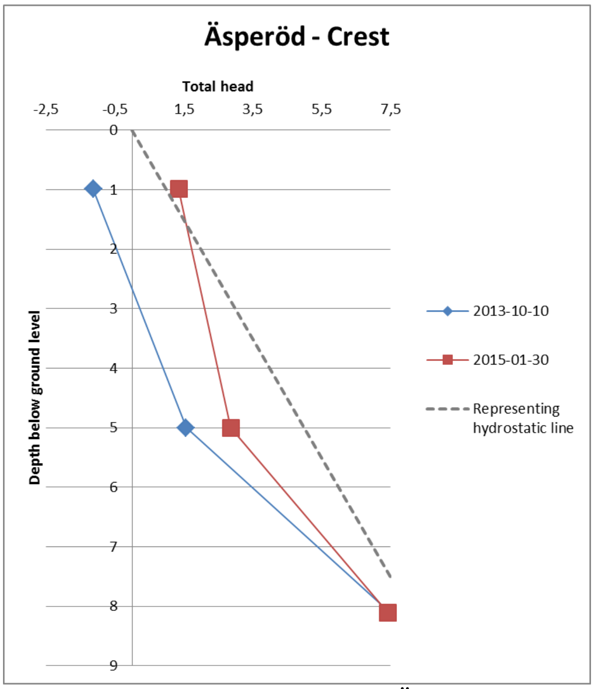


Figure 13 Pore pressure profile, Äsperöd- Crest.

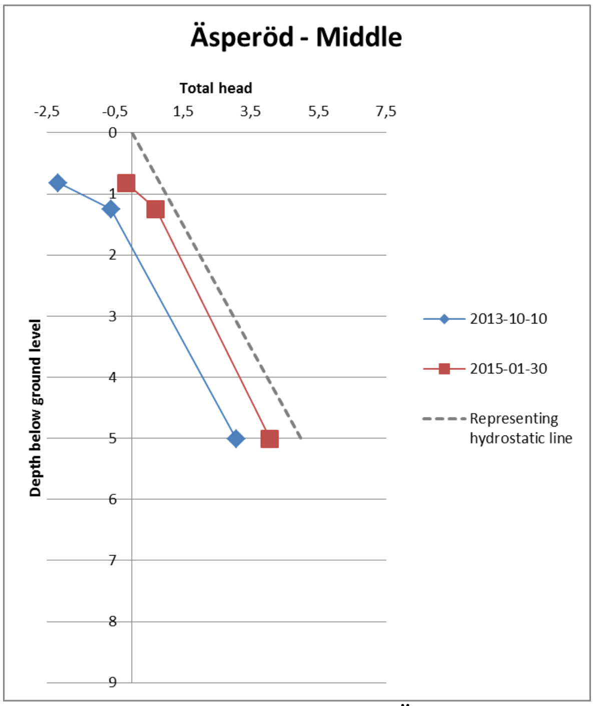


Figure 14 Pore pressure profile, Äsperöd-Middle.

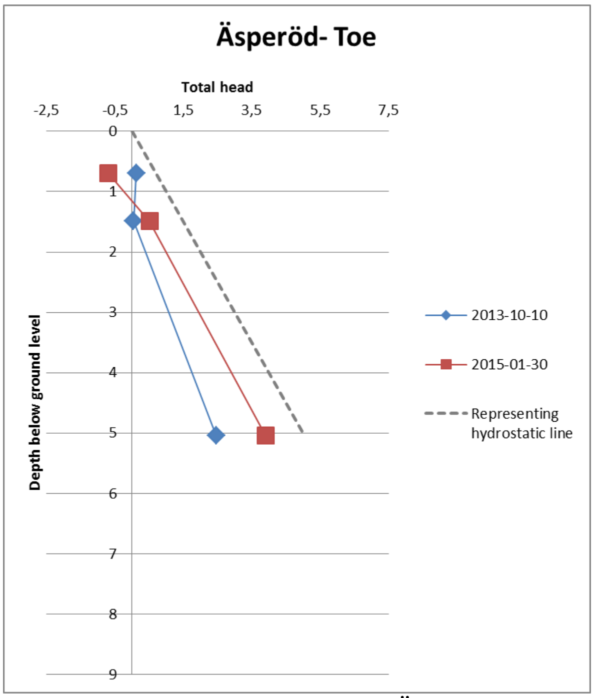


Figure 15 Pore pressure profile, Äsperöd- Toe.

As seen in Table 2 the water level in Göta River varies between 6.7-7.1 meters for the period January 2013- April 2015. Those variations are analyzed together with the rainfall for the period. No correlation is found between the water level in the river and the rainfall for the studied period. Instead it can be concluded that the water level in the river is controlled by the power producer in favor of the power production and locks.

