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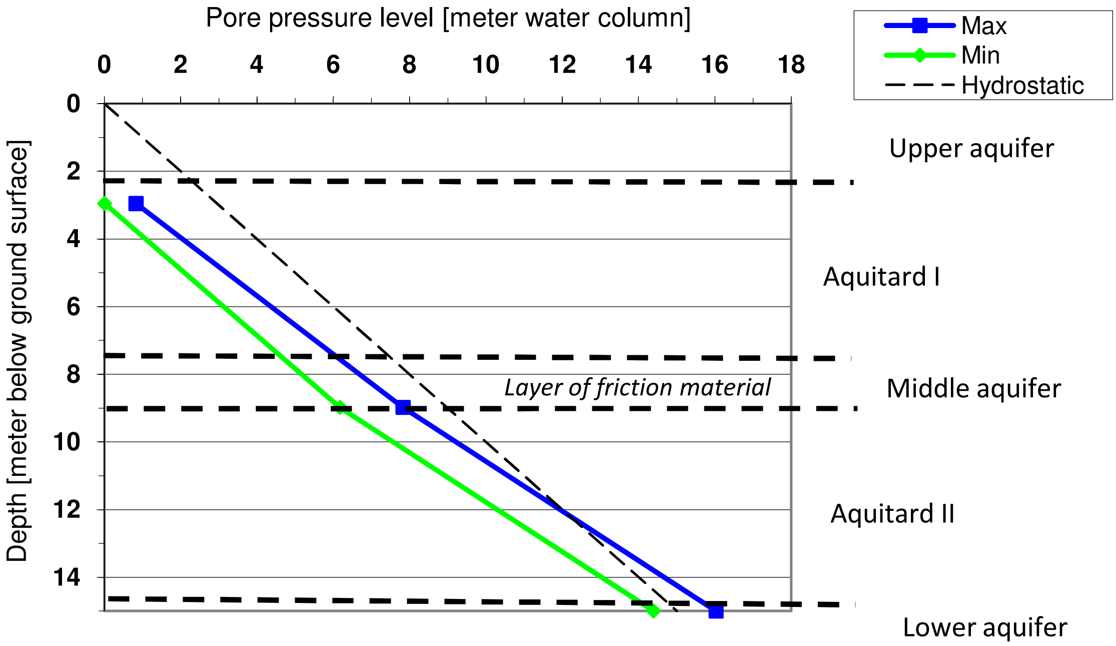

Evaluation of Pore Pressure Measurements in Småröd

Measured values compared to pore pressures in typical clay profiles in the Gothenburg region

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

HELENA LINDGREN
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Measured pore pressure levels in borehole BG151 plotted against depth from the ground surface. The different zones described in chapter 5 are marked in the figure.

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Göteborg 2010

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ABSTRACT

In this Master's Thesis pore pressure measurements from Småröd, located north of Gothenburg, have been compiled and evaluated. By using information about the soil profiles and the pore pressure levels in the area, the groundwater flows have been mapped. The measured pore pressures have been compared to a model for pore pressure distributions, developed by Jan Berntson. The model used for the comparison, states that typical clay profiles in the southwest of Sweden can be divided into zones with different characteristic properties.

In the thesis, the different zones have been identified in a selected number of measurement points in the studied area. The application of the model showed that it is valid in most of the studied measurement points. However, there are measurement points where the measured pore pressures in the upper five to seven meters of the profile deviate from the model. The measured pore pressures in a number of points also deviate from the model in deeper layers where the values are still affected by the landslide in 2006.

As a last step in the analysis, the pore pressure situation in a selected section has been modelled in the GeoStudio programme Seep/W. The result from the Seep/W analysis has been compared to measured pore pressures and the earlier evaluated groundwater flow situation. The comparison confirmed the groundwater flow situation but the pore pressures in the Seep/W model were lower than the measured ones.

The result of this thesis is that the model is applicable in most cases but since deviating pore pressures in the upper five to seven meters of the clay profile have been observed, it is recommended that the pore pressures in these layers are carefully monitored to get relevant information in slope stability analyses.

Key words: Pore pressure, groundwater flow, Småröd, clay

Table of Contents

List of Appendixes

Preface

The work with this Master's Thesis was carried out in spring 2010 at the Swedish Geotechnical Institute (SGI) in Gothenburg. The thesis has been supervised by Håkan Persson, SGI, and by Karin Odén, Geosigma.

The thesis has been performed for the Department of Civil and Environmental Engineering, Division of GeoEngineering at Chalmers University of Technology. Claes Alén, Chalmers, has been the examiner.

First, we would like to thank our supervisors and our examiner for their help and support. We would also like to thank Bohusgeo and Ramböll for providing us necessary data. Last, we would like to thank SGI for providing us necessary computer software and a nice place of work.

SGI, Göteborg, June 2010

Notations and Abbreviations

σ	total stress [kPa]
σ'	effective stress [kPa]
σ'_c	preconsolidation pressure [kPa]
τ_f	shear strength [kPa]
φ	friction angle [^{o}]
A	Area [m^2]
c	cohesion [kPa]
dH/dL	Hydraulic gradient [m/m]
E	evaporation [mm]
k	hydraulic conductivity [$m^3/s\ m^2$]
P	precipitation [mm]
Q	waterflow [m^3/s]
ΔS	changes in storage of water in the soil or bedrock [m^3]
u	pore pressure [kPa]
mwc	meter water column
SGI	Swedish Geotechnical Institute
SGU	Geological Survey of Sweden
SMHI	Swedish Meteorological and Hydrological Institute

1 Introduction

When dealing with geotechnical problems, it is important to use the right pore pressures. The pore pressure is often measured at a few depths in a soil profile. At all other depths in the profile, the pore pressure has to be estimated. In this thesis, a model for estimation of pore pressure distributions in clay profiles in southwest of Sweden will be applied on the Småröd area. The aim is to prove if the pore pressure profile from the model coincides with the measured pore pressures.

1.1 Background

In stability calculations in Småröd, it has been discovered that there is an interest of investigating the pore pressures in the area more carefully. Especially, there have been concerns about the pore pressure distribution in the two upper zones of the clay profile, which is described in the following chapter.

1.1.1 The model

The model that will be used in this thesis was published in the licentiate's thesis “Pore pressure variations in clay soil in the Gothenburg region" (Berntson, 1983). The result of the thesis was a model for predicting pore water pressures in typical clay profiles in the south west of Sweden. The model and the typical soil profile are described in Figure 1.1.

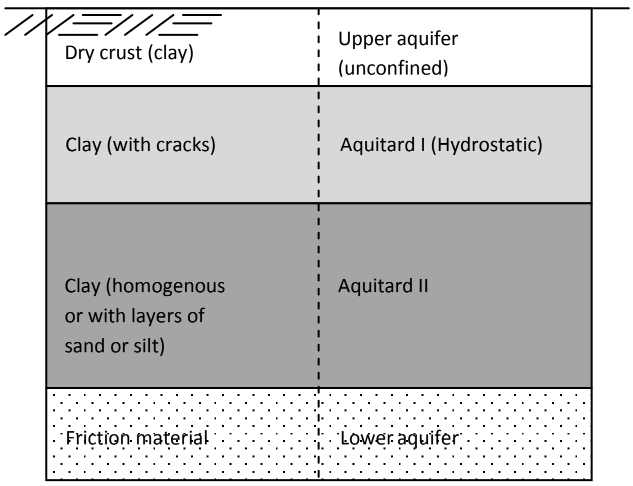


Figure 1.1: Geological model of a typical western Swedish soil profile (after Berntson, 1983, p. 82)

In the model, the soil profile is divided into four different zones. The upper aquifer consists of dry crust clay and is characterised by cracks that give instant changes in the pore pressure profile because of the high permeability. The layer called aquitard I is also characterised by clay with cracks, which results in relatively fast changes in the pore pressure profile and a situation which is close to hydrostatic here.

The aquitard below, called aquitard II in Figure 1.1, also consist of clay that is either homogenous or have elements of sand or silt. Here, the conditions are stable. Because of the low permeability of the clay pore pressure changes does not take place instantaneously. Eventual layers of friction materials within aquitard II is denoted as middle aquifers.

At the very bottom of the profile there is friction material with high permeability, denoted as lower aquifer. Since this aquifer is situated below a layer with lower permeability it can be described as a closed aquifer. The gradient between the lower part of aquitard I and the lower aquifer is usually linear and hydrodynamic.

1.1.2 Investigation area in Småröd

After the landslide in Småröd in December 2006, large geotechnical investigations were performed on the area. The results from these investigations were used to evaluate the cause of the landslide, but measurements of pore pressure have continued until today in many points. There are today many measurement series from after 2008 that have not been deeply studied, but have been used during the reconstruction of the landslide area.

1.2 Purpose

The purpose of this thesis is to describe the groundwater situation in Småröd, and to investigate if Berntson's model can be applied here.

1.3 Method

The procedure of the study, also the structure of the thesis is described in the following subchapters.

1.3.1 Literature study

As a first part of the study, a literature study of hydrogeological definitions and soil properties was performed. Also reports from the evaluation of the cause of the landslide in Småröd (Hartlén, 2007 and Statens Haverikommision, 2009) were studied to get information about the investigation site and the performed geotechnical investigations.

1.3.2 Compilation of data

Data from geotechnical investigations from Småröd performed after the landslide in 2006 is used in this study. All points for pore pressure measurements were marked on a plan (see Appendix A) and information about the accessible measurement points were collected in an excel sheet (see Appendix B). Results from geotechnical investigations were also collected to give information about topography, geology, hydraulic conductivities, and pore pressures on the investigation site.

1.3.3 Analysis

The geotechnical investigations, including the pore pressure measurements were used to analyse the soil profile and the groundwater flows in the investigation site. The measured pore pressures were compared to Berntson's model.

1.3.4 Modelling in Seep/W

As a last step in the analysis, the pore pressures in a section in the investigation site were modelled in Seep/W, by using the theories in Berntson's report. The modelled values were compared to the measured values.

1.4 Scope

This thesis will only analyse pore pressures in Småröd. The impact of the pore pressures on the stability or soil strength in Småröd will not be discussed.

2 Hydrogeological definitions

Hydrogeology is the knowledge about groundwater. When calculating slope stability, it is of great importance to have good knowledge about the groundwater, since it affects the stability.

2.1 Groundwater formation

Groundwater is created from infiltration of precipitation, either through the ground or from leakage from surface water like creeks, lakes or rivers. The water is then transported back to the ground surface because of capillary forces, or through growths. The transpiration of the growths and evaporation brings the water back to the atmosphere, where it becomes precipitation again. Groundwater formation takes place when the precipitation is larger than the evaporation. This water balance can be described by the following general water balance equation (2.1).

$$\mathbf{P} = \mathbf{Q} + \mathbf{E} + \boldsymbol{\Delta}\mathbf{S} \qquad (2.1)$$

P = precipitation
Q = runoff
E = evaporation
ΔS = changes in storage of water in the soil or bedrock

2.2 Hydraulic conductivity

Groundwater fluctuations are dependent on the water transmitting ability of the soil. Hydraulic conductivity is a measurement of how easy water can pass through a medium. The hydraulic conductivity is defined through Darcy's law in saturated soils, which is defined in equation 2.1 below. The hydraulic conductivity may vary in different directions in the media.

$$\mathbf{Q} = -\mathbf{K}\,\mathbf{A} \times \frac{\mathbf{dH}}{\mathbf{dL}} \qquad (2.2)$$

Q	*Waterflow [m^3/s]*
K	*Hydraulic conductivity [$m^3/s\ m^2$]*
A	*Area [m^2]*
dH/dL	*Hydraulic gradient [m/m]*

The hydraulic conductivity varies for different soils depending on the grain size, examples of hydraulic conductivities for sedimentary soils are given in Table 2.1.

Table 2.1: Hydraulic conductivity for sedimentary materials (Häggström, 2006. p 55)

Material	**Grain size [mm]**	**Hydraulic conductivity [$m^3/s\ m^2$]**
Fine gravel	2 – 6	10^{-1} - 10^{-3}
Coarse sand	0,6 – 2	10^{-2} - 10^{-4}
Medium sand	0,2 – 0,6	10^{-3} - 10^{-5}
Fine sand	0,06 – 0,2	10^{-4} - 10^{-6}
Coarse silt	0,02 – 0,06	10^{-5} - 10^{-7}
Fine - Medium silt	0,002 – 0,02	10^{-7} - 10^{-9}
Clay	<0,002	$< 10^{-9}$

2.3 Pore water

A soil is a two part material, consisting of particles and pores. The pores are filled with water or gas. It is the pores that store the groundwater in the soil. When the groundwater level rises, the pressure in the pores of the soil rises. This means that a larger part of the load is carried by the water, and a smaller part is carried by the grain structure. The result of this process is lowered soil strength. In many cases, a raised pore pressure means a higher probability for a landslide.

2.4 Variations in groundwater level

Seasonal variations are of great significance when it comes to the groundwater and pore pressure situation. Precipitation, evaporation and run-off make the groundwater level vary during a year, which was described in equation 2.1. The fluctuations also vary between different layers of the soil profile. How these parameters affect the situation is dependent on geology and geography.

In south of Sweden, the maximum levels usually takes place during late autumn or winter. In summer, the levels are low since the evaporation is high. In north of Sweden, the minimum groundwater levels usually take place in the winter. This is because most of the precipitation comes as snow, and the upper part of the soil profile is frozen, which prevents infiltration. Instead, the levels in north of Sweden are high when the snow melts in the spring, and in the summer. (Sällfors, 2001 p 3.11) These seasonal variations in Sweden are illustrated in Figure 2.1.

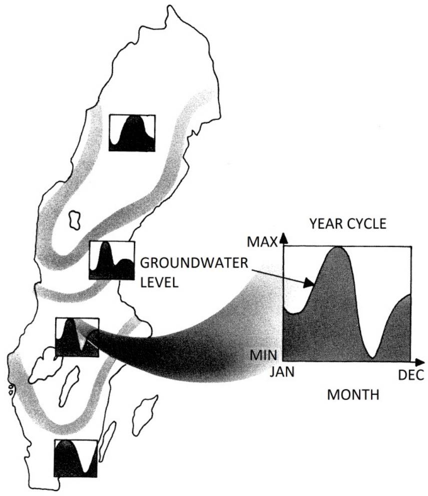


Figure 2.1: Seasonal variations for groundwater levels in Sweden (Tremblay, 1990, p. 11).

Since groundwater is flowing from high pressure level to lower pressure level, the topography is of interest when studying groundwater levels. The groundwater level usually more or less follows the topography of the ground level. In Sweden, it is common to find the groundwater table at a depth of one or two meters into the ground in a soil profile. Since the groundwater flow is caused by the gravity, watersheds make the water flow in different directions depending on the topography. This may result in higher pore pressures in a soil profile in a valley surrounded by mountains, than the same soil profile in a flat landscape.

2.5 Aquifers

A groundwater source in the ground, holding usable amounts of water, is called an aquifer. These aquifers are often found in sand or gravel materials since the hydraulic conductivity is high here. If the groundwater is stored in a low permeable material like clay or silt, the storage is called an aquitard.

There are two different kinds of aquifers, unconfined and confined. If the aquifer is in direct contact to the air, it is called an unconfined aquifer. An aquifer covered by a low permeable layer that prevents contact to air is called confined. This situation may result in a raised pressure in the aquifer. If the groundwater in an open pipe raise above the ground surface, the pore pressure is called artesian (see Figure 2.2).

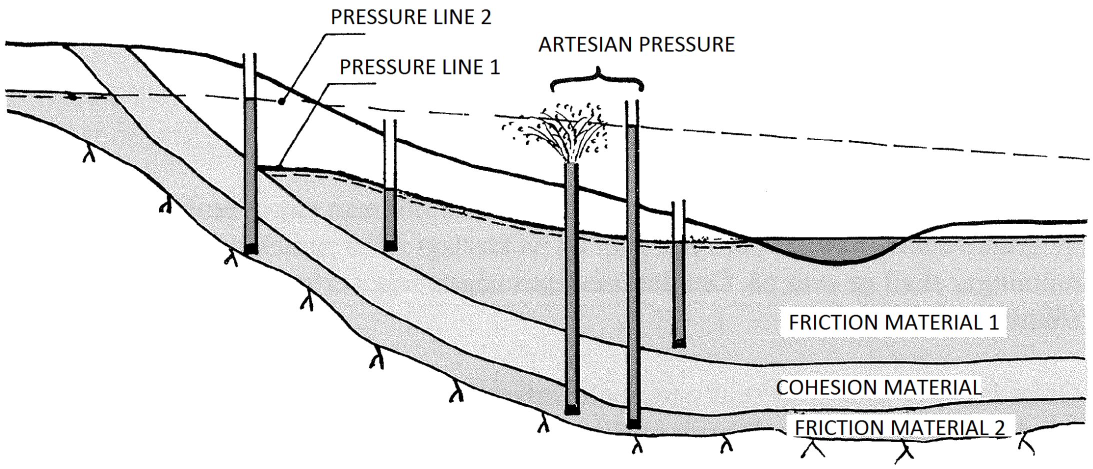


Figure 2.2: Artesian pore pressure (Tremblay, 1990, p. 15).

2.6 Pore pressure distributions

The groundwater and pore pressure distribution in a soil profile is dependent on which type of materials the profile consists of. Also, factors like topography, geology and precipitation have influence on the hydrological situation in a soil profile. Friction materials like sand, gravel or coarse-grained till have a high a permeability which means that the pore pressure distribution will react faster to a changed precipitation or infiltration situation. Cohesion materials like clay, silt or fine-grained till have low permeability which implies slower changes of the pore pressure distribution.

The pore pressure distribution in the ground can be described as hydrostatic or hydrodynamic. If no vertical flow occurs in the soil profile the situation is said to be hydrostatic. In a hydrostatic profile, the water pressure below the groundwater table is only affected by the weight of the water, and will have a constant increment throughout the whole profile. If water is flowing in the profile the situation is called hydrodynamic. Flow of water may occur because of natural conditions such as a draining layer in cohesion material, or because of infiltration. Also, human interferences such as pumping or excavating may cause a hydrodynamic situation.

2.7 Pore pressures in shallow soil layers

In a clay profile, the first layer of soil consists of a zone with dry crust clay that is characterized by vertical cracks which have higher permeability than the clay layer below. This appearance is a product of natural climate processes like weathering, drought and thawing, but also an effect caused by of roots from growths.

It is likely that the pore pressures in shallow soil layers react fast on precipitation and evaporation, while pore pressure fluctuations in deeper layers are delayed and equalized due to flow resistance in the soil layers. The pore pressure fluctuations in deep soil layers are not affected by precipitation and evaporation to the same extent. Instead, the pore pressure is dependent on groundwater flow in deeper layers.

The pore pressure distribution in the dry crust is theoretically assumed to be hydrostatic, since this zone is considered to be an open aquifer. The thickness of this zone is said to be about 1-5 meters (Berntson, 1983, p.37-39).

3 Pore pressure measurement

There are two main groups of systems for monitoring pore pressure, open and closed systems. Basically, in an open system, the water table is in direct contact to the air (see Figure 3.1). Open systems are suitable in soils with high permeability, such as sand and gravel materials.

In a closed system, the pore pressure is measured in a container, which is not in direct contact with air (see Figure 3.1). Closed systems are more sensitive to minor pressure changes why these systems are more suitable in low-permeability soils (Tremblay, 1990, p. 20).

Usually, the pore pressure is measured at several depths in every measurement point, to make it possible to describe how the pore pressure varies with depth. This type of installation can be seen to the left in Figure 3.1. The measurements can be registered either manually or automatically. Manual registration means that a person records the pore pressure, which is a method suitable for short term measurements or only a few occasions, since it is expensive in the long run.

The pore pressure can also be registered automatically by a logger that is installed at the ground surface. The installation of the logger may be expensive why this is an appropriate solution for longer measurement series. Also, a logger can record measurement values several times a day if it is desirable, which is often not possible if the registrations are done by a person.

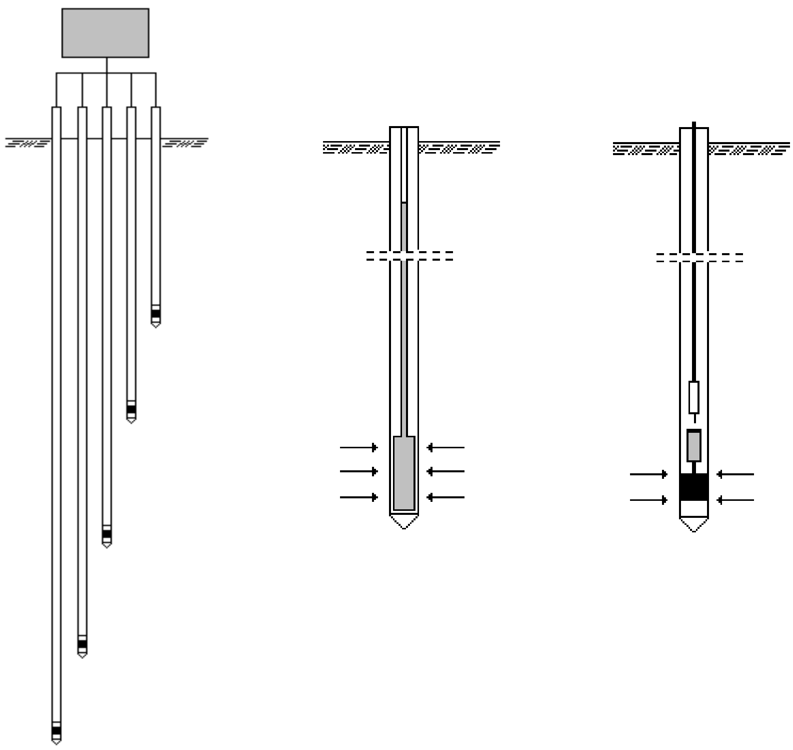


Figure 3.1: Left: Installation of piezometers at different depths. Middle: Open system. Right: Closed system

3.1 Open systems

The simplest way to measure the groundwater table is to install a vertical pipe in the ground, and measure to which height the water rise within the pipe. The same principle can be used with a filter tip connected to a container installed in the bottom of the pipe. The filter prevents particles from blocking the water flow into the pipe. These are both examples of open systems, since the groundwater is in direct contact to air.

3.2 Closed systems

A piezometer, also known as pore pressure meter, is an instrument used for monitoring pore pressures. The piezometer is a closed system, suitable for monitoring pore pressures in low permeable soils.

The piezometer is connected to an extension pipe, which is inserted in the ground to the desired depth. If the soil is soft, the instrument can be pushed into the ground. When penetrating layers of coarse soil, it is sometimes necessary to pre-drill before installation.

The piezometer which is inserted to the ground contains of a porous filter tip connected to a container, which is sealed by a rubber membrane. An electric transducer, consisting of a pressure meter, a needle and a memory connected to a cable is inserted to the pipe as well. Figure 3.2 shows the principle of a piezometer.

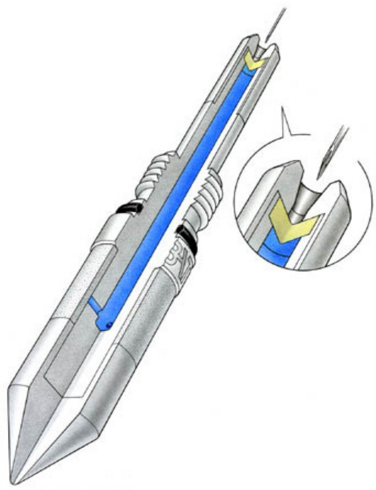


Figure 3.2: Cross section of a piezometer (BAT, 2010)

When a pore pressure measurement is desired, the needle penetrates the rubber membrane and the water pressure inside the container is measured. The pore pressure is registered, and the registration can also contain data about temperature, date, time and serial number. The values can be measured and stored automatically within the logger at the ground surface, but manual registrations can also be made by connecting a computer to the electric transducer. Data from the logger can also be viewed live on the internet if the logger is connected to the GSM net.

3.3 Presentation of results

Results from pore pressure measurements can be viewed in different ways depending on which analysis the results will be used for. Usually, the pore pressures are viewed in diagrams showing how pore pressure varies over time or depth.

In Figure 3.3, results from measurement series over 18 months period where piezometers are installed at three different depths, are shown. These diagrams can be used for determining maximum and minimum values of pore pressures for use in stability analyses and pore pressure modelling.

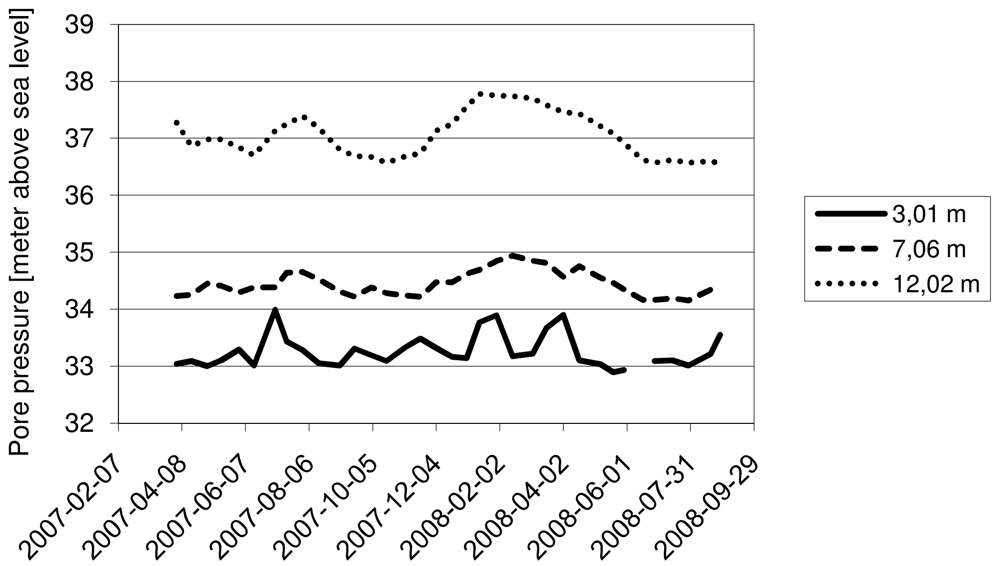


Figure 3.3: Pore pressure at different depths plotted versus time.