### *5.2 Measurements in Linnarhult*

The pore pressure measurements in Linnarhult have been going on for less than one year, January- September 2015. Most of the piezometers in section 1 have a very coherent pattern over the period with a variation around 10 kPa between the min- and max-values (Figure 16). Also for section 2 the piezometers has a pattern that looks almost the same for most of them with a variation between 5-10 kPa (Figure 17). The piezometers installed at deeper levels vary less than the others.

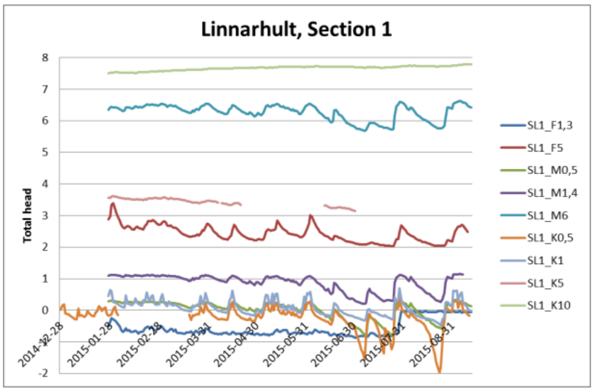


*Figure 16 Pore pressure variations in Linnarhult section 1, January- September 2015.*

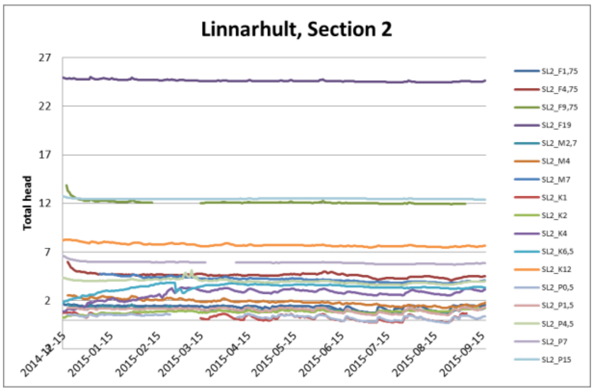


*Figure 17 Pore pressure variation in Linnarhult section 2, January- September 2015.*

The pore pressure profiles for the piezometers in Linnarhult section 1 has been evaluated the same way as the ones in Äsperöd. Representing a period with low pore pressure values, in this case July 1st 2015 is chosen, and high pore pressure values are from February 2nd 2015. The pore pressures show a situation with almost hydrostatcial values for all stations, see Figure 18- Figure 20.