The pore pressure can also be viewed in diagrams showing pore pressure and depth. By plotting pore pressure (meter water column) against depth below ground surface (m), it is possible to see how the pore pressure varies between different layers, throughout the soil profile where pore pressure is measured. It is also possible to see if there is any water flowing in the profile (see Figure 3.4).

In the diagram shown in Figure 3.4, the hydrostatic pressure can be drawn as a diagonal line increasing one meter water column per meter depth from the groundwater table and downwards. If the pore pressure increases less than the hydrostatic pressure, there is a downward flow in the profile. If the increase is more than the hydrostatic pore pressure, the flow is directed upwards. There is no flow in the profile if the increase is the same as the hydrostatic pore pressure.

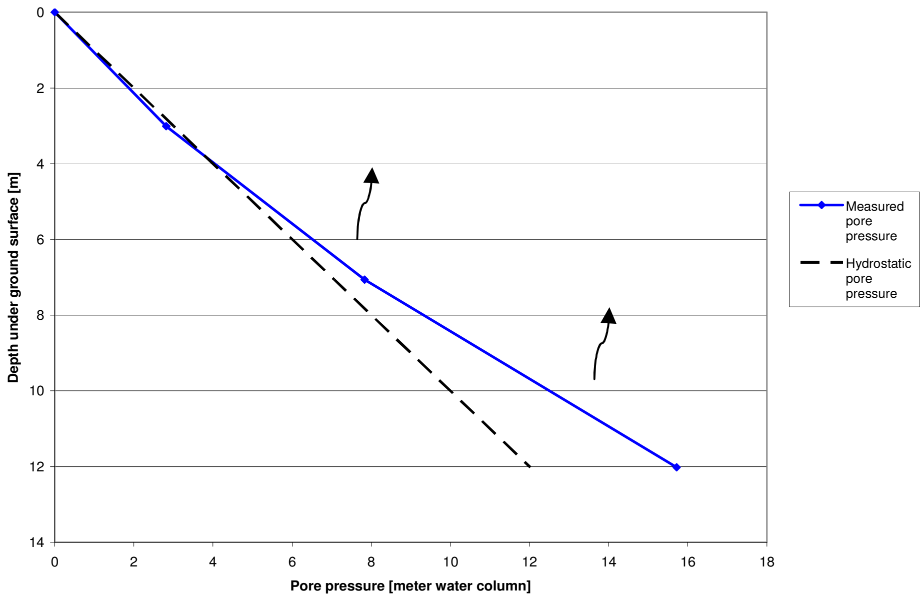


Figure 3.4: Pore pressure in meter plotted versus depth below ground surface. Groundwater is flowing upwards in this example.

Another way to display pore pressure versus depth is to change the units to meters above sea level and pore pressure level. This results in a diagram where a vertical line at the level of the groundwater table represents a hydrostatic pore pressure through the whole profile (see Figure 3.5). If the pore pressure line inclines to the right, there is an upward flow in the layer. The flow is directed downwards if the pore pressure line inclines to the left.

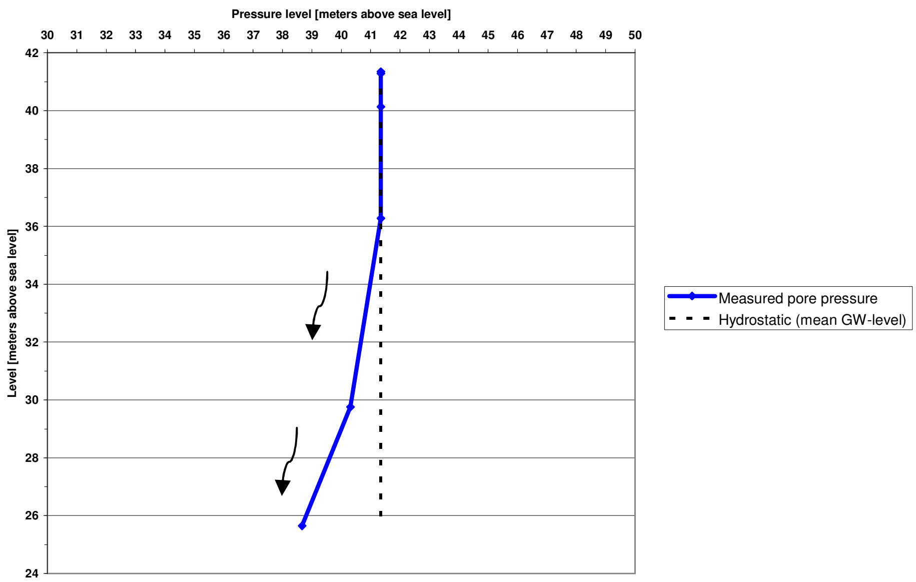


Figure 3.5: Pore pressure level plotted versus meters above sea level. In this example groundwater is flowing downwards.

There are different purposes for using the different types of diagrams. The second type (Figure 3.4) where pore pressure is plotted versus depth is used to detect flows, but it is also easy to read the values of the pore pressure for use in calculations. The third type (Figure 3.5), pore pressure level versus meters above sea level is suitable for detection of groundwater flow since it is easy to interpret the inclination of the lines.

4 Fundamentals of Soil Properties

The pore pressure situation and the effective stress distribution in a soil profile are closely correlated. This is common knowledge when it comes to soil mechanics. Also, the presence of water influences on strength properties of the soil which is of significance when performing stability analyses.

4.1 Soil mechanics

It is necessary to have basic knowledge about soil mechanics and how a soil acts when it is exposed to loading. As mentioned earlier in chapter 2.3, soil can be described as a two part material and is of great importance when dealing with stress distribution in a soil. One part of the stress, the effective stress (σ'), is carried by the grain structure, and the other part of the stress is carried by the pore water (u). Together this results in the total stress (σ). This can be expressed as the following equation:

$$\boldsymbol{\sigma = \sigma' + u} \tag{4.1}$$

In cohesive soils, which are composed by fine-grained particles with intermediate links and aggregates (see Figure 4.1), the ability to take up stresses are almost entirely depending on the strength of the links between the particles.

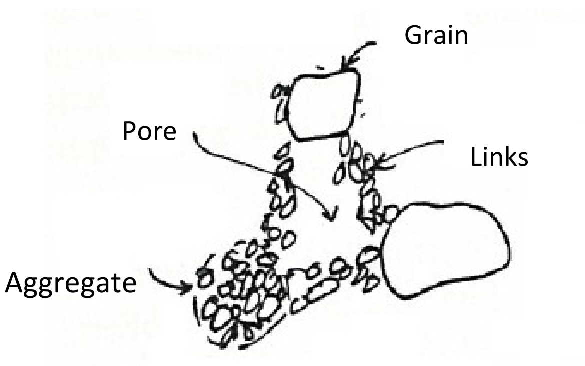


Figure 4.1: Schematic figure of the microstructure of a cohesion material (Sällfors, 2001, p 5.2)

4.2 Strength parameters

It is also necessary to have an understanding for different strength properties and strength parameters. Shear strength (τ_f) is one important parameter, which basically is explained as the strength against forces that makes the particles in a soil move in relation to each other (see equation 4.2). High pore pressures in a soil results in lower shear strength because higher water content results in fewer contact areas between the particles.

Cohesion (c) is defined as the binding forces between the particles in a soil. The value of c is of significance for cohesion materials while the cohesion in friction materials often are assumed to be equal to zero. Another parameter that has to be considered is the internal friction angle (Φ). The friction angle is also depending on the type of material.

$$\boldsymbol{\tau_f = c' + \sigma' \times tan\,\Phi'} \tag{4.2}$$

4.3 Drained and undrained conditions

The strength of a soil is partly dependent on type of soil material and its properties, but the presence of water influence as well. Cohesive material such as clay has a low permeability which means that water will start to leave the soil very slowly when it is exposed to loading. Therefore, the strength calculation for a cohesive material is said to be performed as an undrained analysis which gives the undrained shear strength. If consolidation takes place, in other words if the volume of the soil decreases while water leave the soil, drained strength parameters can be evaluated as well. Friction material, on the other hand, such as sand has high permeability why a drained situation will take place in this soil type.

Since a soil profile often consist of both layers of cohesive material and layers of friction material, different cases of draining will occur at the same time in the profile. Different cases of draining can occur in a profile with only cohesive material as well, because of the rate of over-consolidation. Then, a so called combined analysis can be performed in slope stability analyses. In this kind of analysis both the drained strength and the undrained strength is calculated, and the lowest value of the shear strength is chosen since this will be dimensioning. Figure 4.2 schematically shows the how the shear strength varies with the rate of over-consolidation and when the drained or the undrained strength is dimensioning.

When a soil is exposed to loading it will deform and eventually a failure will occur, which will be either drained or undrained. Which failure that will occur depends on if the drained or undrained strength is dimensioning. For example, in shallow layers of a clay profile or in parts where the soil has been exposed to erosion, the soil is often over-consolidated. Therefore, the drained strength will be dimensioning here. If failure occurs in normally-consolidated clay, the undrained strength will be dimensioning (Skredkommissionen, 1995, p 5.4).

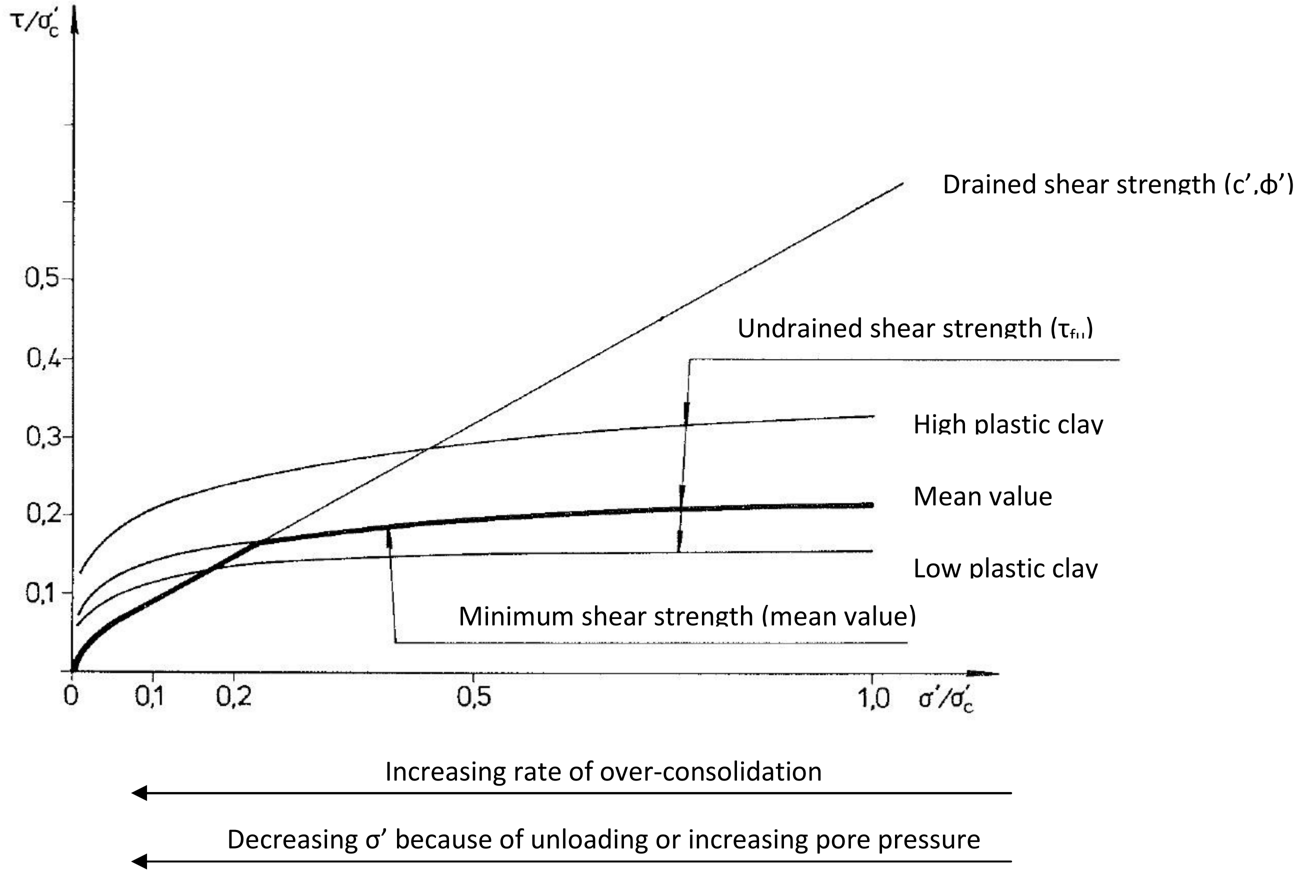


Figure 4.2: The variation of shear strength in relation to the rate of over-consolidation of the soil (Skredkommissionen, 1995, p.5.4).

5 Investigation area: Småröd

The investigated area, Småröd, is situated in south west of Sweden (see Figure 5.1). The area has been thoroughly geotechnical investigated after a landslide in the area, which took place in December 2006.

5.1 The landslide in Småröd

In December in 2006 a landslide took place in Småröd where a new national road E6 was under construction. Småröd is situated about 85 kilometers north of Gothenburg along national road E6 (see Figure 5.1). The landslide affected an area 500 meters long and more than 200 meters wide (Hartlén, 2007, p 4). The area can be seen in Figure 2 in Appendix C.

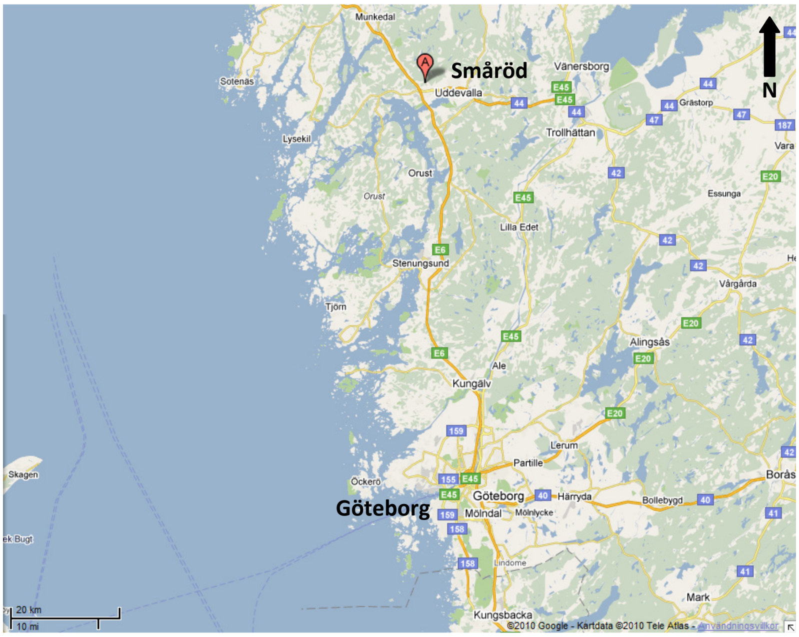


Figure 5.1: Location of investigation area, Småröd.

After the landslide, a large number of geotechnical investigations have been performed in the area to determine the cause of the slide, as well as to be able to rebuild the area and finish the new national road E6. The Swedish Road Administration and the Swedish Accident Investigation Board have done two separate investigations of the cause of the landslide and came to the same conclusion. During the construction of the road, landfill was placed on the upper part of the slope, which made the slope unstable. The weight and allocation of the landfill was the cause of the landslide (Statens haverikommission, 2009 p 69), and the great magnitude of the slide was caused by quick clay.

5.2 Pore pressure measurements

Pore pressures have been measured in Småröd since the planning phase of the new stretch of national road E6. The first measurements took place in autumn 1998 to spring 1999 and autumn 2002 to spring 2003 (Hartlén, 2007, p 29). These measurements were situated along the national road E6 and close to the bridge over Taske å in the south (see Figure 5.2). After the landslide in December 2006, additional investigations were made in the area. Several new measurement points were established, with start only a week after the landslide. Most of the new installations were made closer to the river Taske å, east of the new road.

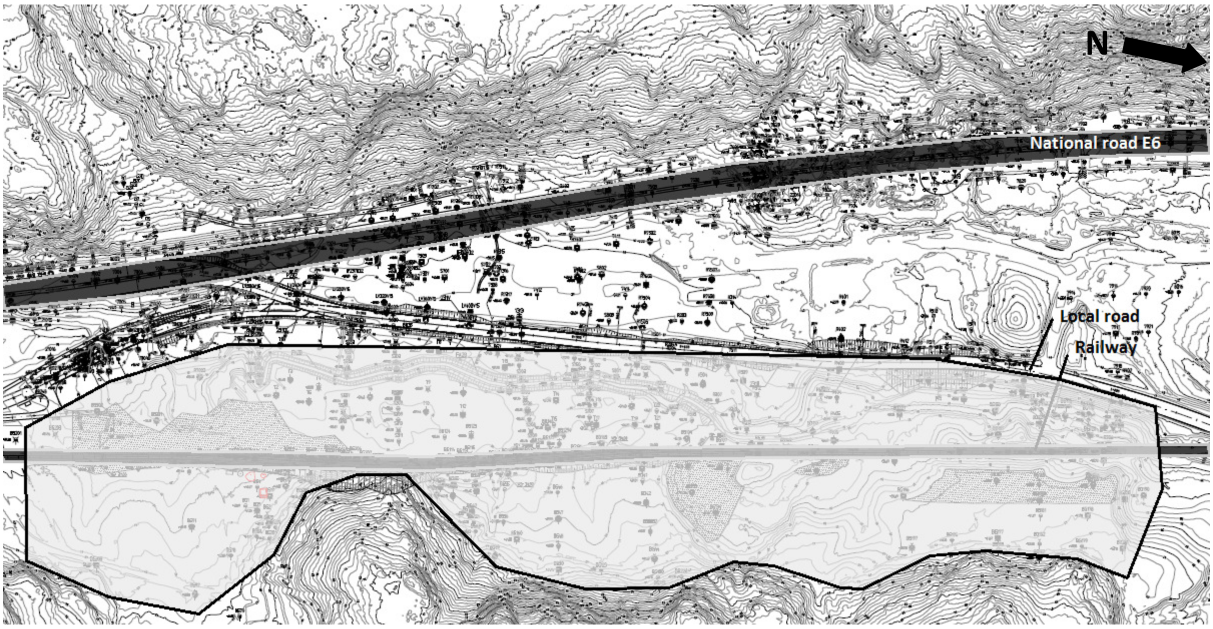


Figure 5.2: Area for most of the additional geotechnical investigations after the landslide.

Information about precipitation has not been collected in the area. Swedish Meteorological and Hydrological Institute (SMHI) provides such data from climate stations in nearby located communities and this data have been used by the Swedish Road Administration and Swedish Accident Investigation Board to estimate the precipitation situation in Småröd. Neither any pore pressure nor groundwater measurements were performed in autumn 2006.

In the measurements in early 2007, the pore pressures in some measurement points within the landslide area were affected by the landslide. In these points, the landslide caused dramatic increases of the pore pressure at the depth of the slip surface and the nearby meters of clay. After the landslide, the pore pressures have declined. In Figure 5.3, this can be seen that the pore pressure are risen in the beginning of 2007 at the depths 11,6 meter and 12,8 meter, which was the depth of the slip surface of the landslide in December 2006. The registrations at 4,7 meter and 19,6 meter are not affected by the landslide.

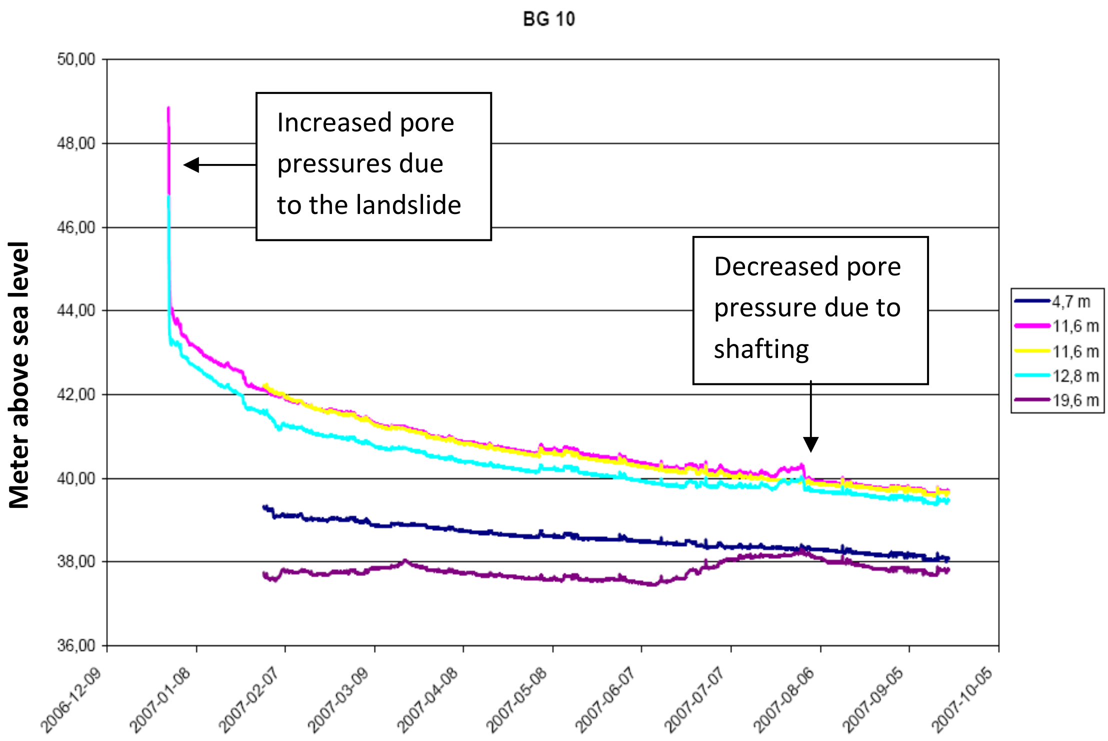


Figure 5.3: Pore pressure registrations from BG10 affected by the landslide.

Measurements have been taken to reconstruct the area after the landslide, and to complete the road construction. Due to this, pore pressure registrations in some points are affected by shafting and changes in length of the groundwater pipes. This can also be seen in Figure 5.3, where the pore pressure is decreased in august 2007 due to shafting.

5.3 Overflow levels

The investigated area is situated in a valley and the groundwater situation here is governed by the topography. A layer of friction material underlies the clay layer in the valley and this layer is the top layer on the hillsides. The maximum groundwater level cannot be higher than the ground surface where the friction material is the topmost layer, since the groundwater aquifer will overflow here. However, this is just the potential maximum level; the actual maximum may be some meters below the surface.

A maximum groundwater level is estimated in the report from the Swedish Road Administration (Hartlén, 2007, Bilaga 3, p 19.). The maximum level is taken from the highest level of the friction layer that provides the aquifer with water, which is +44 meter on the west side of the valley. On the east side of the valley the maximum level of the friction layer is +41 meter. In the report from Swedish Road Administration, the pressure line is assumed to decline linearly between +44 meter and + 41meter over the valley since no measurements of pore pressure or permeability in the friction layer were available at that point of time.

6 Analysis

As a first step in the analysis, the result from the geotechnical soundings is analysed to get a picture of the soil profile in Småröd. The analysis continues with studies of pore pressure measurements, which gives information about the groundwater flows in the valley. These measurements are also used to study the overflow levels in the aquifer. As a last step in the analysis, the groundwater flow in a section is modelled in Seep/W.

6.1 Geology

The investigated area is situated in a valley between hillsides. The materials in the valley have glacial origin, and are also affected by marine conditions. Closest to the bedrock, there is a layer of friction material, probably till or sediment from an ice river. The friction material is overlaid by silty clay (Statens haverikommission, 2009, p 30). On both of the sides of the valley, at the hillsides, the friction material is the topmost layer. The depth of the clay in the valley varies between 10 to 35 meters.

Part of the clay in Småröd is a so called quick clay. Quick clay is high sensitive clay, which was settled in salt water. Clay that is suspended in salt water is built up by large and compact aggregates, which are linked together. With time, the land was raised from the sea, and salt ions were leached from the clay by freshwater. This process results in high sensitive clay. If the clay is disturbed, the large aggregates will not be able to be recreated. By that, the property of holding the original amounts of pore water is decreased. The result is a watery clay solution with small clay particles with low shear strength when disturbed (Rankka, 2003, p 20).

In the south part of the investigation area, the clay layer is as deepest in the middle of the valley and is less thick towards the sides of the valley (see Figure 6.1). Furthermore, soundings show layers of friction material within the clay in the north part of the landslide area, which connects to a layer of friction material further north.

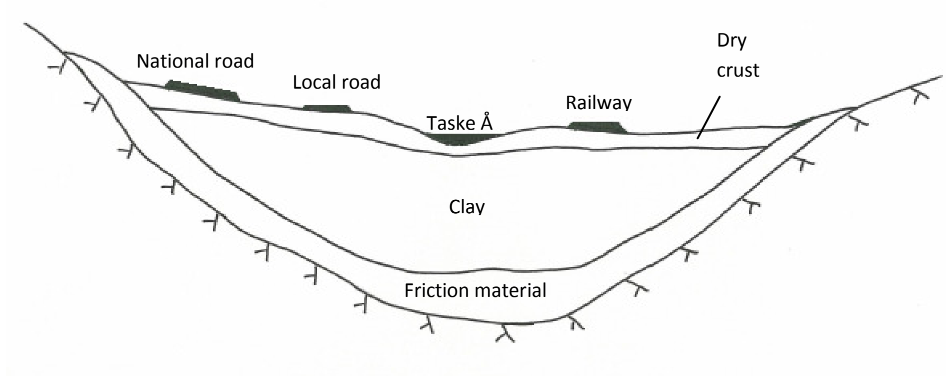


Figure 6.1: Schematic drawn soil profile for the south part of the investigated area. View from south.

In the north part of the valley, the layer of clay is not as deep as in the south part. In the middle of the valley, near Taske å, the depth to the bedrock is only a few meters. On the sides of Taske å the layer of clay are thicker but this depth decreases towards the hillsides (see Figure 6.2). There are also thin layers of friction material within the clay.

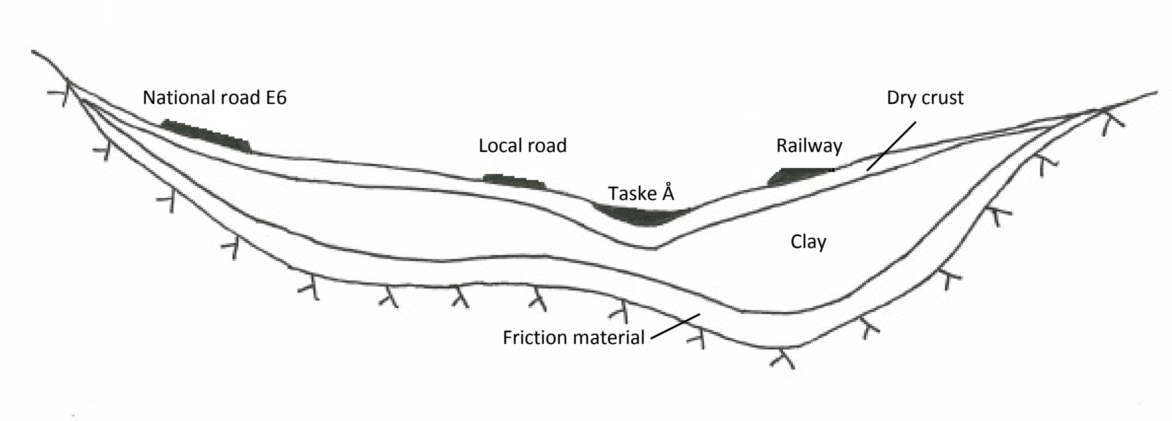


Figure 6.2: Schematic drawn soil profile for the north part of the investigated area. View from south.

At the valley sides, there are more complex layers of washed deposits and clay caused by the rising and lowering of the sea shoreline at the time when the ice melted at the latest ice age (see Figure 6.3). The clay is covered by a dry crust, which is a layer of clay that is affected by weather and erosion. The dry crust is as deepest at the valley sides, up to 3 meters, and is less mighty in the centre of the valley, where it reaches a depth of 1-2 meters.

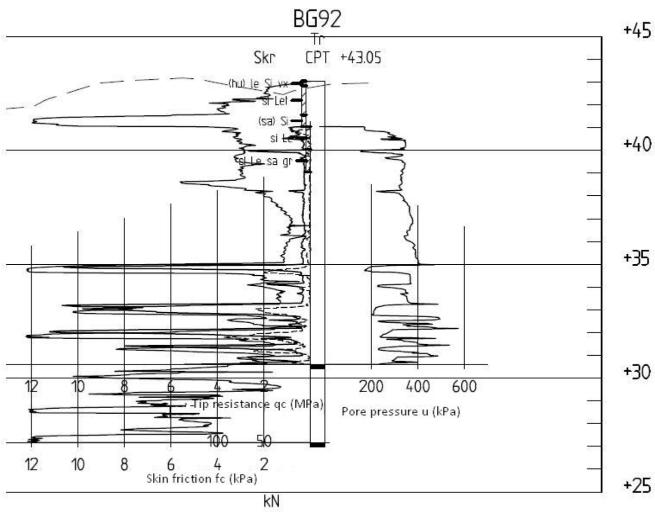


Figure 6.3: Results from a CPT sounding in BG92 (to the left in the figure). Example of a soil profile at the valleyside that has been affected by rising and lowering of the shoreline.

6.2 Groundwater flow situation

Several sections have been studied in order to investigate how the pore pressure levels vary horizontally in the area. In other words, the sections make it possible to see where high and low levels occur and from this get a picture of what the flow looks like in a two-dimensional view.

Also, graphs showing pore pressure versus depth have been constructed and from these the vertical groundwater flow is analysed. By comparing the vertical groundwater flow behaviour with geotechnical investigations of the soil profile, different draining layers are identified. Together with information about the horizontal groundwater flow and topography, it is possible to get an idea of the three-dimensional groundwater flow situation.

The pore pressure profiles have also been compared to Berntson's model, in order to investigate how well the model corresponds to the pore pressures in the area.

6.2.1 North part of the valley

A section that stretches through the north part of the valley between the boreholes BG400 and BG415 (see Figure 1 in Appendix C) has been studied to be able to get a picture of the groundwater flow situation.

Values from February and June are evaluated since the maximum and minimum pore pressure levels seem to normally occur during these time periods. Figure 6.4 shows schematically what the pressure line looks like based on maximum values for piezometers installed at a depth around 10 meters. Here, the piezometers show that the pressure head of the water is more or less above the ground surface in the south part. Also, it can be seen that for the boreholes with piezometers installed at several different depths, the flow gradient is directed upwards. Geotechnical sounding results are not available in all boreholes why it cannot be established if there is any friction material layers in the clay. The bedrock is assumed to be overlaid by friction material since this is the situation in BG151 but this cannot be verified for the other boreholes. The pressure line declines towards north which indicates that there is groundwater flow towards north.

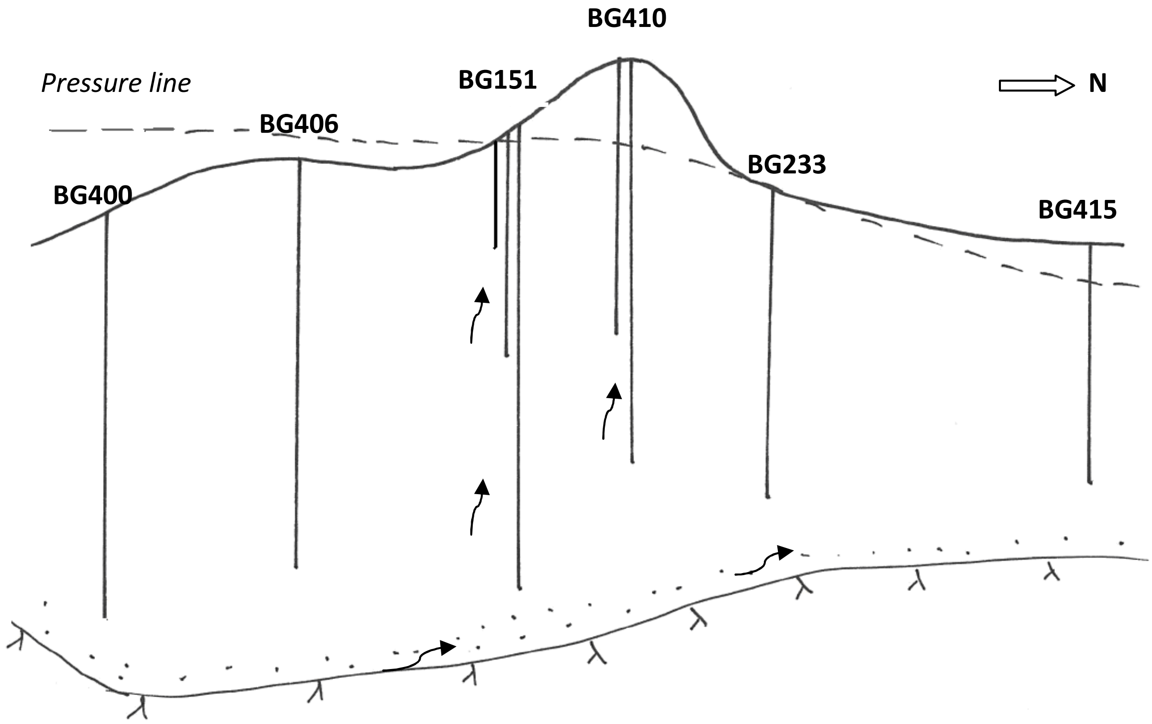


Figure 6.4: Section BG400–BG415 with a schematically drawn pressure line (dotted line) and flow gradients (arrows).

A section across the north part of the valley has been studied as well. This section stretches from borehole BG178 to BG175A (see Figure 1 in Appendix C). Here, it can be observed that east of Taske å in BG178 the flow gradient is directed downwards for maximum pore pressure and the pressure is not artesian. For minimum pore pressure the gradient is close to hydrostatic in the lower part of the profile. Closer to Taske å the ground surface is lower, and the pressures are artesian and the flow gradient is directed upwards. Over all, the pore pressure levels are lower in the valley (see Figure 6.5). This behaviour indicates that there is a groundwater flow from the hillside down into the valley. As described earlier in this thesis, this situation is natural since the groundwater table often more or less follows topography.

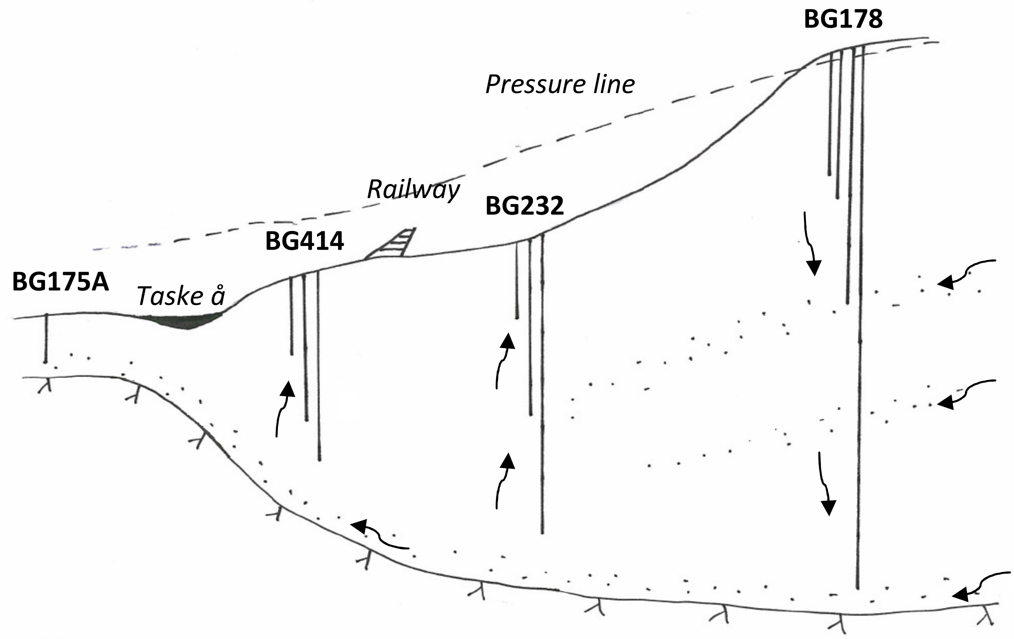


Figure 6.5: Section BG175A–BG178 with a schematically drawn pressure line (dotted line) and flow gradients (arrows).View from south.

Furthermore, the situation in borehole BG151 can be used as an illustrative example of what the groundwater flow behaviour looks like in the north part of the valley, compared to Berntson's model. Figure 6.7 show the pore pressure levels as a function of depth from ground surface. The different zones are identified by using geotechnical soundings (see Figure 6.6) together with pore pressure measurements, and the result is presented in Figure 6.7.

The pore pressure increases hydrostatic in aquitard I, and it is likely that the pore pressure would increase hydrostatic in the upper aquifer as well. The layer of friction material below aquitard I can be identified as a middle aquifer, to which the groundwater in aquitard II flows into. The pore pressure in the lower part of the profile increases more than a hydrostatic situation, this layer is identified as aquitard II. The bottom layer of friction material in the sounding is the lower aquifer.

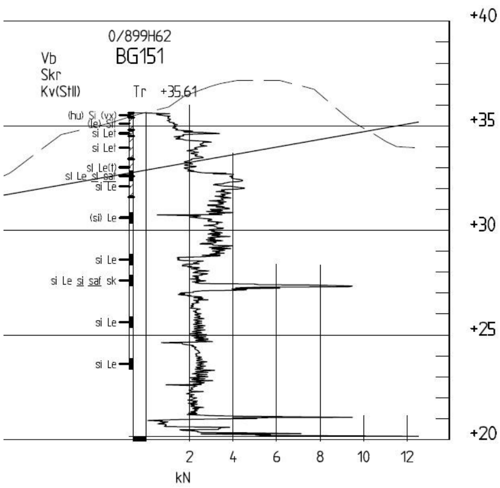


Figure 6.6: Results from geotechnical investigation in borehole BG151.

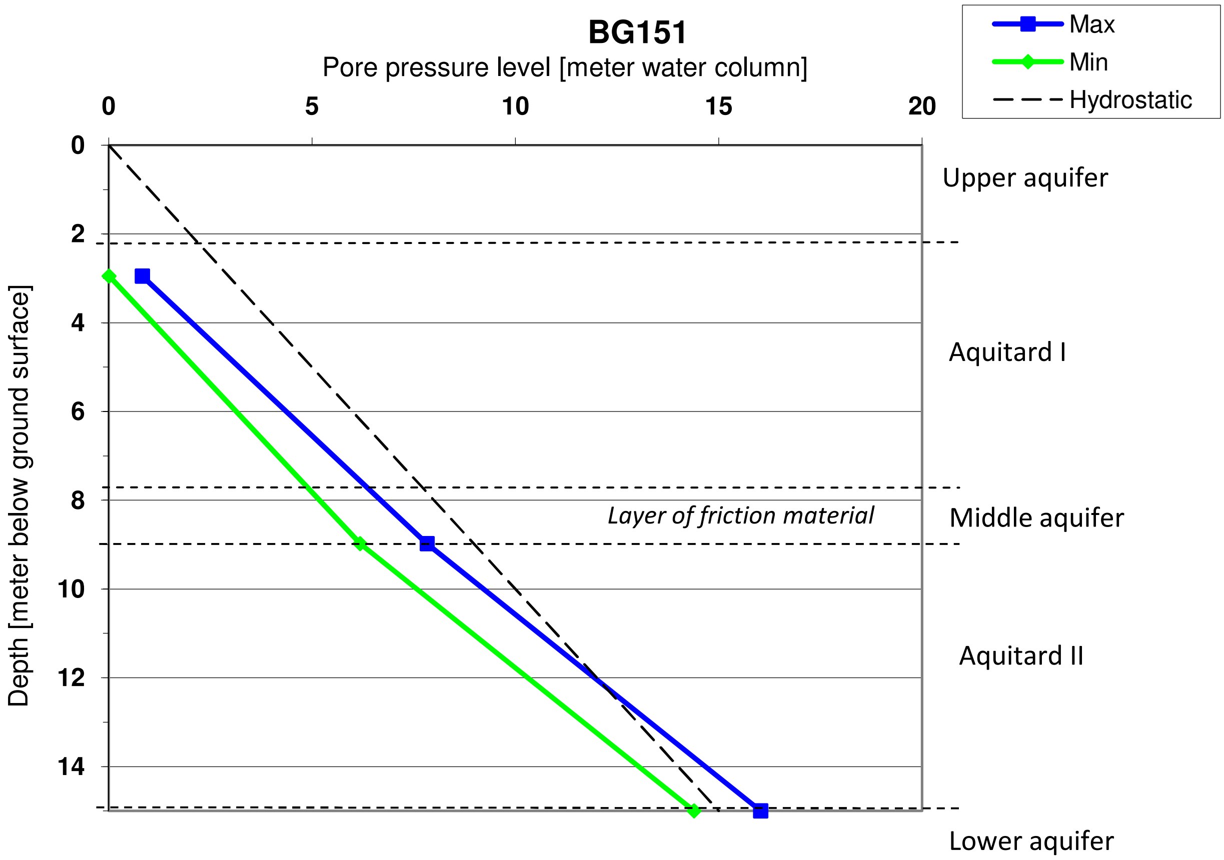


Figure 6.7: Pore pressure levels in borehole BG151 plotted against the depth from the ground surface. The different zones described in chapter 5 are marked in the figure.

The pore pressure gradients have also been studied in a diagram where pore pressure level is plotted against level above sea level, the diagram can be seen in Figure 6.8. In this diagram, the deviation from the hydrostatic pore pressure appears more clearly.

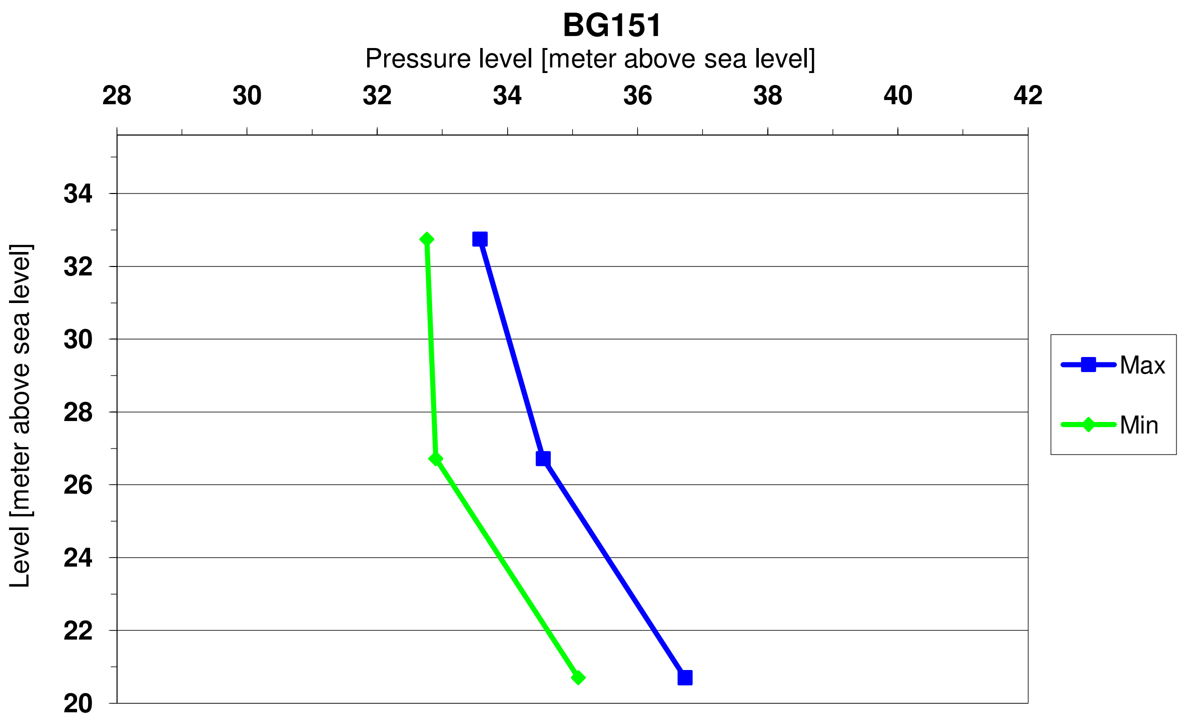


Figure 6.8: Pore pressure levels in BG 151.

The pore pressure measurements indicate that groundwater is flowing into the friction layer, called middle aquifer. This friction layer is present in several of the points in the section in Figure 6.5, which show that the friction layer is spread on a wider area.

6.2.2 South part of the valley

In the south part of the valley the measurement points are not placed as densely as in the north part (see Appendix A). Several measurement points are situated close to Taske å. Here, a section that runs through this area has been analysed. This section connects borehole BG125, BG128 and BG221 (see Appendix C).

The clay layers close to Taske å are deep and none of the performed geotechnical soundings reach friction material. However, soundings in boreholes situated closer to the hillsides show that there is an underlying layer of friction material in the area. Probably this layer is present below Taske å as well, under the deep clay layers. In the measurement points in this section the pore pressure are artesian (see Figure 6.9). The pore pressure situation in borehole BG125 is illustrated in Figure 6.11, which is similar to the situation in the nearby borehole BG128. In the upper part of the profile the flow gradient is directed upwards but in the lower part it is close to hydrostatic. For BG221 no flow gradient can be evaluated since one of the pipes is overflowing. Furthermore, the declining pressure line indicates that there is a groundwater flow towards north.

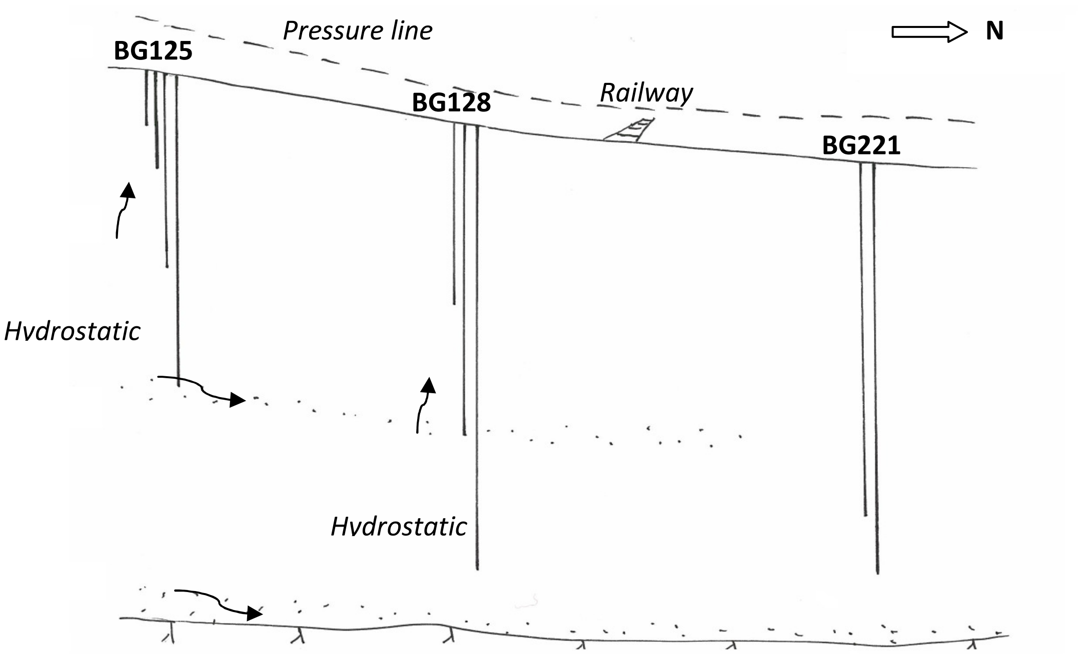


Figure 6.9: Section BG125–BG221 with a schematically drawn pressure line (dotted line) and flow gradients (arrows).

The CPT-sounding in point BG125 have been studied together with the results from pore pressure measurements (see Figure 6.10). The soundings in this point have not reached firm layers. No pore pressure measurements have been performed below 18 meters below ground surface, but it is known that the depth of the profile is at least 30 meters.

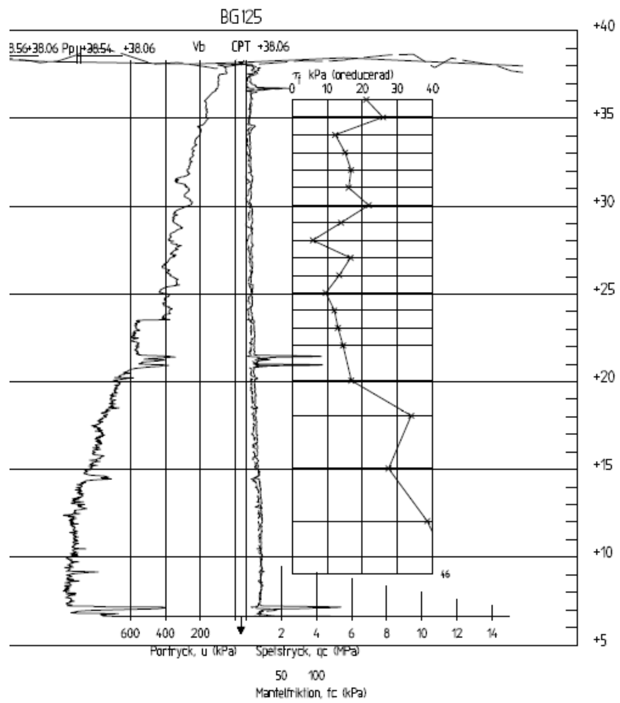


Figure 6.10: Result from CPT-sounding in BG 125

The pore pressure in the piezometer at three meters depth show high values for the maximum case (see Figure 6.11). Also at the measurement at 6 meters depth high pore pressures are observed, compared to Berntson's model. The pore pressure is supposed to increase close to hydrostatic in this part of the profile, called aquitard I. Also in T4, which is located nearby BG125, high pore pressures have been observed in the upper aquifer and aquitard I (see appendix D). This may also be a result of the landslide.