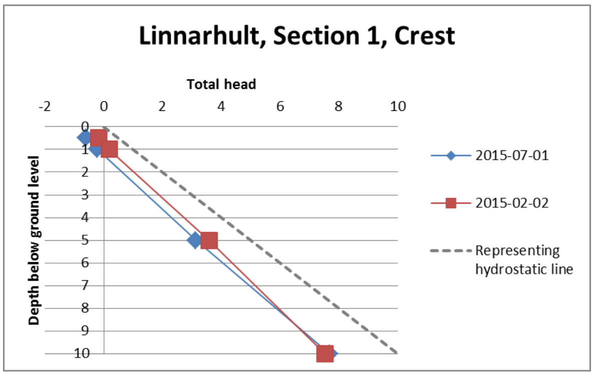


*Figure 18 Pore pressure profile, Linnarhult-Crest.*

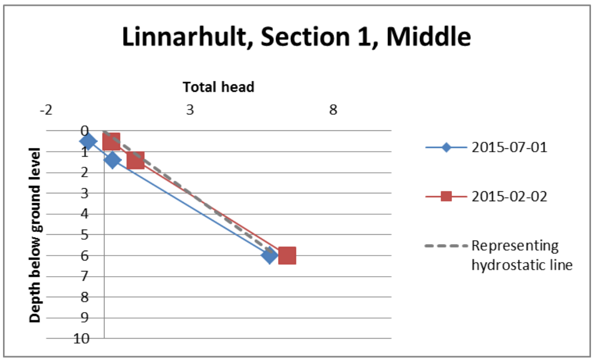


*Figure 19 Pore pressure profile, Linnarhult-Middle.*

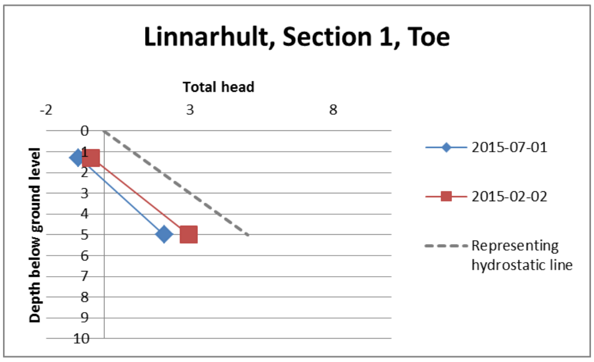


*Figure 20 Pore pressure profile, Linnarhult- Toe.*

### *5.3 Results from seepage modeling simulation*

The results from the simulation with a commercial seepage modeling software are evaluated and compared for two parts of the slope in Äsperöd, behind the crest of the slope and at the toe of the slope. To visualize the results they have been plotted as time series for points located next to the actual piezometers. Those series have been exported to a spreadsheet and the simulated values are compared with the measured values. In general, the results from the simulation give a larger reaction to the rainfall than the piezometers do. This might depend on the dry crust being simulated as ”saturated only” 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. The results from the simulations with the most aquerate permeability, $k=5 \cdot 10^{-10}$ m/s in the dry crust, and $k=1 \cdot 10^{-10}$ m/s in the clay, are shown in Figure 21 and Figure 22. As presented above, the permeability in the clay is $7 \cdot 10^{-10}$ - $2 \cdot 10^{-9}$ m/s according to the CRS-tests so it correlates well to the values from the simulations.

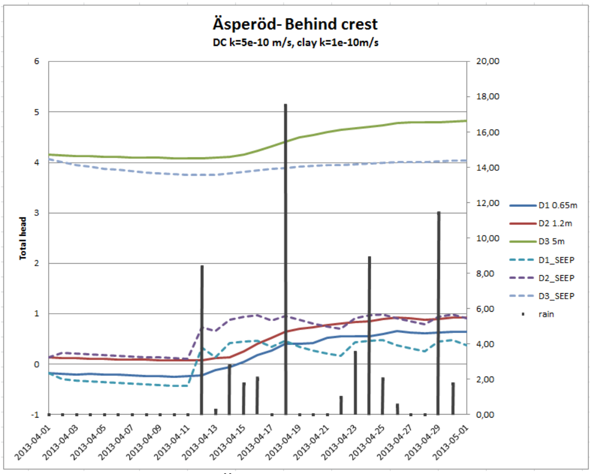


*Figure 21 Station Äsperöd- behind crest. Results from simulation compared to piezometer values.*

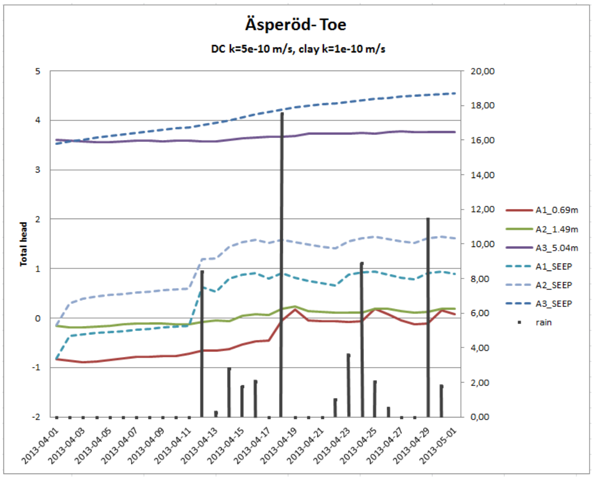


*Figure 22 Station Äsperöd- toe. Results from simulation compared to piezometer values.*

## 6 DISCUSSION AND CONCLUSIONS

- According to the presented results it is fair to say that the uppermost 5-10 meters of the soil profile has a hydrostatical pore pressure. This validates one of the assumptions in the hypothesis.
- The conditions in the two sites are rather similar and a clearly distinguished difference cannot be found. However, it shows that at least within the realm of the conditions prevailing at the sites the presented methods may be applied.
- In order to validate the hypothesis, pore pressure profiles for more stations and with other dates needs to be evaluated, especially with focus on the crest of the slope.
- For the section in Äsperöd the station in the crest does not have hydrostatical properties the uppermost 5 meters. Compared to Linnarhult, section 1, the Äsperöd section has a more distinct crest with a steeper inclination towards the river. This makes the pore pressure distribution different and the area around the crest gets lower pressures.
- More simulations with the seepage modeling software will be performed for other dates and other parts of the slope in Äsperöd to validate the results. After that also the sections in Linnarhult will be simulated to validate a wider use of the method.
- Finally this work will lead to recommendations for placement of piezometers, connections to rainfall and how to include pore pressure profiles in slope stability calculations and thereby improving the validity of stability analyses.

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