It should be mentioned that the pore pressures at 12 and 18 meters depth in BG125 are affected by the landslide, which makes these values unreliable (see Appendix E). This is not the case in the two upper piezometers. The layer of friction material that is seen in the result from the CPT-sounding in Figure 6.10 can be identified as a middle aquifer. No conclusions about the pore pressures in aquitard II can be drawn since the pore pressures have not reached normal values after the landslide.

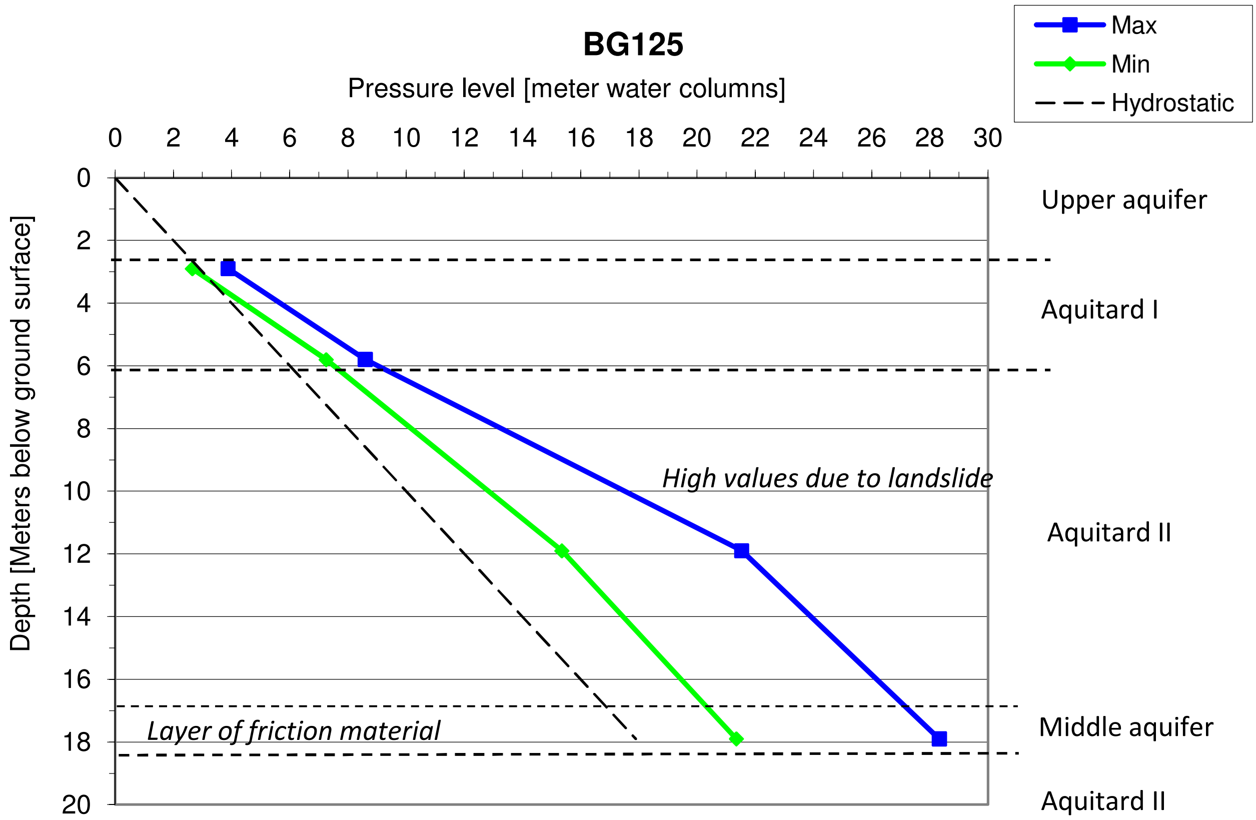


Figure 6.11: Pore pressure levels in borehole BG125 plotted against the depth from the ground surface.

Also, a section that runs from the eastern hillside down to Taske å has been analysed (see Figure 1 in appendix C). This section covers borehole BG48, BG128 and BG10. Here, a similar situation as in the north part of the valley can be seen with a decreasing pressure line towards the valley and with artesian pressures close to Taske å (see Figure 6.12).

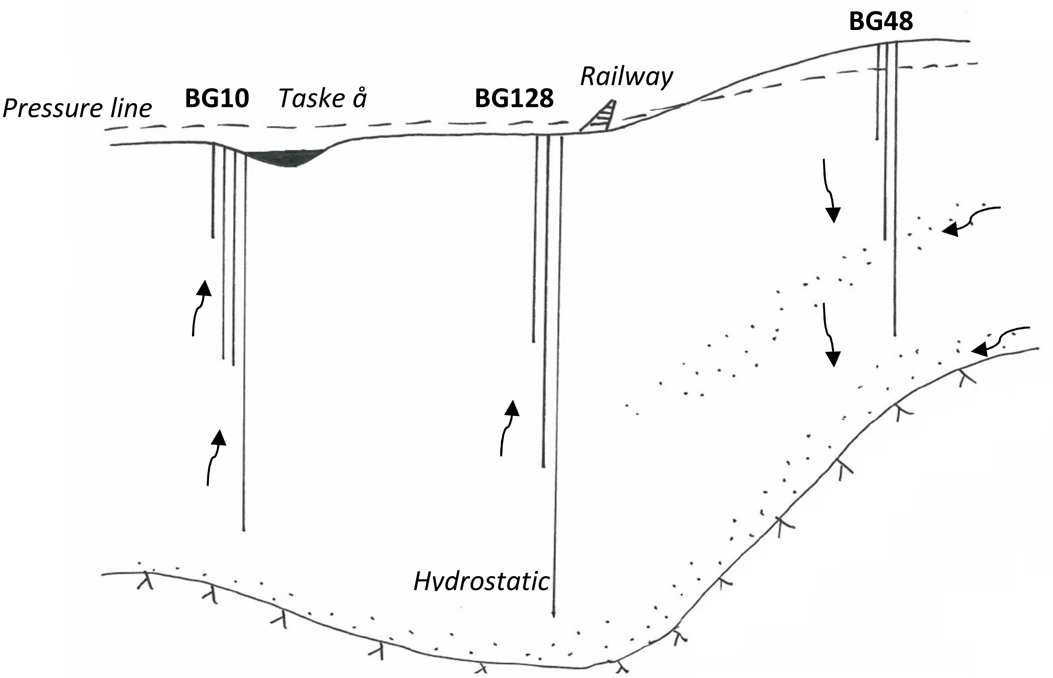


Figure 6.12: Section BG10-BG48 with a schematically drawn pressure line (dotted line) and flow gradients (arrows).

The friction layer is filled with water up on the hillsides where the friction layer is the top layer. The groundwater is led through the friction layer down into the valley. The pressure head is lower in the middle of the valley, which shows that there is a significant flow resistance in the layer of friction material. Even though, the pore pressure is artesian in the friction layer in parts of the valley. The layer can be followed to the west side of the valley as well. In R7507, the friction layer is found at a depth of 11 meters.

In BG48, where there are piezometers installed at several depths, it can be seen that the flow situation can be more or less hydrostatic in the upper aquifer and aquitard I for minimum pore pressures but that the flow gradient is directed downwards in the lower part (see Figure 6.14). For maximum pore pressure levels the flow gradient is directed downwards in the whole profile. The same pattern can be seen in BG42 that is situated close to BG48.

It is also observed that the piezometers in BG48 show higher values than in the other measurement points in the section BG48 – BG10. This means that the pressure head is higher on the hillside than it is in the valley. The geotechnical investigations here show that a layer of friction material is situated at a depth of 10 to 12 meters and it is also observed that this layer is both overlaid and underlaid by clay (see Figure 6.13). At the bottom of the profile it is noticed that the lower aquifer drains the aquitard above.

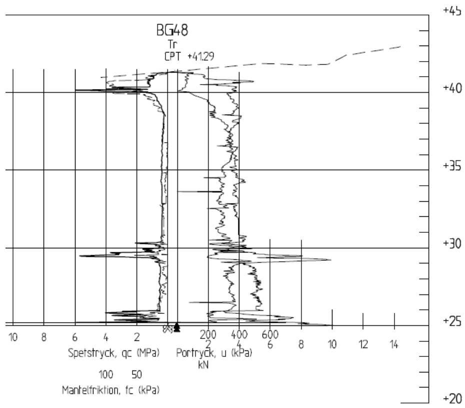


Figure 6.13: Result of geotechnical soundings in point BG 48.

The upper aquifer in BG48 is identified by the result from the CPT soundings in the point, since no pore pressure measurements are made the first five meters of the profile. The pore pressure at five meters depth shows a situation that probably is close to hydrostatic in the upper aquifer and also in aquitard I. There is a layer of friction material around 12 meters depth which is a middle aquifer, which groundwater from aquitard II flows into. Also below this layer, there is also a hydrodynamic situation. Therefore, this layer can be identified as aquitard II as well. From the geotechnical soundings, the lower aquifer is found at 15 meters depth. The result is shown in Figure 6.14.

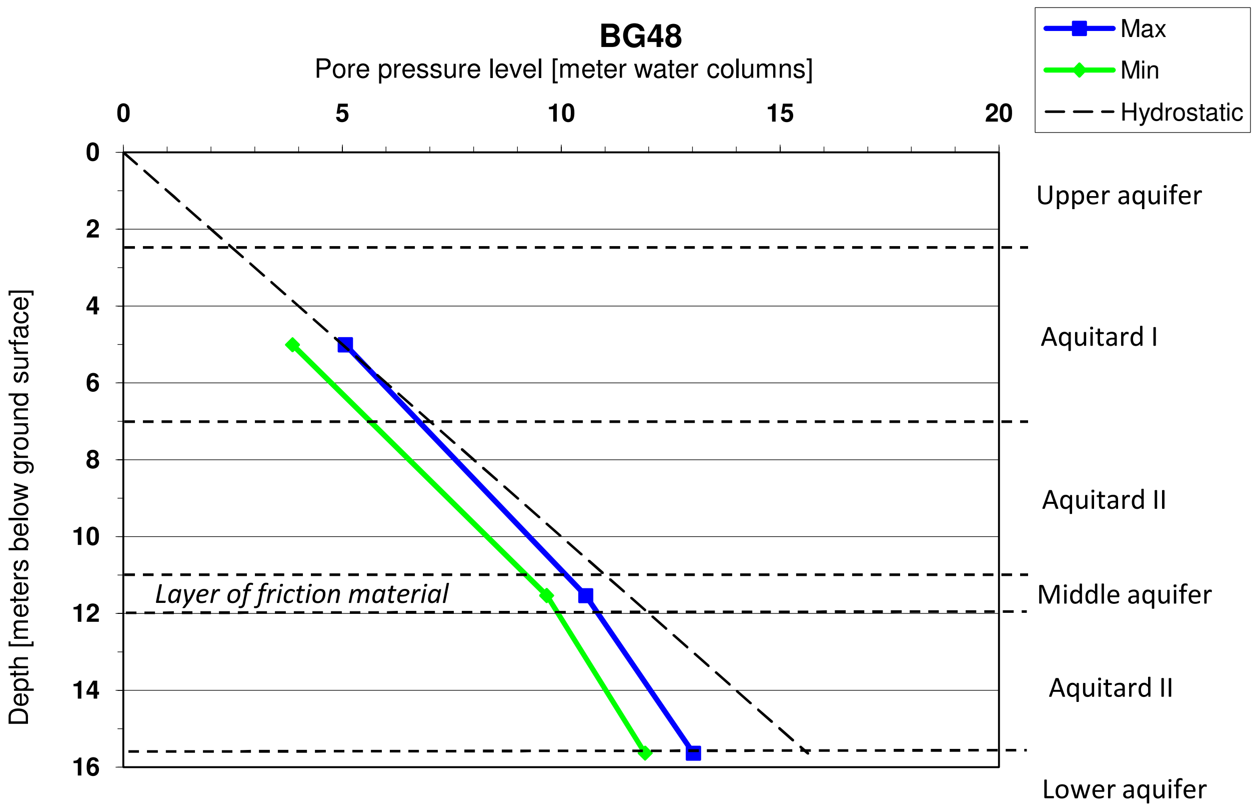


Figure 6.14: Pore pressure levels in borehole BG48 plotted against the depth from the ground surface. The different zones described in chapter 5 are marked in the figure.

6.3 Groundwater flow situation in the lower aquifer

The maximum pore pressures in the lower aquifer from February 2008 and 2009 have been used to illustrate the pore pressures in the friction material. After identifying piezometers in the bottom friction layers, lines have been drawn between the values. The topography has also been taken into consideration when drawing the lines. The result is shown in the map in Figure 6.15.

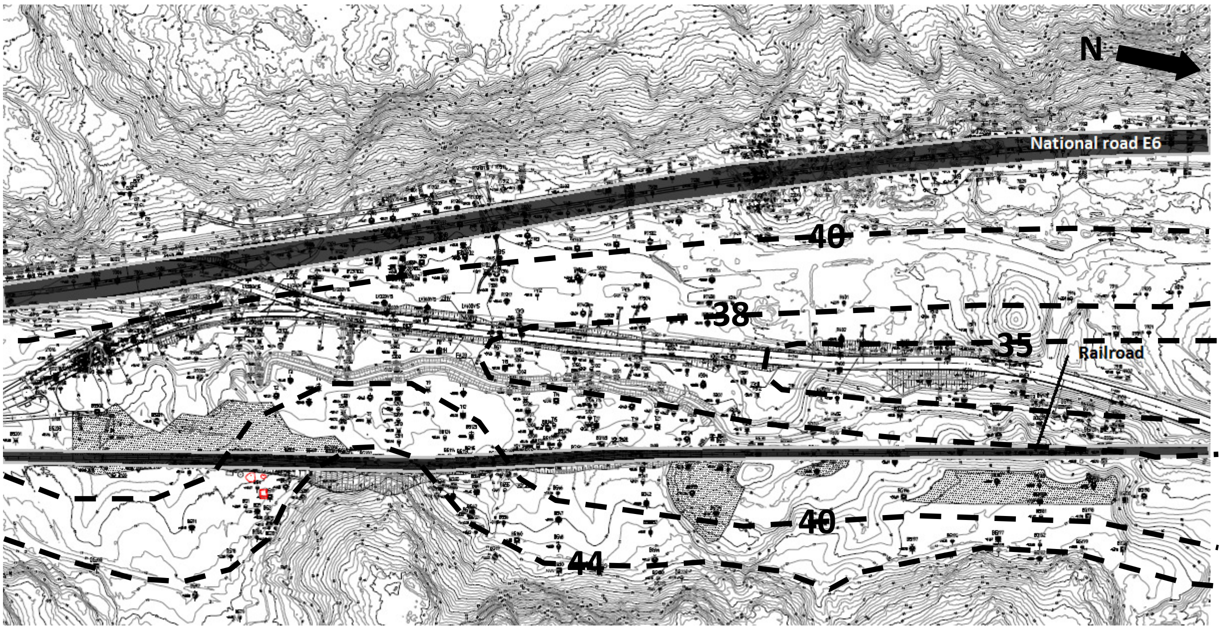


Figure 6.15: Schematic view of measured pore pressure levels in the friction layer.

The pore pressures show a groundwater flow from the south to the north, since the pore pressure is lower in the north. There are also groundwater flows in the lower aquifer into the valley from its sides.

The result also shows that the pore pressures in the lower aquifer have not reached the overflow levels that were stated in the report from Swedish Road Administration (Hartlén, 2007, Bilaga 3, p 19). The overflow levels in the report were +44 meters above sea level on the west side and + 41 meters on the east side, and the pressure line were considered to decline linearly over the valley.

6.4 Pore pressure variations

Measurement series of pore pressures over longer periods are used to study the pore pressure variations in different soil layers. As stated in the model description in chapter 1, the pore pressure changes fast in the upper aquifer. In the lower aquifer, the variations are more equalized and mostly long term variations can be observed.

The pore pressure variations have been studied in the points in Appendix E. It can be seen in these points that the pore pressure in shallow soil layers vary more than in the deeper layers. A displacement in the maximum values can also be observed. The maximum values in the upper aquifer are usually reached before the aquitards and aquifers below reacts. Thus, the pore pressure in the upper aquifer declines before the lower layers reaches maximum levels. This behaviour is observed for example in BG 232, BG 48 and BG 151 (see appendix E).

An example of pore pressure variations in different layers during one year can be seen in Figure 6.16. The diagram shows BG 232 in the north part of the investigation area. Pore pressure is measured at three depths where friction layers are present in the clay. The ground level is at +34,2 meter and the bottom of the clay is found at + 22 meter. At all depths in BG 232, there are piezometers installed, which are read two times a month during one year. The tip at 12 meters depth show equalized variations compared to the tip at 3,01 meter, which shows rising pore pressures in some points where the pore pressure is sinking in the deeper piezometers.

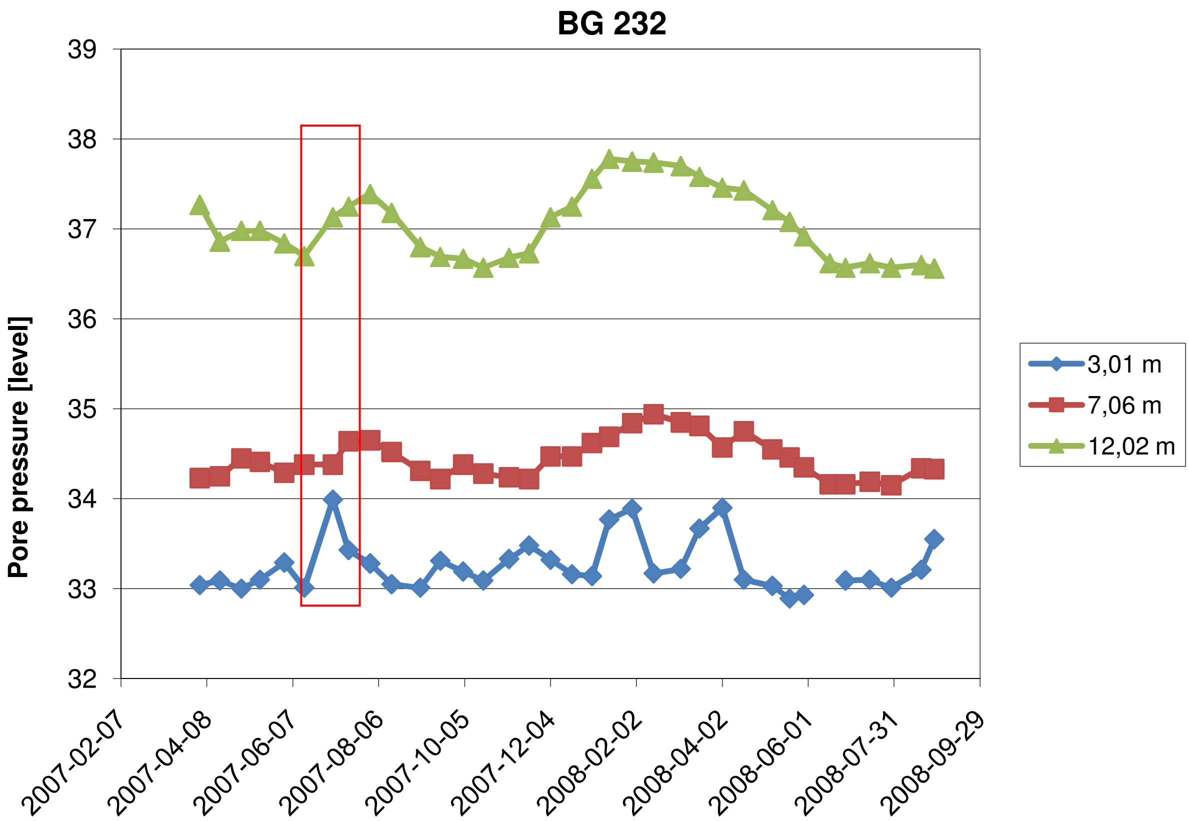


Figure 6.16: Pore pressure variations at three different depths during a period of 18 months in BG232. An example of the displacement between the maximum values is marked in the figure.

In the landslide area, it is more difficult to point out the different variations since the measurements are affected by the landslide, and most of the piezometers are installed in clay layers. This is the situation in for example BG 10, which was shown in Figure 5.3.

6.5 Pore pressure modelling in Seep/W

As a next step in the analysis, the pore pressure situation is modelled in the programme Seep/W from Geostudio. A section in the south part of the valley is chosen to be constructed in the programme, called section A-A (see Figure 6.17). The section is located inside the landslide area.

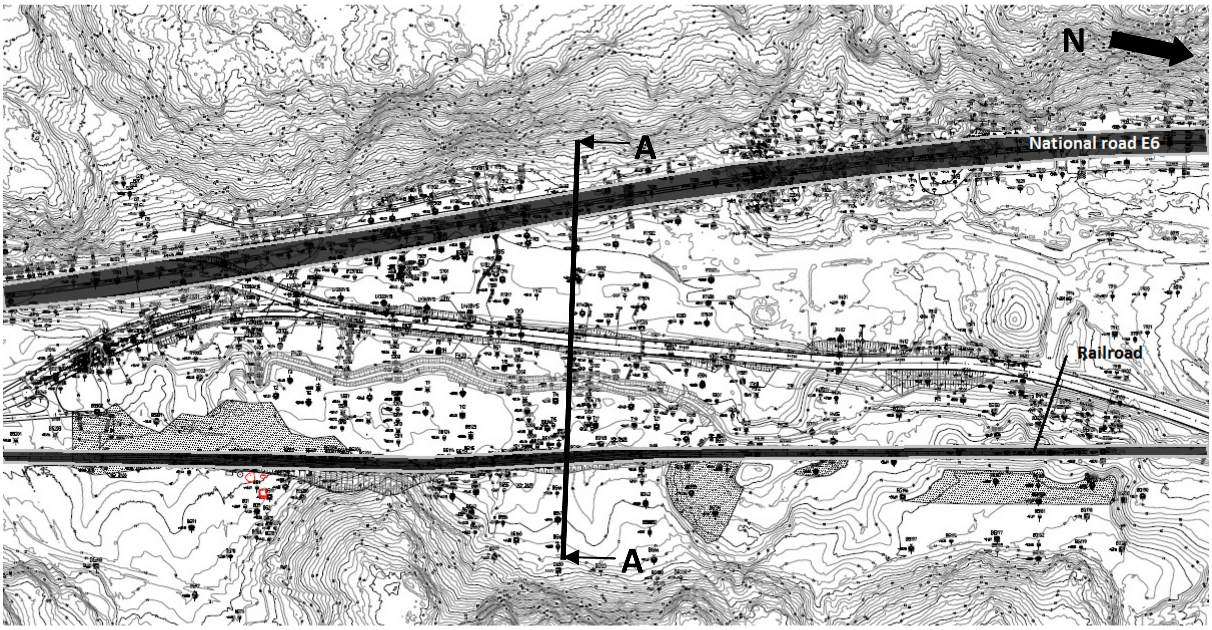


Figure 6.17: Plan of Småröd with section A-A marked.

This section is appropriate since there are measurement points here where pore pressure is measured at several depths in the soil profile. Also, in these measurement points the pore pressure has been registered for a long time which makes it possible to distinguish seasonal variations. The chosen measurements points along the section are listed in Table 6.1.

Table 6.1: Chosen measurement points.

Borehole:	**Measurement data available for time period:**
BG10	Dec 2006 – Jan 2010
BG48	Mar 2007 – Jan 2010
BG128	Mar 2007 – Jan 2010

6.5.1 Description of modelled section

The section stretches from the western hillside across the valley to the eastern hillside. The layer of clay is thick throughout the whole chosen section. The deepest soil profile is found in BG128. The level of the bedrock is not established but soundings show that there is a layer of friction material beneath the clay. The friction material is the topmost layer at both the eastern and western hillside. Also, layers of friction material are found in the clay, for example in borehole BG48 (see Figure 6.13). Probably, these are connected to the layers of friction material that are noticeable in BG128. In Figure 6.18, the eastern part of the modelled section is schematically drawn to show where the piezometers are installed in the measurement points.

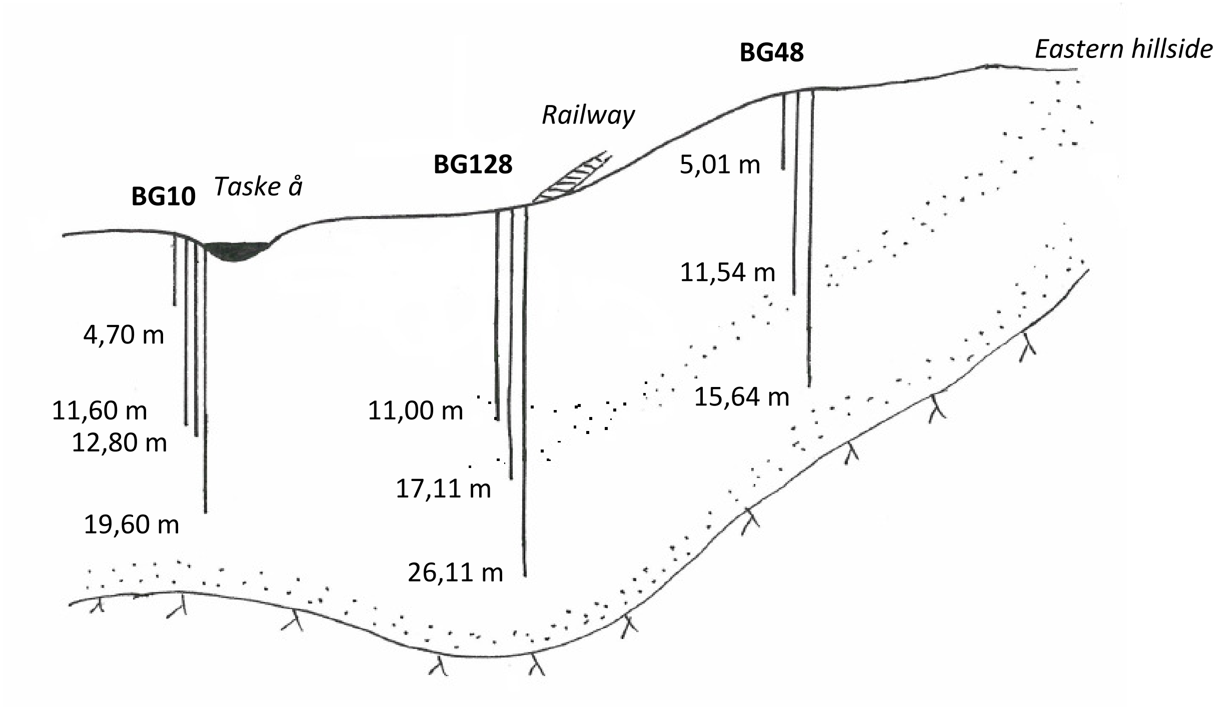


Figure 6.18: Schematic figure of the east part of section A-A which shows at which depths there are piezometers installed.

6.5.2 Seep/W model

Pore pressure values from February 2008 have been used to construct the model in Seep/W since maximum pore pressure during the studied measurement period occurred at that time. The soil profile is simplified in the model. The clay is divided into two layers with different hydraulic conductivities, due to the different properties of aquitard I and II. On top, there is a layer of dry crust, and there is a friction layer in the bottom. In the clay there is a layer of friction material that stretches from the eastern hillside to the western hillside. The bedrock below the friction layer is assumed to be closed.

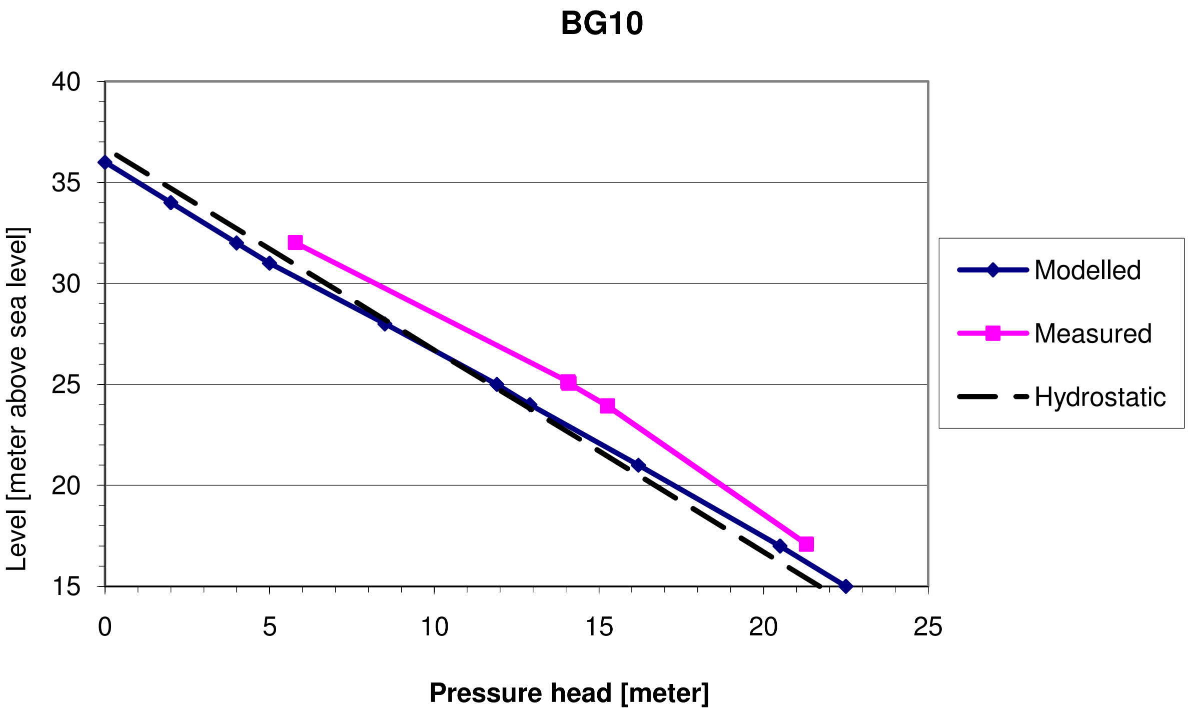
The hydraulic conductivity in the friction material has been measured in connection to an investigation of the consequences of a lowering of the groundwater table in the area (Aqualog, 2008, p 7). These values have been used to estimate the hydraulic conductivities in the friction layers. No measurements of hydraulic conductivity have been performed in the clay layers, therefore typical values for the different aquitards have been used. These values were suggested in Berntson's thesis (1983, p 282), and can be seen in Appendix F together with the Seep/W-model.

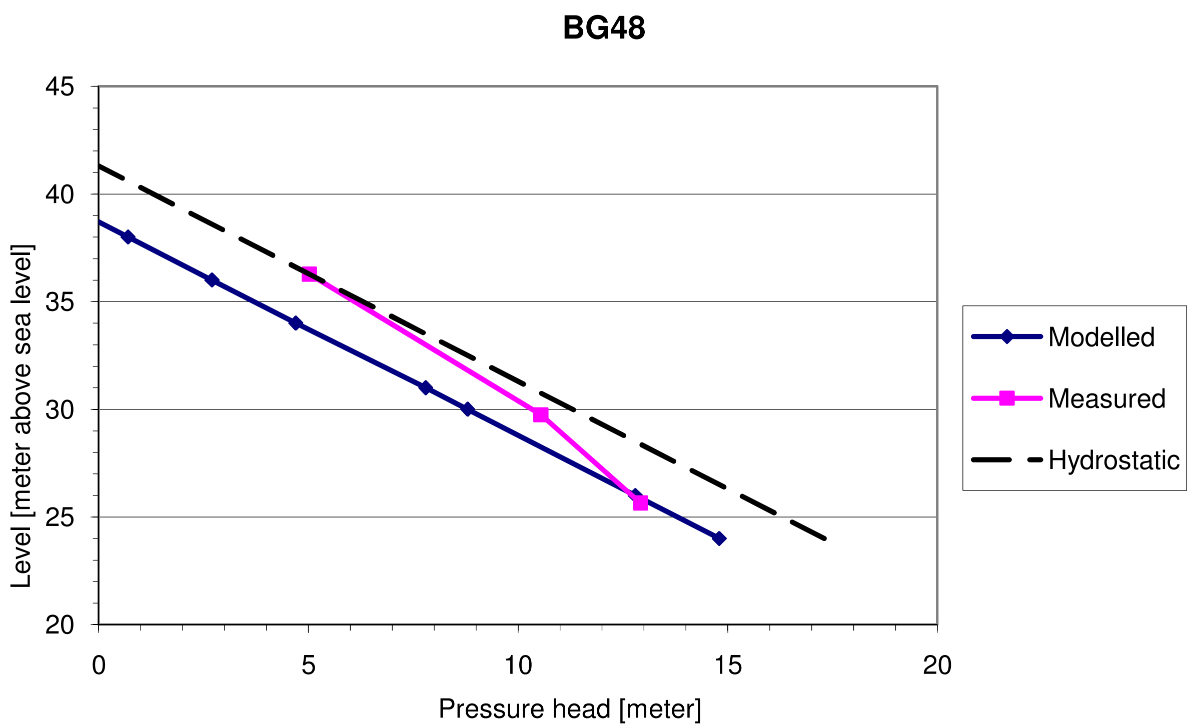
As a starting point in the modeling process a pressure head is assigned to the friction material at the hillsides. These heads are the expected groundwater table here and can be seen together with the Seep/W model in Appendix F. Also, a pressure head is put in Taske å. These values, together with the hydraulic conductivities, will govern the flow of water in the section.

6.5.3 Comparison between modelled and measured values

As expected, the model shows a groundwater flow from the hillsides down to the valley. Mainly, the groundwater flow takes place in the friction material and in the dry crust.

As a next step, the pore pressure values in the model are compared to the measured values. Graphs showing the pore pressure distribution are constructed for the measurement points listed in the table above (see Table 6.1). In the figures below, the pressure heads in BG10, BG128 and BG48 are plotted as a function of level above sea level.





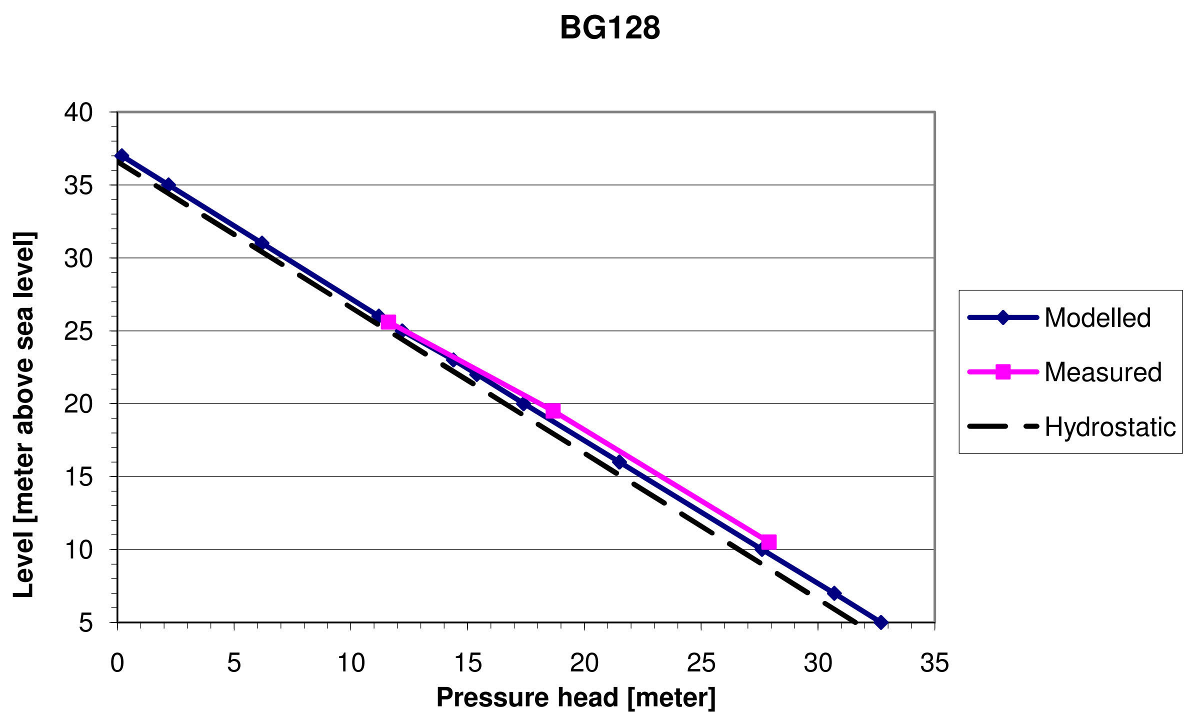


Figure 6.19: Graphs showing the pore pressure distribution with modelled and with measured values in measurement point BG10, BG48 and BG128. The pressure head is plotted against level above sea level.

In BG10 and in BG128 the modelled values show good correlation with the measured values. But in BG10 the measured pressure heads are larger than for the modelled situation. This may be caused by the landslide that made the pore pressure raise which has been mentioned earlier and is shown in Figure 5.3. Also, in BG48 the measured values are larger than the modelled ones probably because the complex structure with friction layers here should be defined more carefully in the model.

Furthermore, the flow gradients for the measured and the modelled values do not correlate very good. In BG48 for example it is clear that the flow gradient is directed downwards but the modelled values are hydrostatic. The same kind of situations can be seen in BG10 and BG128 as well.

7 Discussion

The different zones in the model described in chapter 1 were identified in the chosen different measurement points in the investigation area. The pore pressure profiles mostly followed the typical behavior for a clay profile in the southwest of Sweden. The pore pressures in aquitard II and in the lower aquifer correlated well with the typical pore pressure profiles stated in the model in chapter 1.

As stated in chapter 1, the pore pressure is assumed to increase hydrostatic or close to hydrostatic in the upper aquifer, and also in aquitard I. The result of the analysis is that the pore pressure in some cases seems to increase more than hydrostatic at these depths, for example in point BG125 and BG128. With a hydrostatic increase of the pore pressure, a groundwater table above ground surface would occur, which has not been observed on the investigation site. Probably, there are layers of non permeable soils in the upper aquitard or upper aquifer that makes higher gradients than hydrostatic possible.

In the section modelled in Seep/W, geotechnical soundings show that there are layers of friction material present in the clay. The location and extension of these layers should be investigated further, and also how these layers are connected. Furthermore, the flow gradients could be adjusted by adding precipitation to the Seep/W model. The measured values are taken from February 2008 which means that raining probably has affected them.

Also, the hydraulic conductivities should be investigated further to calibrate the Seep/W model. Another possible source of error in this model may be the fact that the three-dimensional flow is not taken into account. Earlier evaluations of the measured values show that there is a groundwater flow towards north in the valley in other words a flow that is directed perpendicular into the flat model.

As a next step of the analysis, the pore pressures modelled in Seep/W should be put into a Slope/W model where slope stability analyses take place. Eventually, Seep/W-modelled pore pressures can give a more realistic stability analyses than Slope/W-modelled pore pressures, which was used in the stability analyses in Hartlén (2007).

8 Conclusions

The result of the evaluation of pore pressure measurements in Småröd is that the groundwater is flowing into the valley from the south. Groundwater is also flowing into the valley from the sides of the valley. This confirms the groundwater flow situation that was stated in the report from Swedish Road Administration.

Berntson's model is in most cases applicable on the clay profiles. At the maximum cases, the pore pressure in the upper aquifer and aquitard I deviate from the hydrostatic pore pressure in some points in the valley. Therefore, when measuring pore pressures in clay profiles like these in Småröd, it is recommended to perform measurements also in the upper aquifer and aquitard I. To measure the pore pressure at two depths in those layers, for example at three and six meters depth is desirable.

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Appendix B

Point	Ground surface level [+]	Depth [m]	Level [+]	Start	End	Length of series [months]	Bottom of clay level [+]	Soil layer
BG10	36,70	12,80	23,90	Dec-06	Feb-10	38	17	si Le
BG10	36,70	11,60	25,10	Dec-06	Jan-10	37	17	si Le sa/si
BG10	36,70	4,70	32,00	Jan-07	Jan-10	36	17	Le
BG10	36,70	11,60	25,10	Jan-07	Jan-10	36	17	si Le sa/si
BG10	36,70	19,60	17,10	Jan-07	Dec-08	23	17	Friction material
BG125	38,06	5,80	32,26	Feb-07	Jan-10	35	7	Le
BG125	38,06	11,90	26,16	Feb-07	Jan-10	35	7	Le
BG125	38,06	17,90	20,16	Feb-07	Jan-10	35	7	Friction material
BG125	38,06	2,90	35,16	Feb-07	Jan-10	35	7	Le
BG128	36,61	26,11	10,50	Mar-07	Jan-10	34	9	Le
BG128	36,61	11,00	25,61	Mar-07	Jan-10	34	9	Le
BG128	36,61	17,11	19,50	Mar-07	Jan-10	34	9	Le
BG151	35,70	2,95	32,75	Sep-07	Dec-09	27	20	si Le(t)
BG151	35,70	8,98	26,72	Sep-07	Jan-10	28	20	si Le
BG151	35,70	15,00	20,70	Sep-07	Jan-10	28	20	Friction material
BG175A	30,90	2,30	28,60	Apr-07	Jan-10	33	28	(le) sa Si
BG178	41,93	22,70	19,23	Dec-07	Jan-10	25	20	Friction material
BG178	41,93	11,09	30,84	Jan-08	Jan-10	24	20	Friction material
BG178	41,93	5,07	36,86	Dec-07	Jan-10	25	20	si Le
BG178	41,93	5,95	35,98	Jan-08	Jan-10	24	20	Le
BG180	39,11	22,67	16,44	Mar-07	Jan-10	34	16	Friction material
BG180	39,11	10,22	28,89	Mar-07	Jan-10	34	16	Friction material
BG180	39,11	5,31	33,80	Mar-07	Jan-10	34	16	Le
BG197	40,75	12,40	28,35	Mar-07	Jan-10	34	28	Friction material
BG2	42,17	6,07	36,10	Jan-07	Jan-10	36	36	Friction material
BG213	37,87	7,02	30,85	May-07	Jan-10	32	-3	Le
BG213	38,87	16,01	22,86	May-07	Jan-10	32	-3	Le
BG213	39,87	27,13	12,74	May-07	Jan-10	32	-3	Le
BG214	38,87	16,01	22,86	May-07	Jan-10	32	-2	Friction material
BG216	41,05	4,10	36,95	Feb-07	Jan-10	35	37	Friction material
BG221	34,20	24,99	9,21	Mar-07	Jan-10	34	15	Friction material
BG221	34,20	20,61	13,59	Apr-07	Jan-10	33	15	Friction material

BG227	31,19	6,02	25,17	Apr-07	Jan-10	33	25	Friction material
BG227	31,19	2,97	28,22	Apr-07	Jan-10	33	25	si Le
BG229	30,73	7,06	23,67	Aug-07	Jan-10	29	24	Friction material
BG229	30,73	5,00	25,73	Sep-08	Jan-10	16	24	Le
BG232	34,17	12,02	22,15	Apr-07	Jan-10	33	22	Friction material
BG232	34,17	7,06	27,11	Apr-07	Jan-10	33	22	si Le (gr)
BG232	34,17	3,01	31,16	Apr-07	Jan-10	33	22	Si Le sa sk
BG233	33,70	10,54	23,16	Aug-07	Jan-10	29	22	Friction material
BG233	33,70	5,00	28,70	Aug-07	Jan-10	29	22	Le
BG234	32,56	5,87	26,69	Aug-07	Jan-10	29	20	Le
BG234	32,56	11,86	20,70	Aug-07	Jan-10	29	20	Friction material
BG42	39,79	25,60	14,19	Feb-07	Jan-10	35	14	Friction material
BG42	39,79	10,10	29,69	Feb-07	Jan-10	35	14	Friction material
BG42	39,79	18,20	21,59	Feb-07	Jan-10	35	14	Friction material
BG420	31,64	8,46	23,18	Jan-09	Dec-09	11		
BG421	31,20	4,75	26,45	Nov-08	Jan-10	14		
BG43	41,20	7,20	34,00	Jan-07	Jan-10	36	26	Friction material
BG44	43,27	14,15	29,12	Jan-07	Jan-10	36	32	Stopp mot sten
BG48	41,29	5,01	36,28	Mar-07	Jan-10	34	25	Le
BG48	41,29	15,64	25,65	Mar-07	Jan-10	34	25	Friction material
BG48	41,29	11,54	29,75	Mar-07	Jan-10	34	25	Friction material
BG49	46,20	6,08	40,12	Feb-07	Jan-10	35	40	Friction material
BG66	40,15	5,29	34,86	Mar-07	Jan-10	34	34	Friction material
BG88	51,09	8,44	42,65	Apr-07	Jan-10	33	42	Friction material
BG92	43,05	14,06	28,99	May-07	Jan-10	32	35	Friction material
BG92	43,05	8,55	34,50	May-07	Jan-10	32	35	Friction material
R304	35,86	10,20	25,66	Apr-07	Jun-08	14	25	siLe si
R304	35,86	9,20	26,66	Apr-07	Jun-08	14	25	siLe si
R304	35,86	5,00	30,86	Apr-07	Jun-08	14	25	grsaLe
R402	42,43	15,40	27,03	Jan-07	May-09	28	27	Friction material
R402	42,43	12,40	30,03	Jan-07	May-09	28	27	Le
R402	42,43	6,00	36,43	Jan-07	May-09	28	27	Le
R504	31,57	8,90	22,67	Jan-07	Apr-09	27	22	grsasi Le
R504	31,57	8,90	22,67	Mar-07	Sep-08	18	22	
R513	36,12	6,35	29,77	Jan-07	Apr-09	27	29	
R7001	41,46	4,30	37,16	May-07	Apr-09	23	32	si Le

R7001	41,46	6,80	34,66	May-07	Apr-09	23	32	Le
R7001	41,46	6,50	34,96	May-07	Apr-09	23	32	Le
R705	30,70	4,82	25,88	Mar-07	Jan-10	34	26	Friction material
R7402	39,05	19,00	20,05	Apr-07	Jan-08	9	20	Friction material
R7402	39,05	10,10	28,95	Apr-07	Jun-08	14	20	
R7402	39,05	6,50	32,55	Apr-07	Jun-08	14	20	Friction material
R7506	42,77	6,00	36,77	Apr-07	Jun-08	14		Le
R7507	38,09	12,20	25,89	Apr-07	Jun-08	14	25	Friction material
R7507	38,09	7,41	30,68	Apr-07	Jun-08	14	25	Le
R7507	38,09	5,01	33,08	Apr-07	Jun-08	14	25	Le
S605	39,17	20,10	19,07	Feb-07	Jun-08	16	5	siLe si sa
S605	39,17	10,10	29,07	Mar-07	Jun-08	15	5	susiLe
S605	39,17	5,00	34,17	Feb-07	Jun-08	16	5	suLe (sk)
S605	39,17	33,20	5,97	Feb-07	Jun-08	16	5	Friction material
T17	37,21	3,80	33,41	Feb-08	Apr-09	14	13	sasiLe
T17	37,21	3,90	33,31	Feb-08	Apr-09	14	13	sasiLe
T17	37,21	6,00	31,21	Feb-08	Apr-09	14	13	Le
T17	37,21	23,50	13,71	Feb-08	Apr-09	14	13	Friction material
T17	37,21	14,20	23,01	Feb-08	Apr-09	14	13	Le
T4	37,77	12,30	25,47	Apr-07	Jun-08	14	5	Le
T4	37,77	5,90	31,87	Apr-07	Jun-08	14	5	Le
T4	37,77	16,90	20,87	Apr-07	Jun-08	14	5	Le
T4	37,77	18,30	19,47	Apr-07	Jun-08	14	5	Le
T4	37,77	32,00	5,77	Apr-07	Jun-08	14	5	Le
T5	37,49	20,00	17,49	Feb-08	Jun-08	4		
T5	37,49	10,00	27,49	Feb-08	Jun-08	4		Le
T8	38,32	6,00	32,32	Apr-07	Jun-08	14	-5	Le
T8	38,32	10,50	27,82	Apr-07	Apr-09	24	-5	Le
T8	38,32	24,50	13,82	Apr-07	Jun-08	14	-5	Le
T8	38,32	20,00	18,32	Apr-07	Apr-09	24	-5	Le
T8	38,32	33,80	4,52	Apr-07	Jun-08	14	-5	Le
T8	38,32	3,00	35,32	Feb-08	Jun-08	4	-5	Le

Appendix C

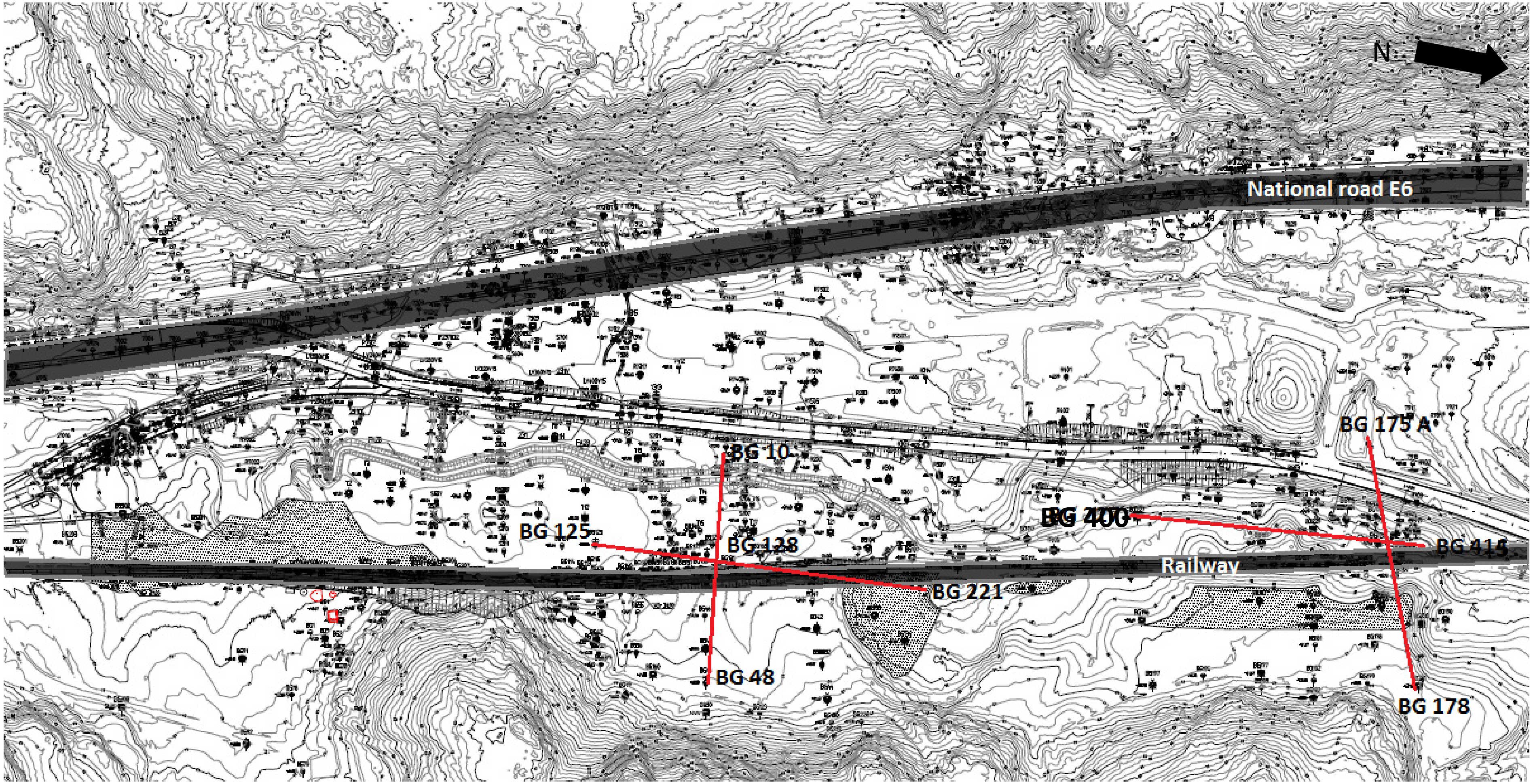


Figure 1: Plan of investigated area with studied sections marked with lines.

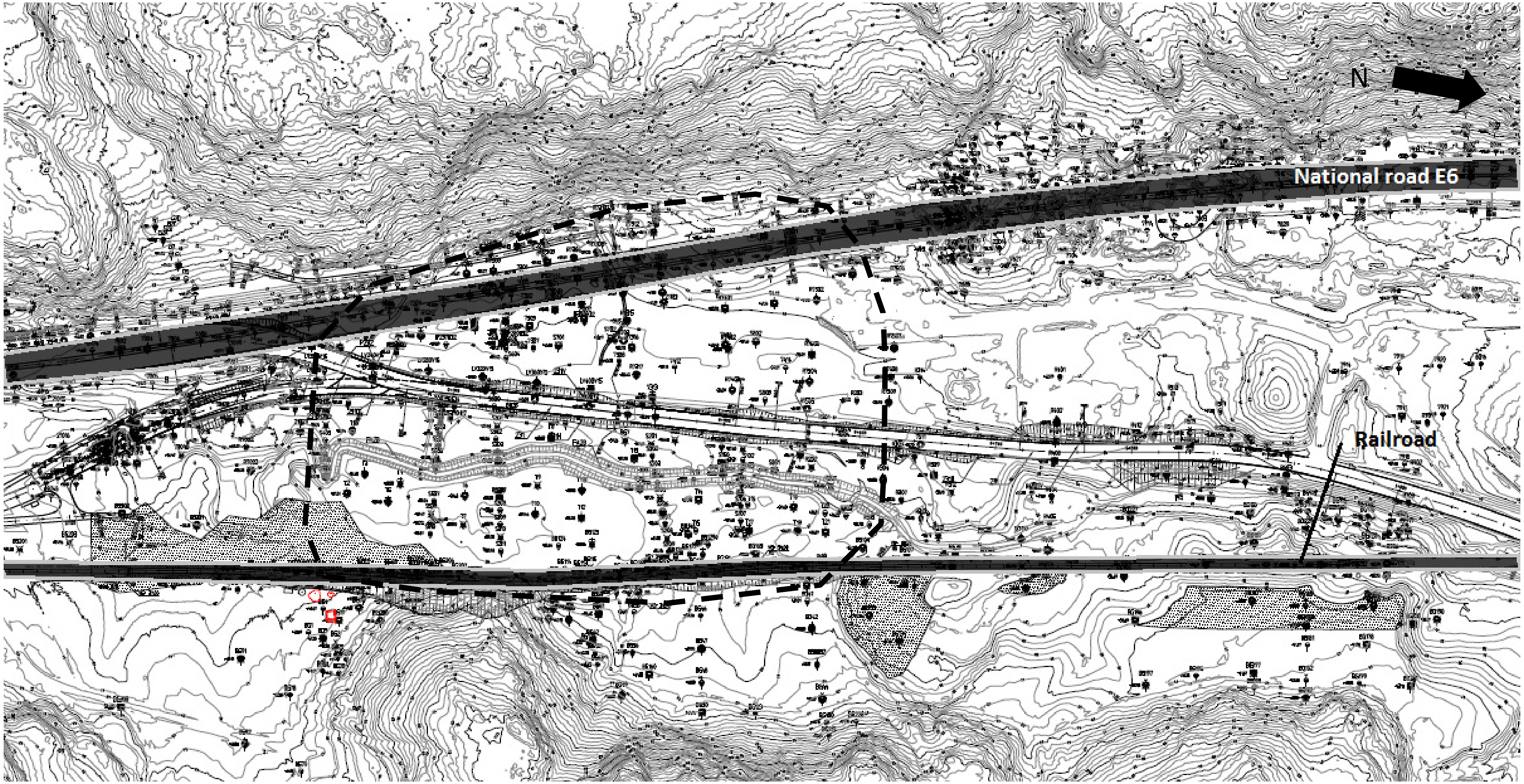
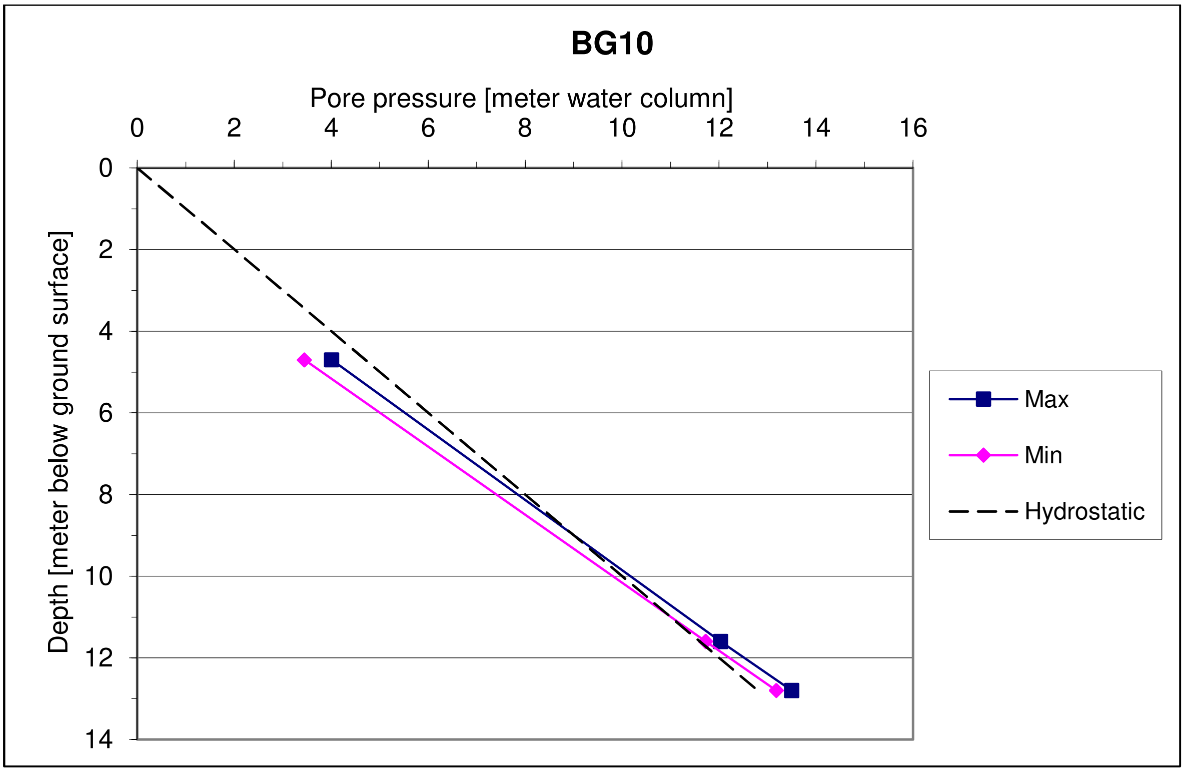
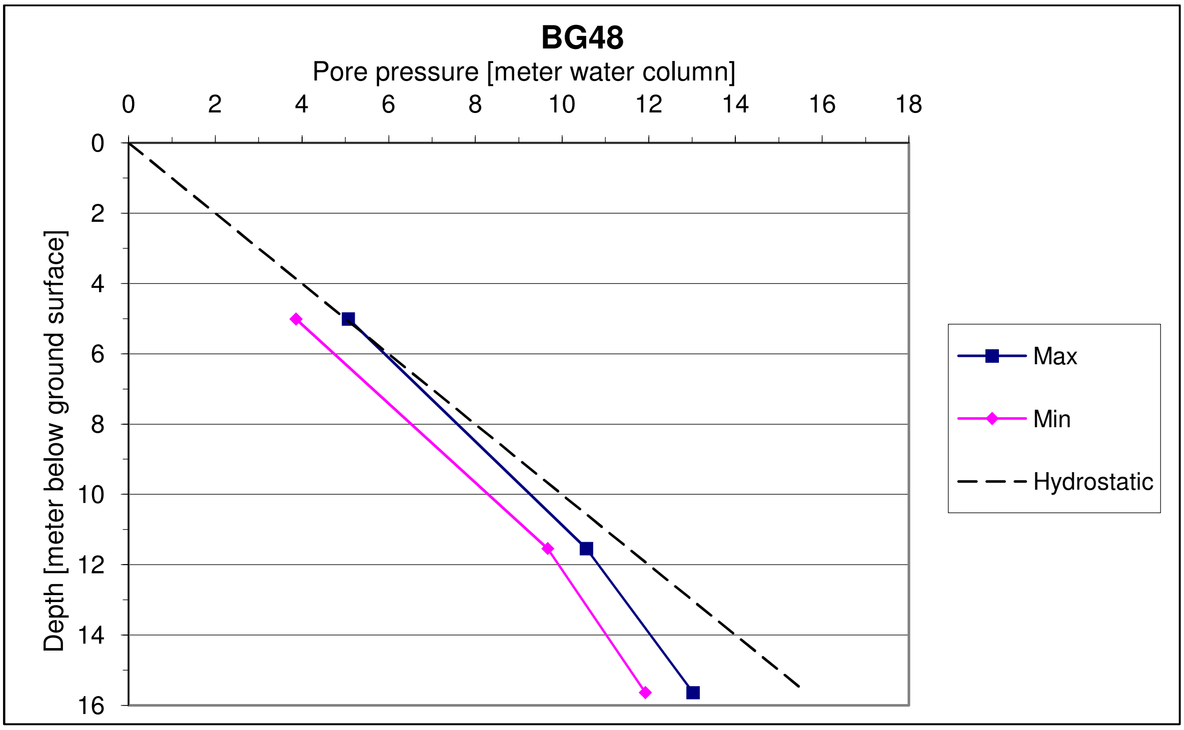


Figure 2: Plan of investigated area. The approximate area affected by the landslide is marked by a dotted line in the figure.

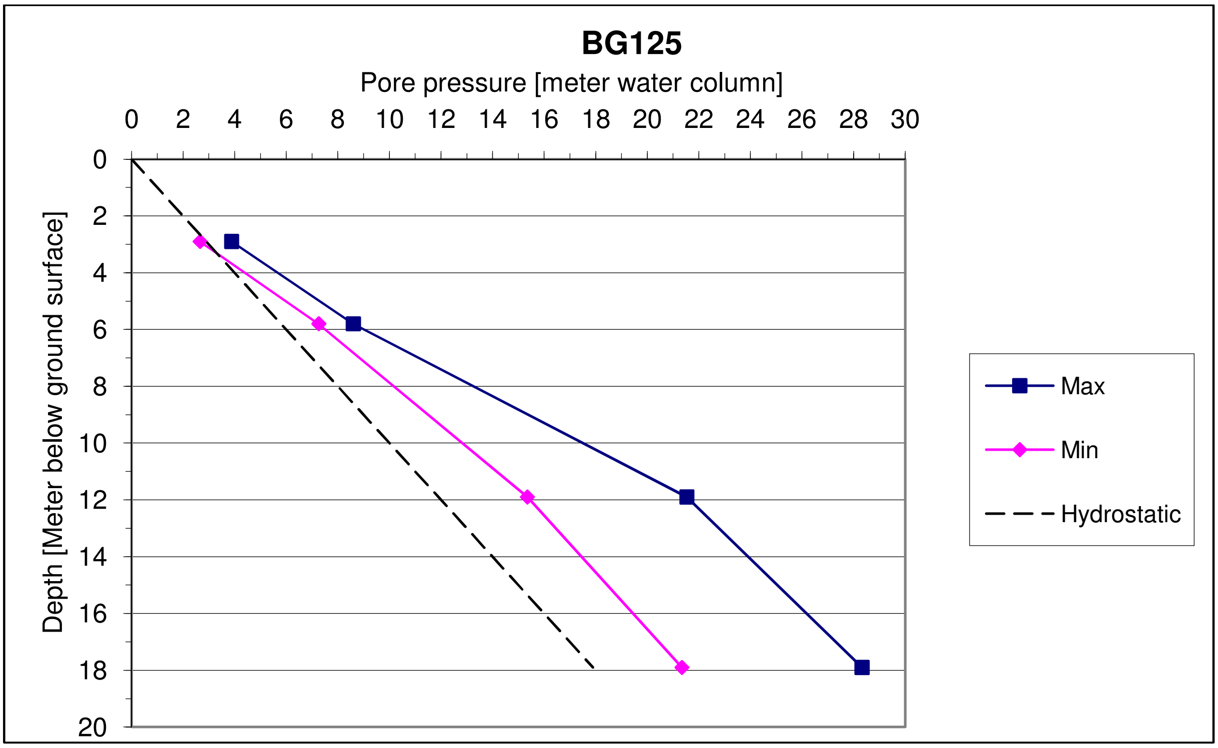
Appendix D

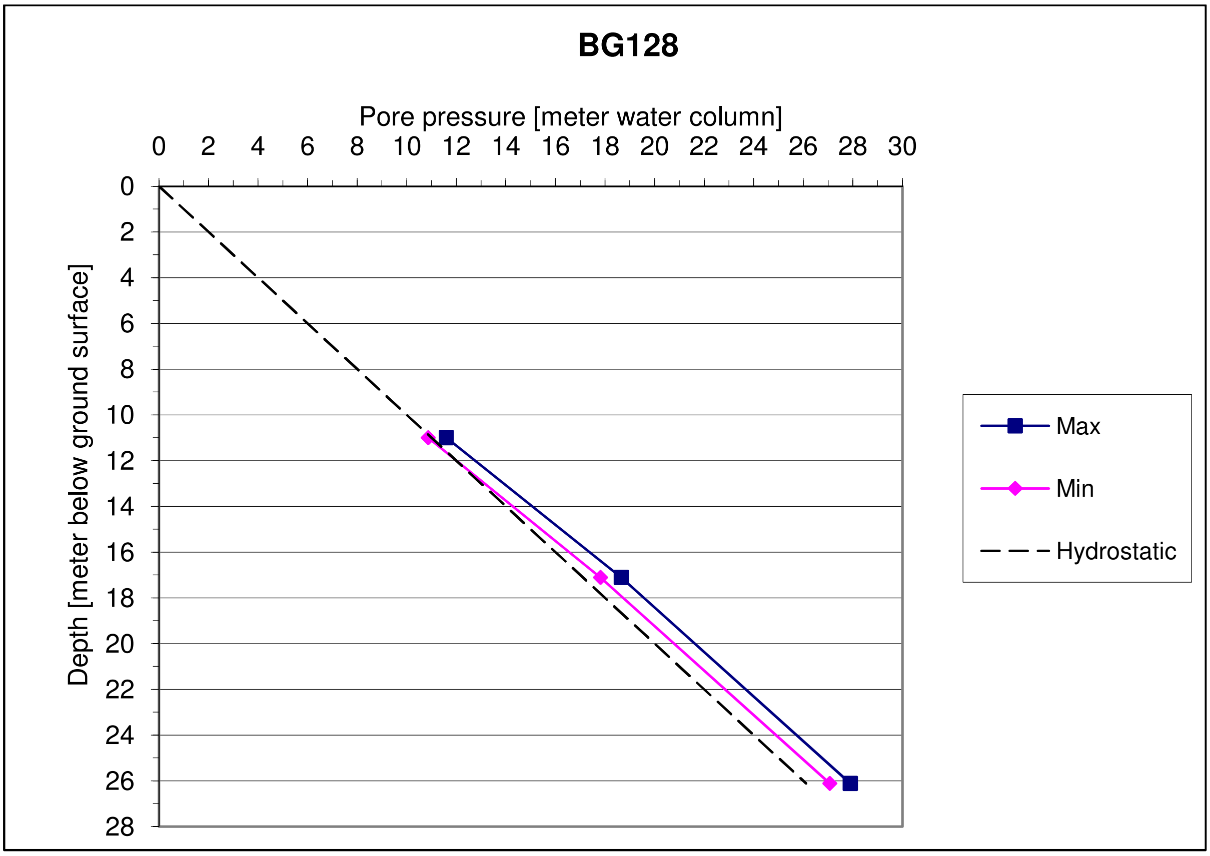


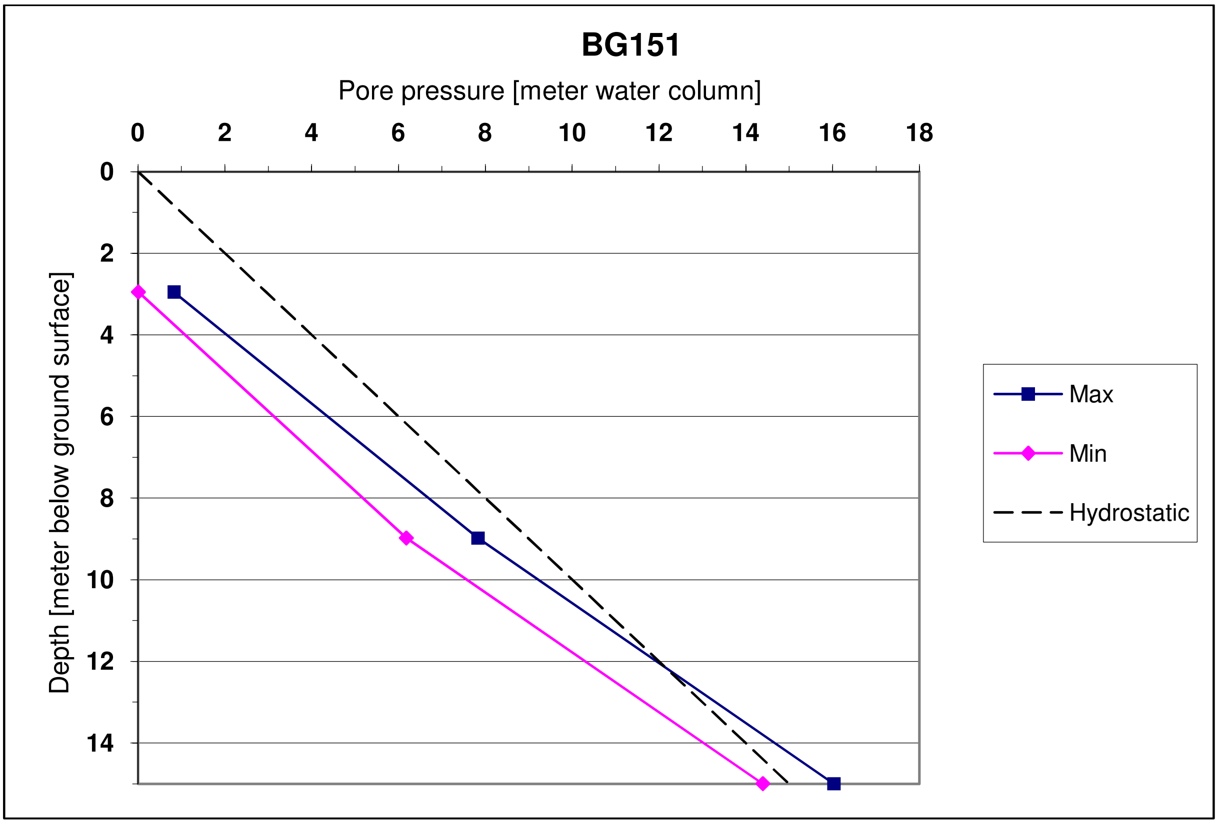
BG10
Pore pressure [meter water column]
0
2
4
6
8
10
12
14
16
Depth [meter below ground surface]
0
2
4
6
8
10
12
14
Max
Min
Hydrostatic

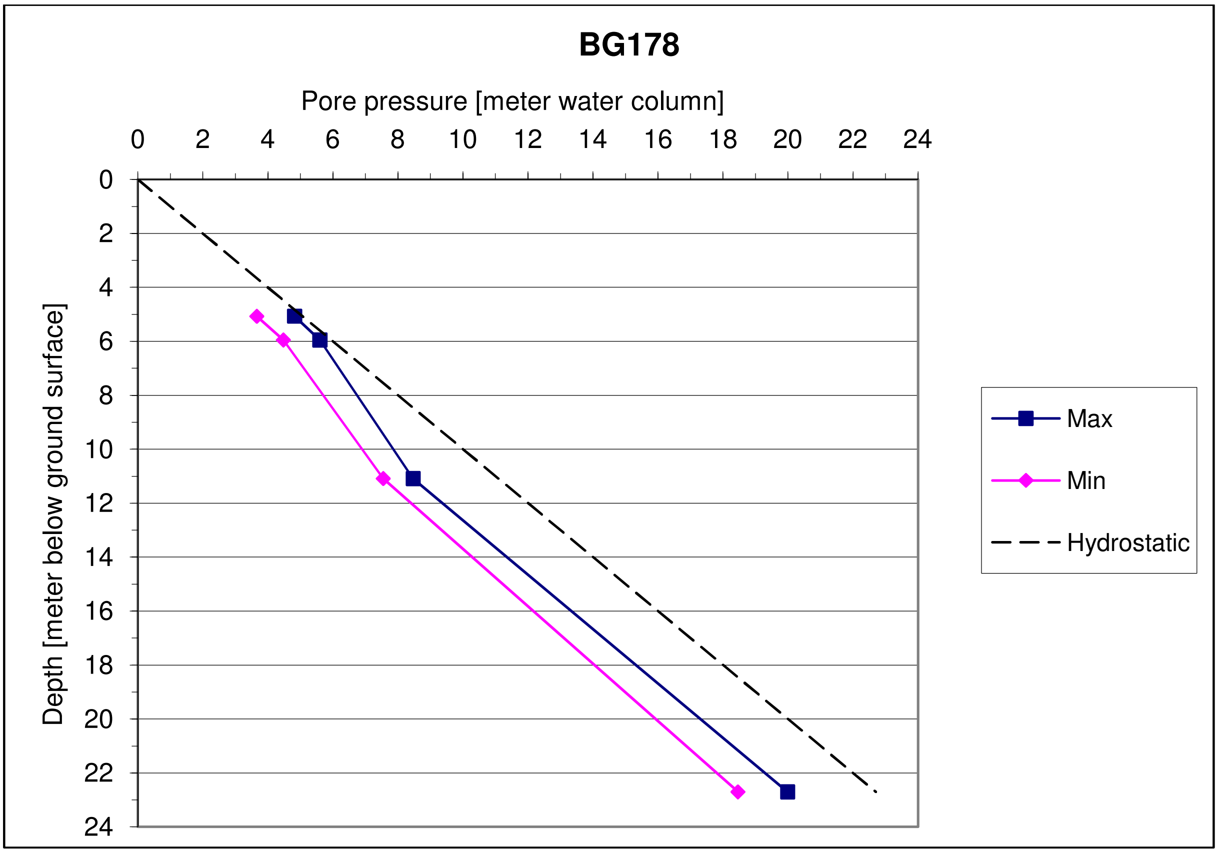


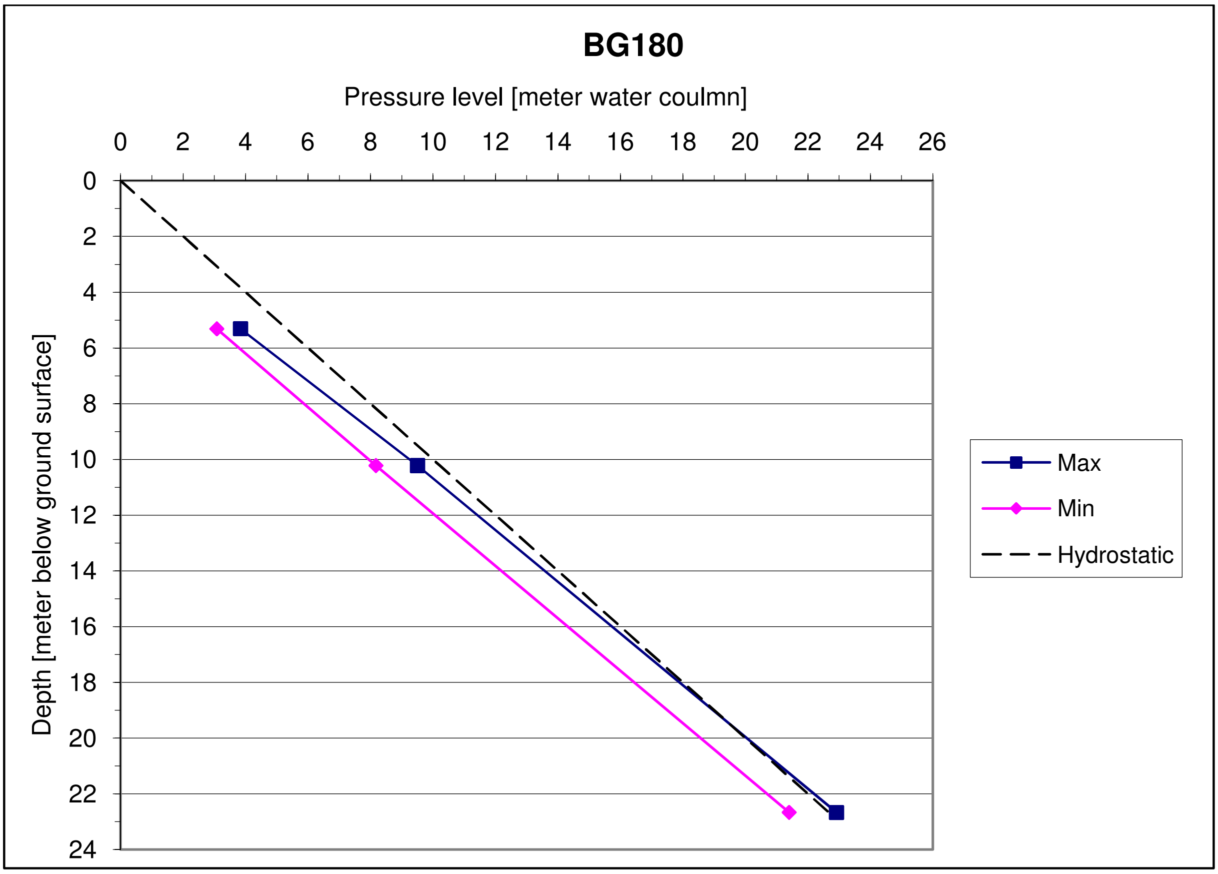
BG48
Pore pressure [meter water column]
0
2
4
6
8
10
12
14
16
18
Depth [meter below ground surface]
0
2
4
6
8
10
12
14
16
Max
Min
Hydrostatic

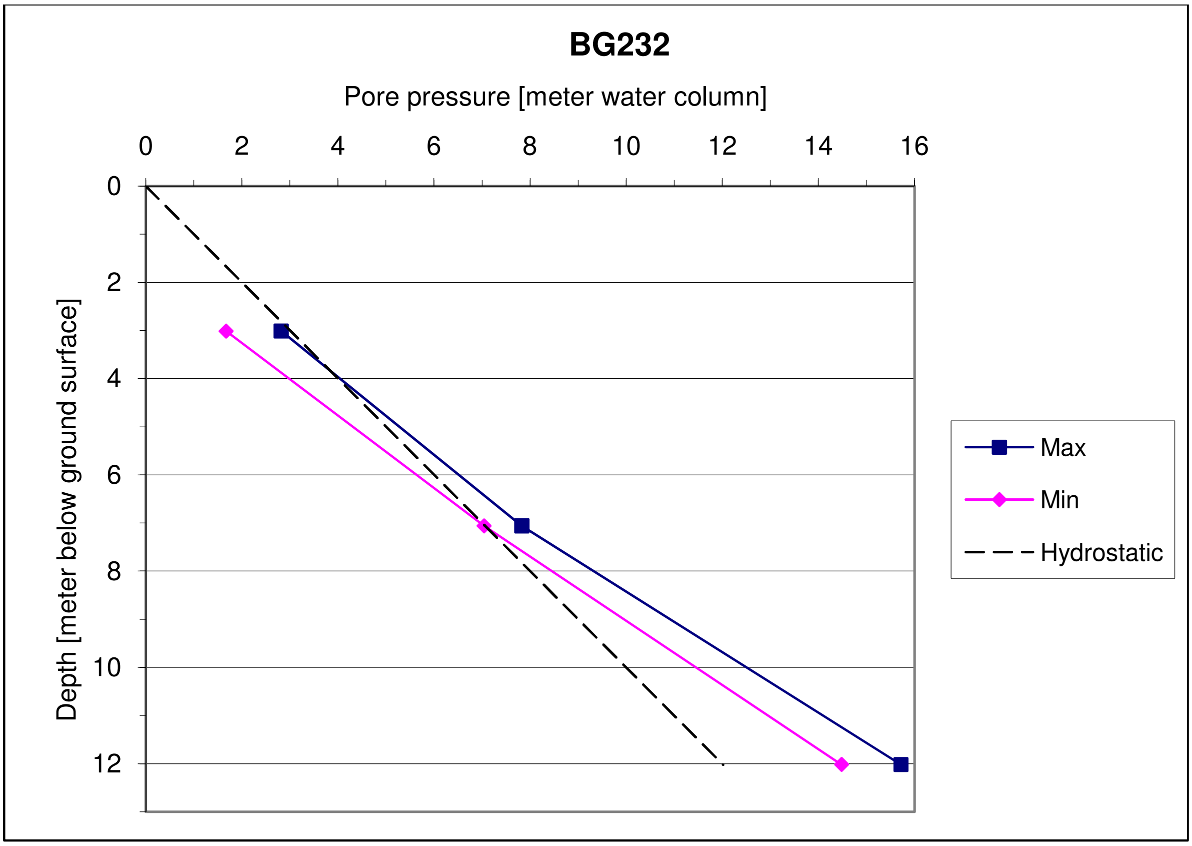

BG125
Pore pressure [meter water column]
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Depth [Meter below ground surface]
0 2 4 6 8 10 12 14 16 18 20
Max
Min
Hydrostatic

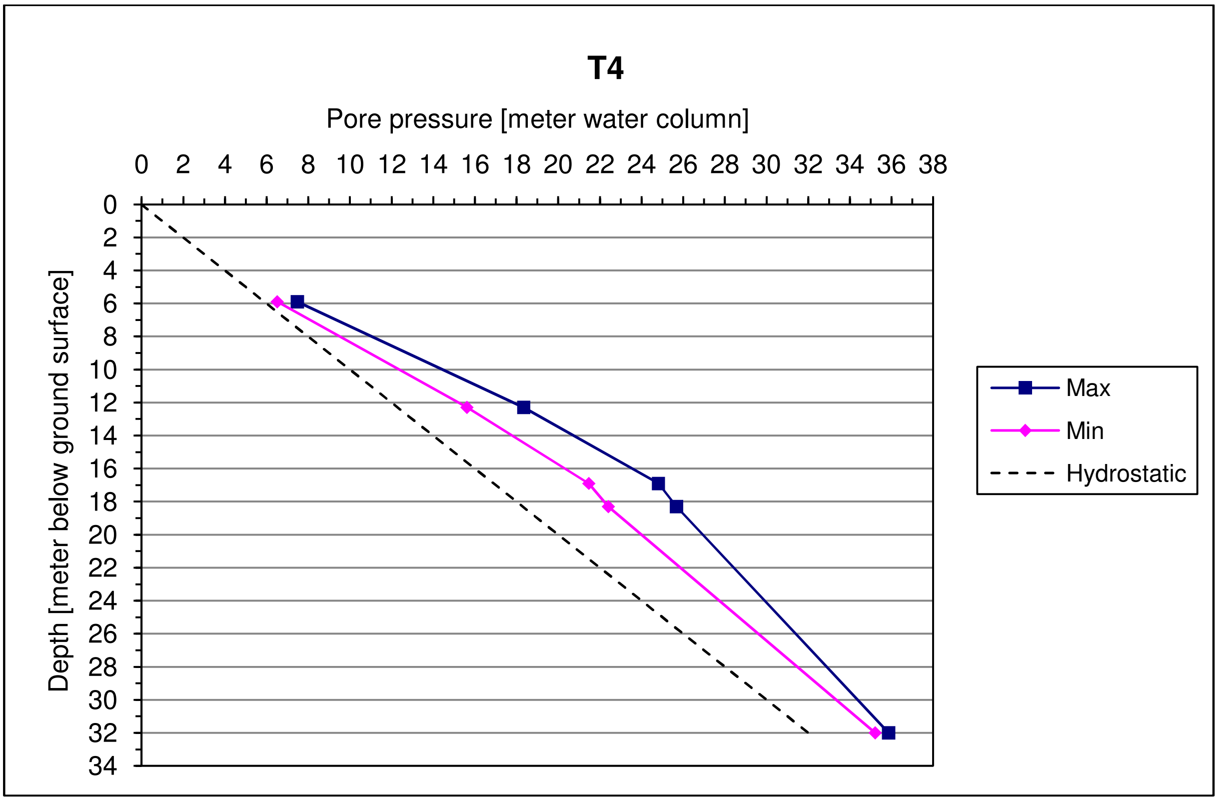

BG128
Pore pressure [meter water column]
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Depth [meter below ground surface]
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28
Max
Min
Hydrostatic

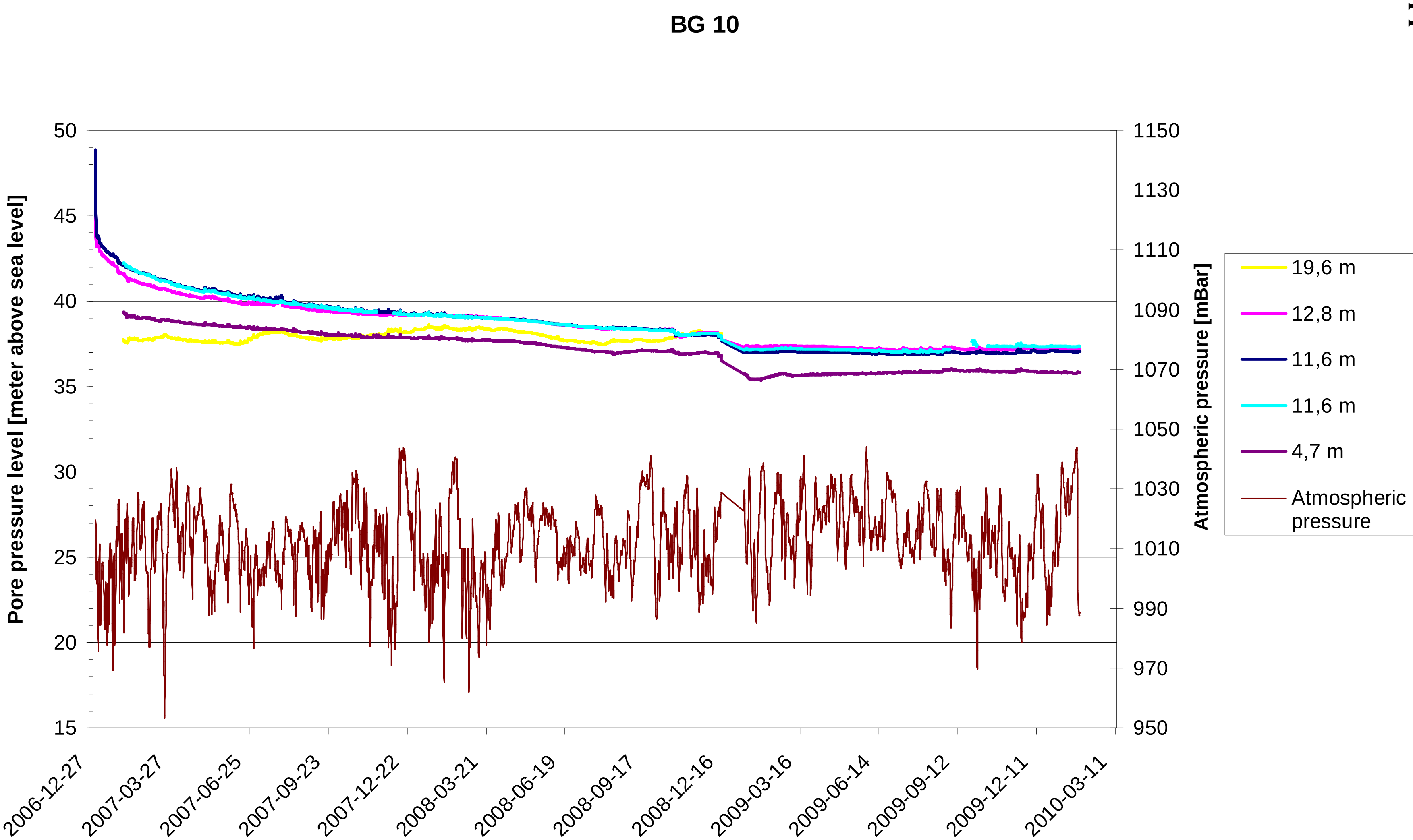

BG151
Pore pressure [meter water column]
0
2
4
6
8
10
12
14
16
18
Depth [meter below ground surface]
Max
Min
Hydrostatic

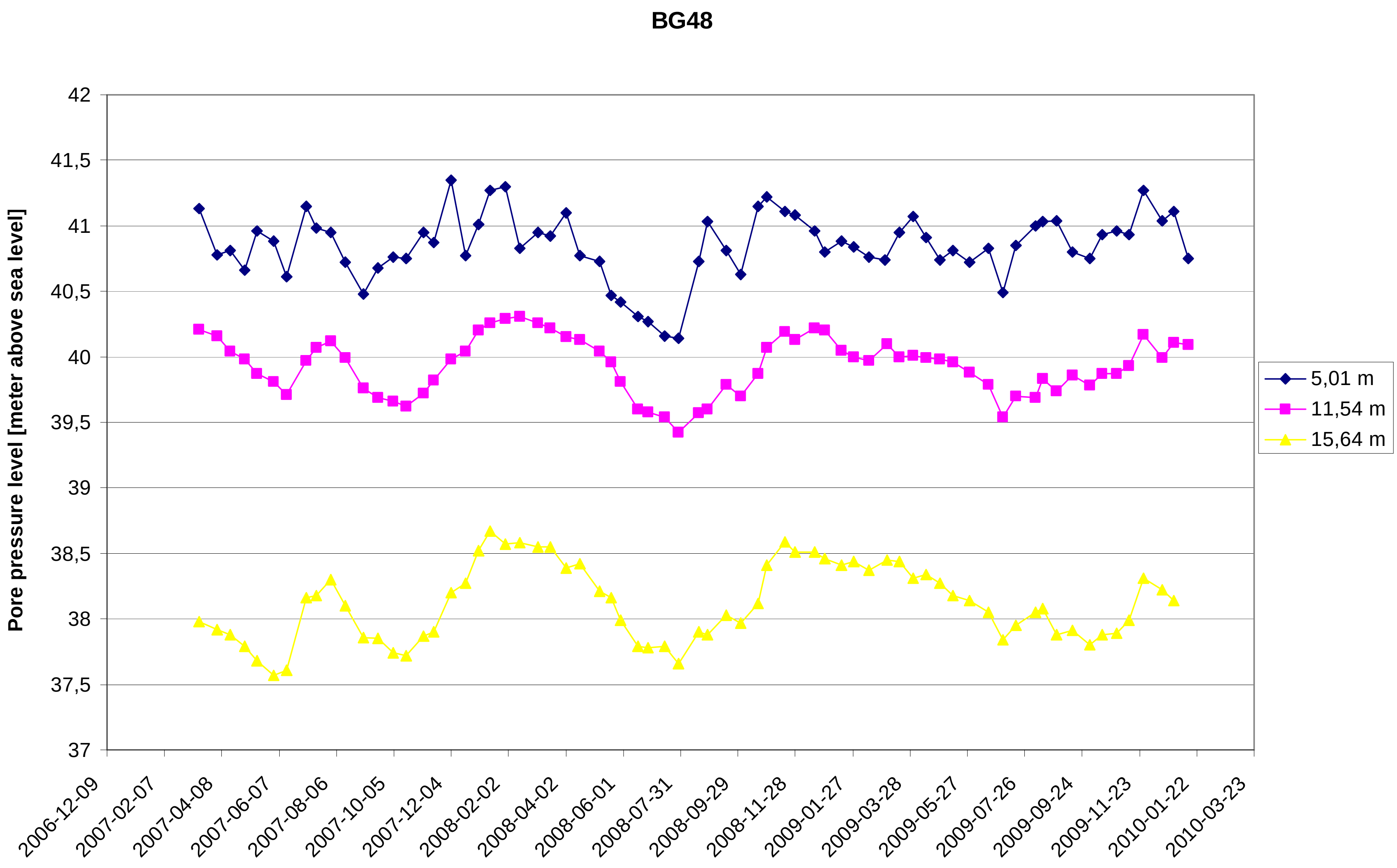

BG178
Pore pressure [meter water column]
0
2
4
6
8
10
12
14
16
18
20
22
24
Depth [meter below ground surface]
Max
Min
Hydrostatic

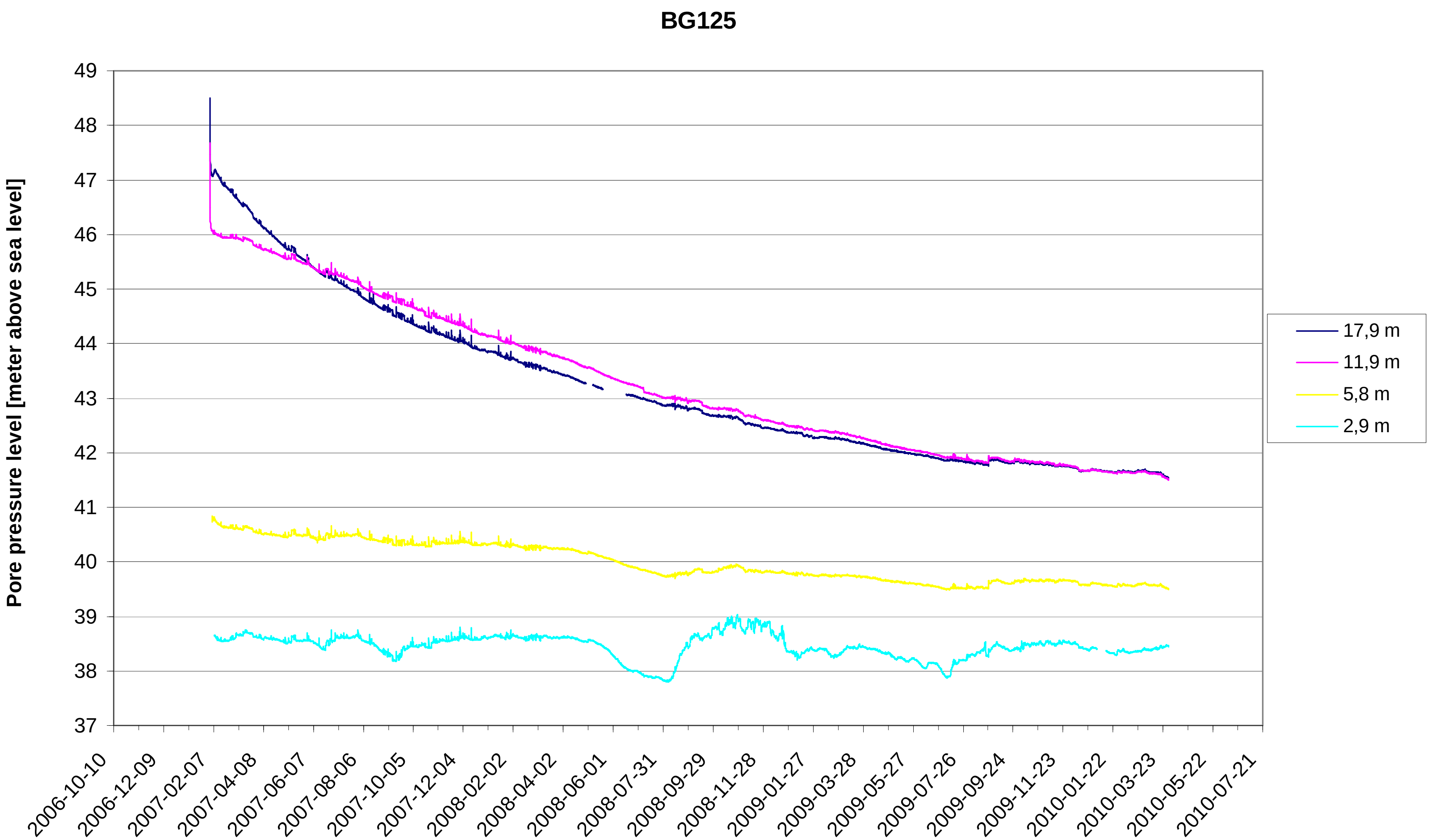

BG180
Pressure level [meter water coulmn]
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Depth [meter below ground surface]
Max
Min
Hydrostatic


BG232
Pore pressure [meter water column]
0
2
4
6
8
10
12
14
16
Depth [meter below ground surface]
Max
Min
Hydrostatic

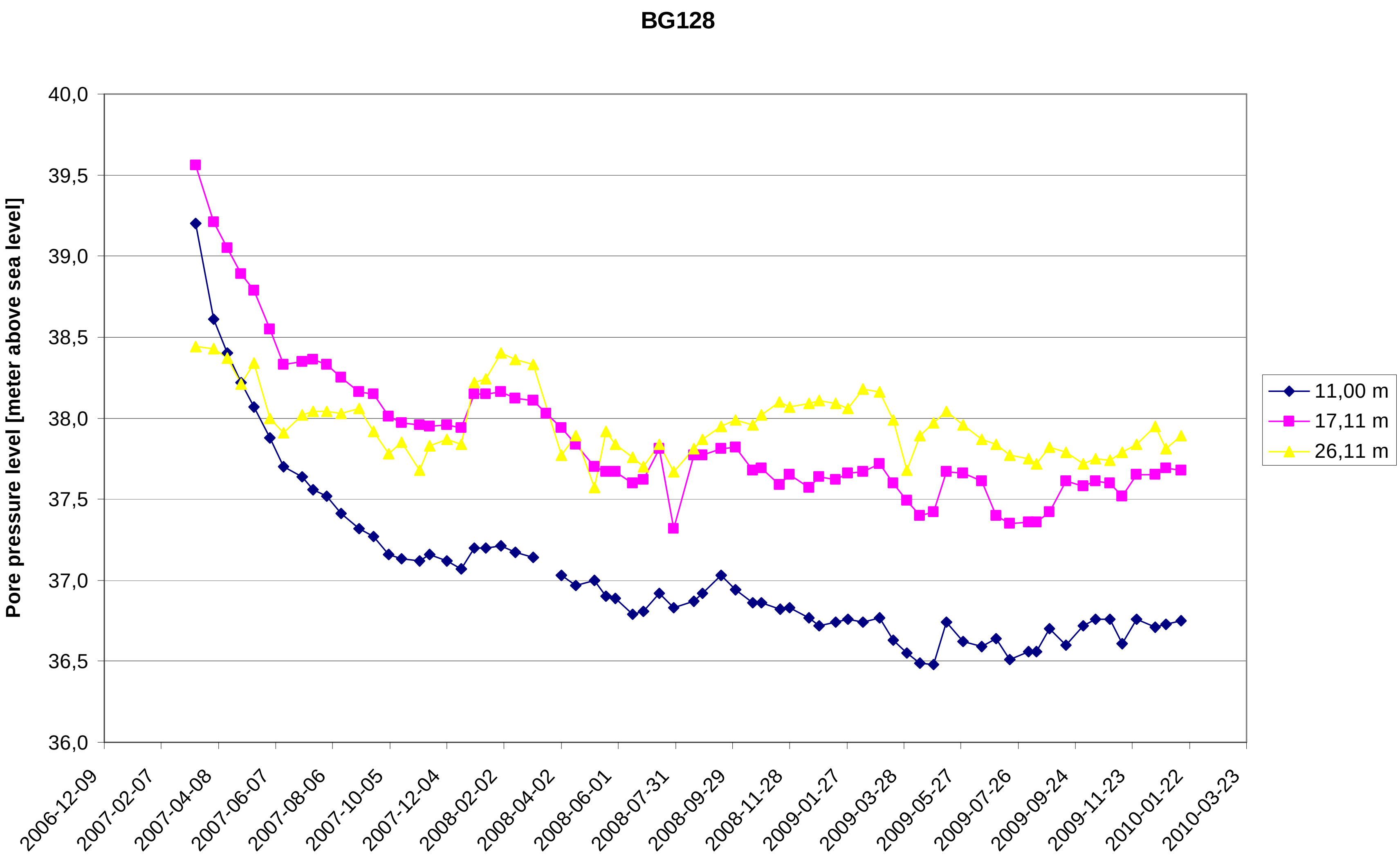

T4
Pore pressure [meter water column]
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Depth [meter below ground surface]
Max
Min
Hydrostatic

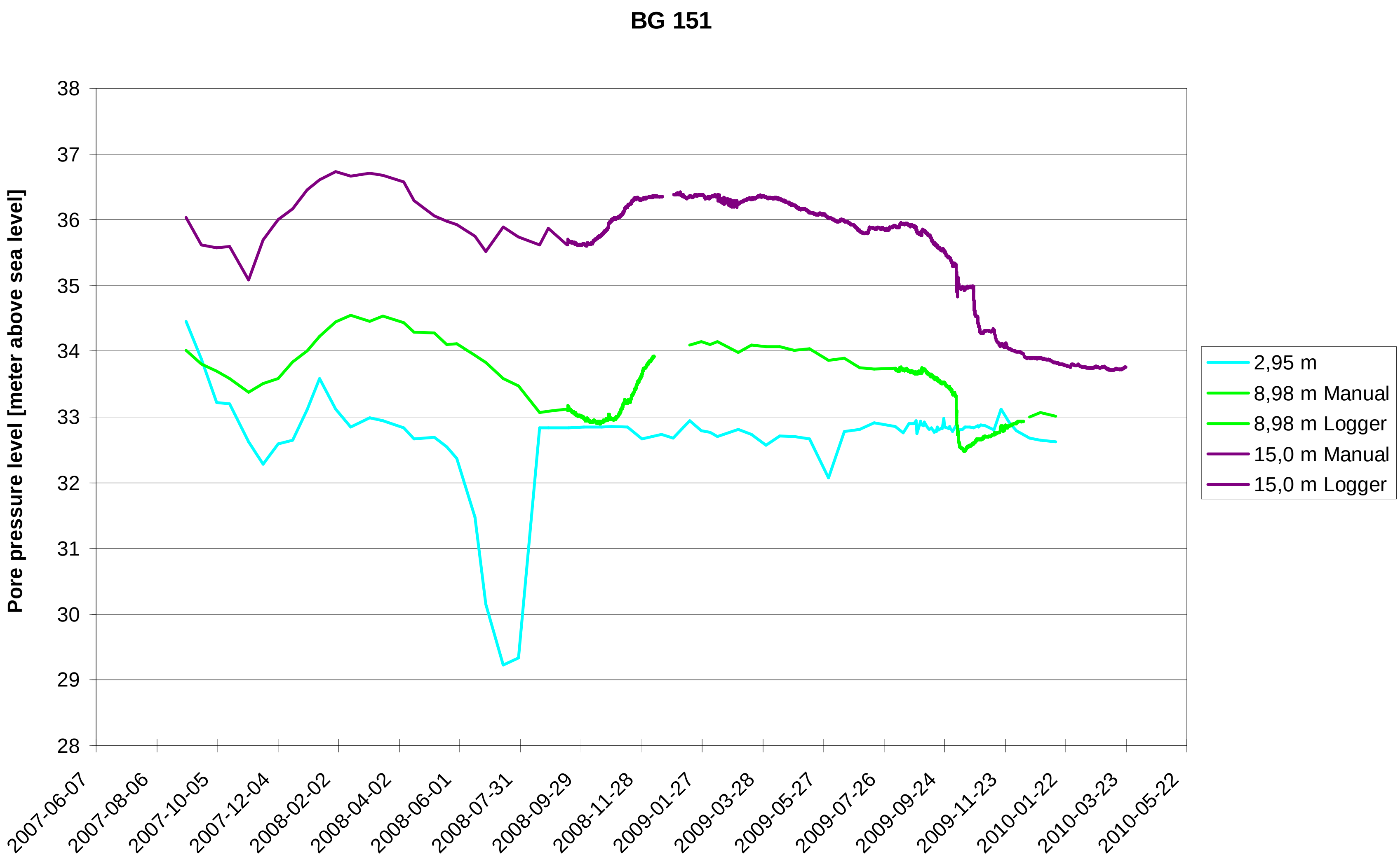

BG 10
Pore pressure level [meter above sea level]
Atmospheric pressure [mBar]
50
45
40
35
30
25
20
15
1150
1130
1110
1090
1070
1050
1030
1010
990
970
950
2006-12-27
2007-03-27
2007-06-25
2007-09-23
2007-12-22
2008-03-21
2008-06-19
2008-09-17
2008-12-16
2009-03-16
2009-06-14
2009-09-12
2009-12-11
2010-03-11
19,6 m
12,8 m
11,6 m
11,6 m
4,7 m
Atmospheric pressure

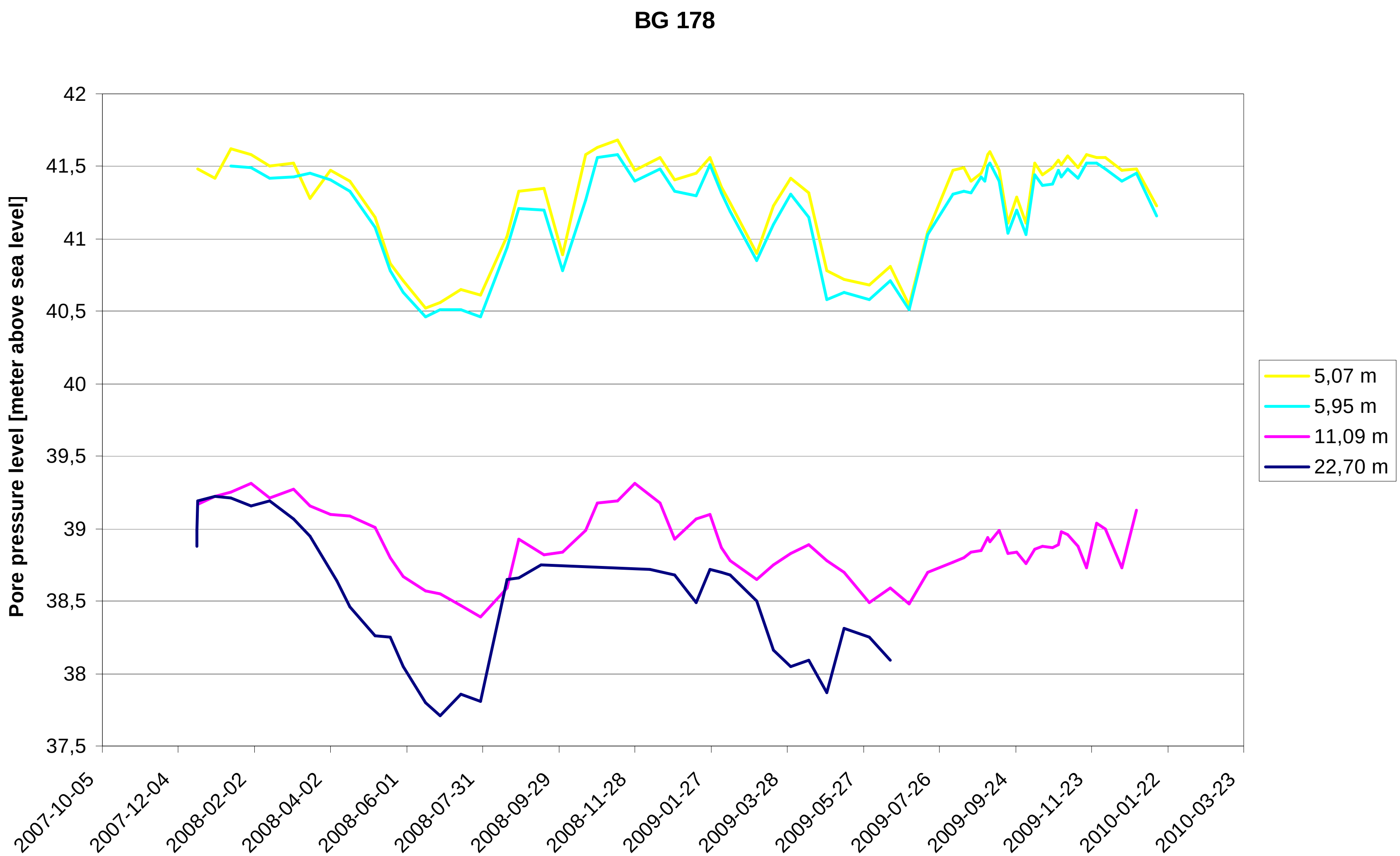

BG48
Pore pressure level [meter above sea level]
42
41,5
41
40,5
40
39,5
39
38,5
38
37,5
37
2006-12-09
2007-02-07
2007-04-08
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
5,01 m
11,54 m
15,64 m

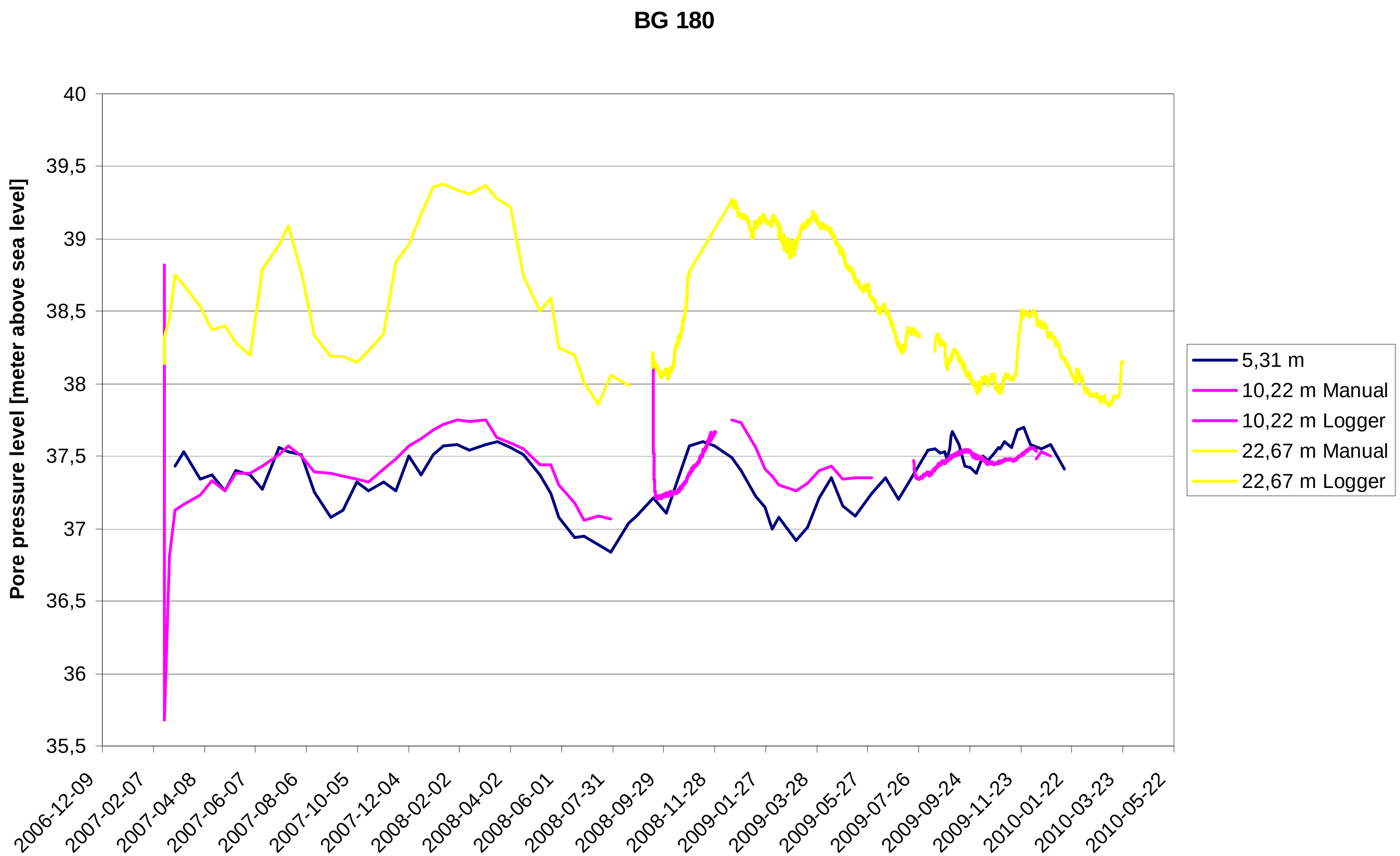


BG125
Pore pressure level [meter above sea level]
49
48
47
46
45
44
43
42
41
40
39
38
37
2006-10-10
2006-12-09
2007-02-07
2007-04-08
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
2010-05-22
2010-07-21
17,9 m
11,9 m
5,8 m
2,9 m


BG128
Pore pressure level [meter above sea level]
40,0
39,5
39,0
38,5
38,0
37,5
37,0
36,5
36,0
2006-12-09
2007-02-07
2007-04-08
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
11,00 m
17,11 m
26,11 m

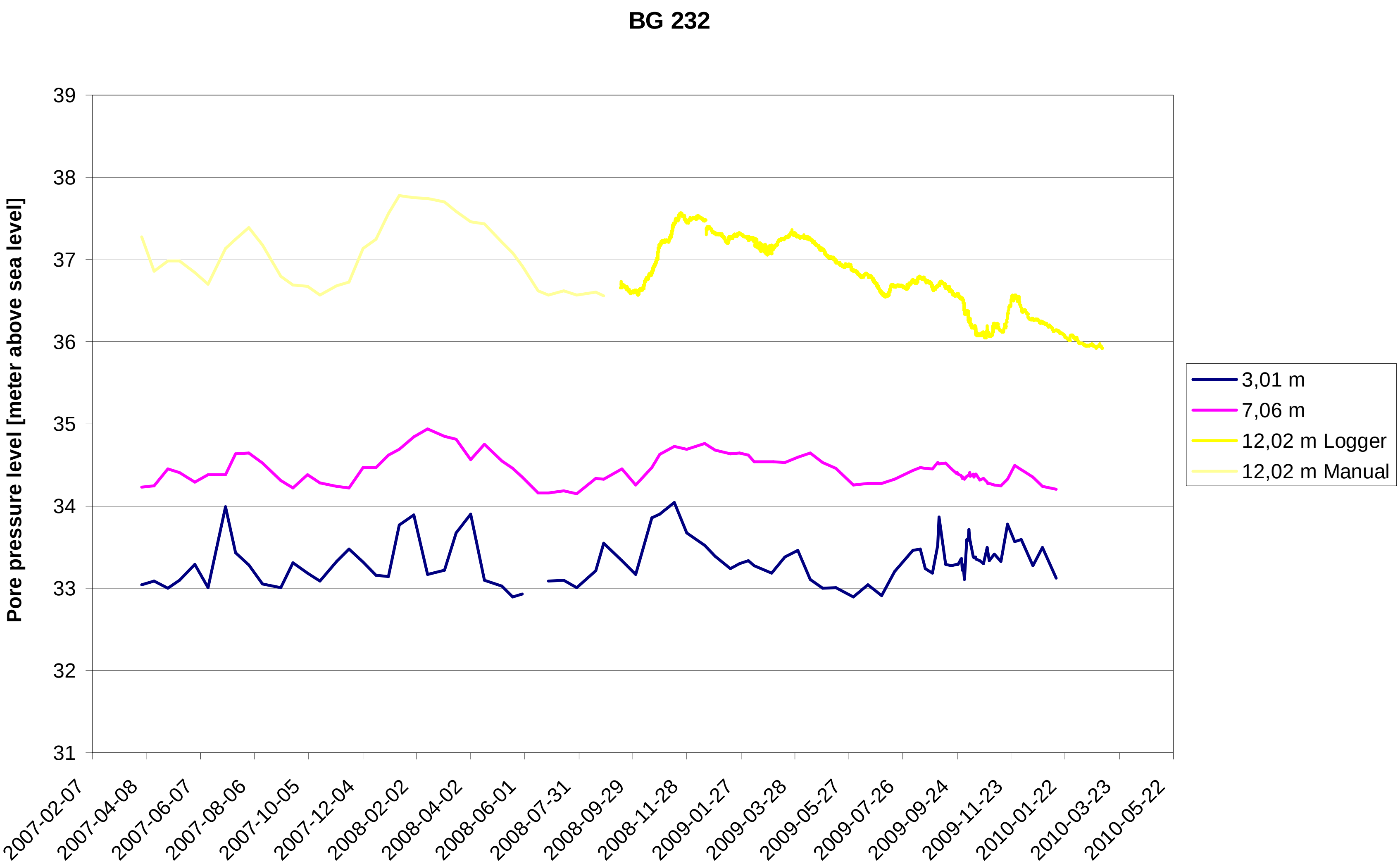

BG 151
Pore pressure level [meter above sea level]
38
37
36
35
34
33
32
31
30
29
28
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
2010-05-22
2,95 m
8,98 m Manual
8,98 m Logger
15,0 m Manual
15,0 m Logger


BG 178
Pore pressure level [meter above sea level]
42
41,5
41
40,5
40
39,5
39
38,5
38
37,5
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
5,07 m
5,95 m
11,09 m
22,70 m



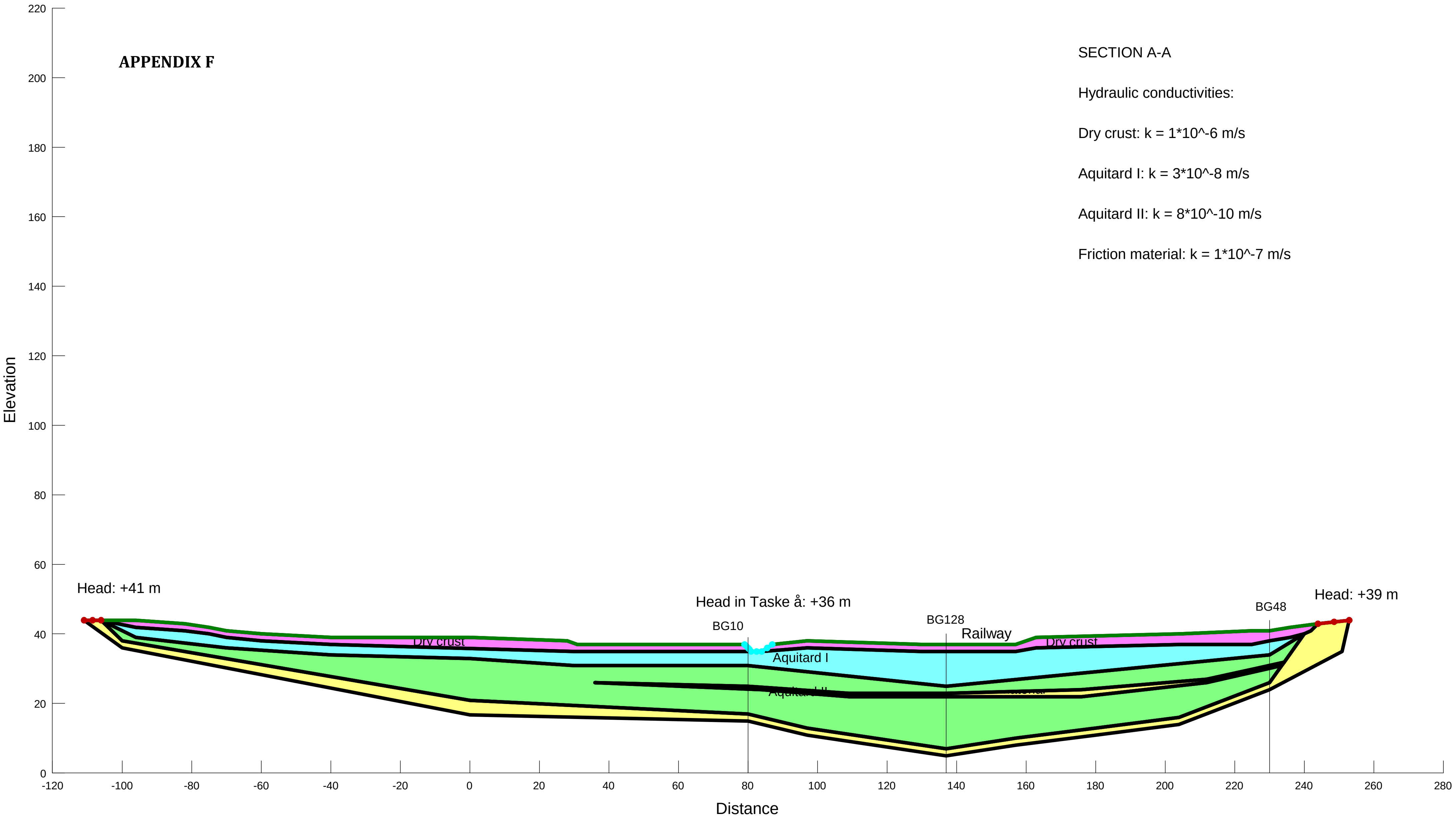
BG 180
Pore pressure level [meter above sea level]
40
39,5
39
38,5
38
37,5
37
36,5
36
35,5
2006-12-09
2007-02-07
2007-04-08
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
2010-05-22
5,31 m
10,22 m Manual
10,22 m Logger
22,67 m Manual
22,67 m Logger

BG 232



BG 232
Pore pressure level [meter above sea level]
39
38
37
36
35
34
33
32
31
2007-02-07
2007-04-08
2007-06-07
2007-08-06
2007-10-05
2007-12-04
2008-02-02
2008-04-02
2008-06-01
2008-07-31
2008-09-29
2008-11-28
2009-01-27
2009-03-28
2009-05-27
2009-07-26
2009-09-24
2009-11-23
2010-01-22
2010-03-23
2010-05-22
3,01 m
7,06 m
12,02 m Logger
12,02 m Manual

APPENDIX F



SECTION A-A
Hydraulic conductivities:
Dry crust: k = 1*10^-6 m/s
Aquitard I: k = 3*10^-8 m/s
Aquitard II: k = 8*10^-10 m/s
Friction material: k = 1*10^-7 m/s
Head: +41 m
Head in Taske å: +36 m
Head: +39 m
BG10
BG128
BG48
Railway
Dry crust
Dry crust
Aquitard I
Elevation
Distance
0
20
40
60
80
100
120
140
160
180
200
220
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280

APPENDIX F

SECTION A-A

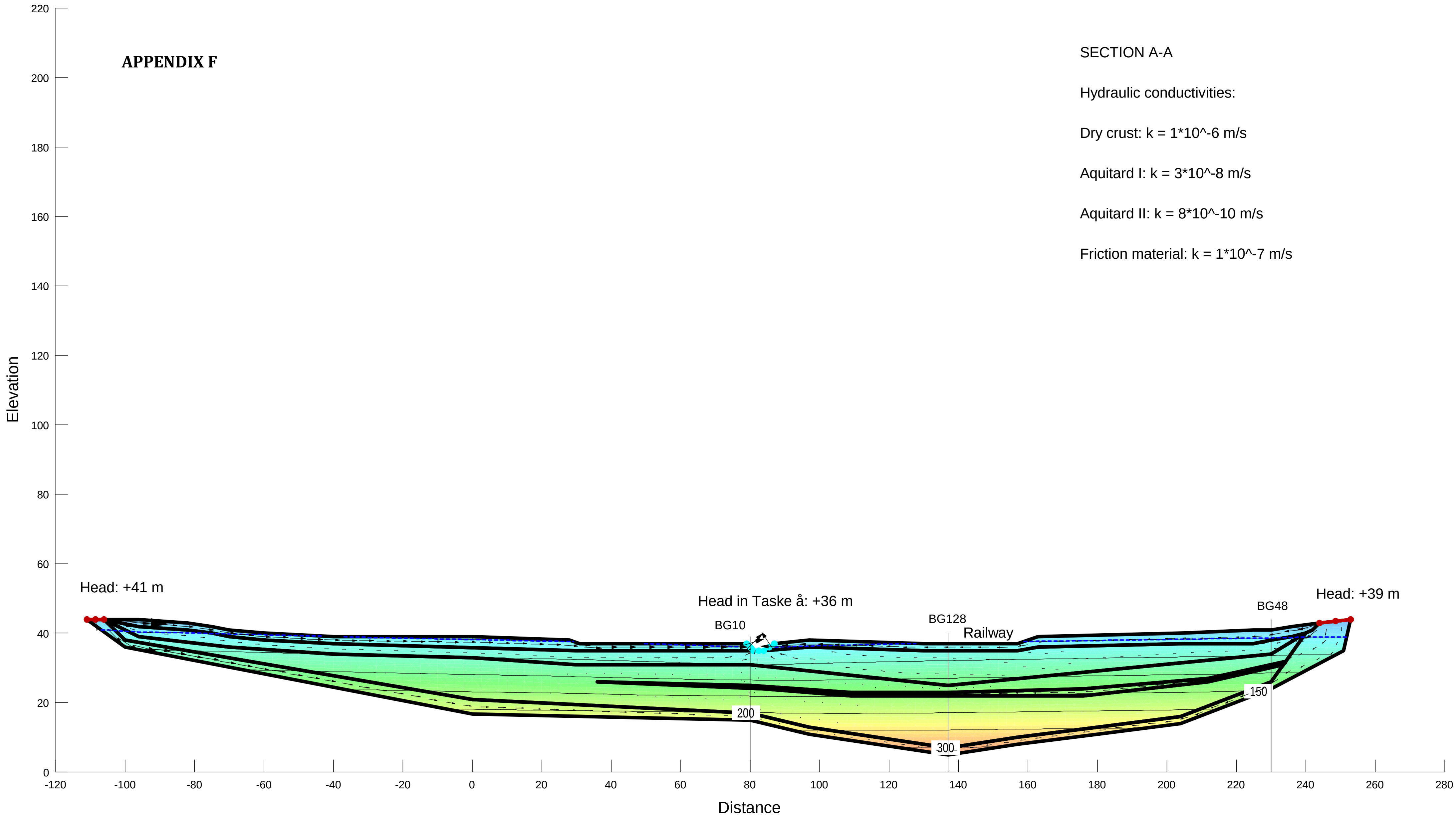
Hydraulic conductivities:

Dry crust: k = 1*10^-6 m/s

Aquitard I: k = 3*10^-8 m/s

Aquitard II: k = 8*10^-10 m/s

Friction material: k = 1*10^-7 m/s



Appendix A