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Characterisation of fractures in crystalline rock using steady state and transient hydraulic test analyses - A case study

Master's thesis (BOMX02-17-45) in Infrastructure and Environmental engineering

Rickard Österlund

Pramod Surendran

Department of Civil and Environmental Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Supervisor: Åsa Fransson, Department of Civil and Environmental Engineering
Examiner: Åsa Fransson, Department of Civil and Environmental Engineering

Master's Thesis BOMX02-17-45
Department of Civil and Environmental Engineering
Division of Geo Engineering
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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RICKARD ÖSTERLUND
PRAMOD SURENDRAN
Department of Civil and Environmental Engineering
Chalmers University of Technology

Abstract

This master thesis work includes a case study where fractures in crystalline rock were conceptualized and characterized using steady and transient hydraulic test analyses. Conceptualization was done on the basis of fractures having varying radial dimensions such as a locally small aperture far away from a borehole or a locally small aperture close to a borehole. The geometry is important since the fracture behaviour related to flow can be investigated using the fracture aperture.

Some of the applications are that inflows and groutability can be estimated which is important for sealing during tunnel construction.

To investigate fracture aperture both transient and steady state analyses were used to estimate transmissivity. For the steady state analysis the transmissvity was obtained using a packer test equation. For the transient analysis the Cooper-Jacob method, Theis solution method and Dougherty-Babu method were taken into consideration. The software Aqtesolv was used for the analysis of the data that originated from the Mölnlycke area.

Estimating transmissivity using different methods made it possible to conceptualize and describe the geometry of fractures and to give initial recommendations on when transient tests have an advantage over steady state testing. The evaluation of these methods is necessary for the construction of tunnels and will help in determining a good grouting design by developing various hydrogeological descriptions.

Keywords: Conceptualization. Transient transmissivity, Steady state transmissivity, Aqtesolv , Fracture aperture, Hydrogeological description.

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Gothenburg, June 2017

Pramod Surendran
Rickard Österlund

Contents

List of notations

α	Compressibility, Pa^{-1}
β	Compressibility of water, $4.7 \times 10^{-10} Pa^{-1}$
Δh	Difference in groundwater head/level, m
Δp	Pressure change, Pa
η	Porosity, ratio between volume and voids and total volume
$\frac{\Delta h}{\Delta l}$	Hydraulic gradient
γ	Specific weight, $\frac{kN}{m^3}$
μ	viscosity, $Pa \times s$
ρ	Density, $\frac{kg}{m^3}$
ξ	Skin factor
A	Area, m^2
b	Hydraulic aperture, m
C_c	Conductance
H_w	Constant head, m
K	Hydraulic conductivity, ms^{-1}
k	Permeability, m^2 or $darcy \approx 10^{-12} m^2$
L	Length of borehole section, m
Q	Flow, $\frac{m^3}{s}$
R_0	Radius of influence, m
r_c	Radius of casing, m
r_w	Radius of borehole/well, m
S	Storativity, $S = bS_s$
s	drawdown, m
S_s	Specific storage, m^{-1}
s_w	drawdown in a borehole/well, m
T	Transmissivity, $\frac{m^2}{s}$
t	time, seconds (s)
t'	Recovery time - time since pumping stopped, s
t_e	Equivalent time, s
t_p	Pumping time, s
u	$\frac{r^2 s}{4Tt}$
v	Ground water velocity, $\frac{m}{s}$

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1
Introduction

1.1 Background

Infrastructure such as railways and roads is developing according to the human needs. When constructing railways and roads, tunnels are often a vital part of these. In order to develop a well functioning tunnel it is important to go through many technical aspects. Many precautions have to be taken during the implementation of such a project. The need for hydrogeological description is important while constructing tunnel. These descriptions will help to determine a good grouting design.
Some of the important parameters used in this thesis are transmissivity which is the ability of fractures to transmit water and the aperture width is the spacing between the planes of the fracture. Skin factor is obtained due to the effect of skin. The condition of the well can be characterized by using skin factor. A high skin factor means that there is some conditions close to the borehole that limits the flow, which could be due to clogged fracture, smaller local aperture etc. A smaller skin factor means that the flow is not limited as much by local conditions and if the skin factor is negative it could be due to a local bigger aperture or if the area around the borehole is more fractured (Gustafson, 2012).

There were two analysis methods were taken into account in the report, they are steady state analysis method and transient analysis method (Kruseman and De Riddler, 1994). Each of these methods have its own assumptions. There are several boreholes spread through the stretch between Mölnlycke and Bollebygd and each of the borehole have a lot of fractures. The fractures were present in the borehole but there is no information regarding the fracture characteristics such as aperture width etc. Therefore, in order to determine this these two methods are important.

Steady state analysis is a mathematical analysis, where the flow and hydraulic head are considered to have reached a steady state. Whereas in transient analysis the flow is considered as a time varying solution. It also helps to hypothesize the properties of the aquifer. Different test methods where followed in order to obtain better results. For transient analysis some of the solution methods that can be taken into consideration are Cooper-Jacob test solution, Doughtery-Babu method and Theis solution method (Duffield, 2017). Moreover for obtaining steady state transmissivity the packer test equations can be used (Gustafson, 2012).

1.2 Aim and Objective

The main aim of this master thesis was to determine the characteristics of fractures in rock by comparing the transmissivities obtained by analyzing steady state analysis and transient analysis methods. The main objectives were:

- To describe and conceptualize the geometry of a individual fracture
- To investigate the differences in results for steady state and transient test analyses and if they have a good agreement
- To investigate if possible differences can be explained
- To establish if using transient test have an advantage over steady state and if so when are they advantageous

1.3 Limitations

This project was limited to the study of hydraulic test result for five particular boreholes for the Mölnycke and Bollebygd stretch. The borehole data are available from the field tests conducted during the period of field analysis and field study. There are 17 boreholes spread along the stretch, however in this report 5 of those will be investigated in depth.

1.4 Geological site description

The area where the water pressure tests were conducted was along a part of the stretch for the planned high speed railway between Gothenburg and Borås. More specifically it is a 25 km stretch between Mölnlycke and Bollebygd which is shown in figure 1.1 below.

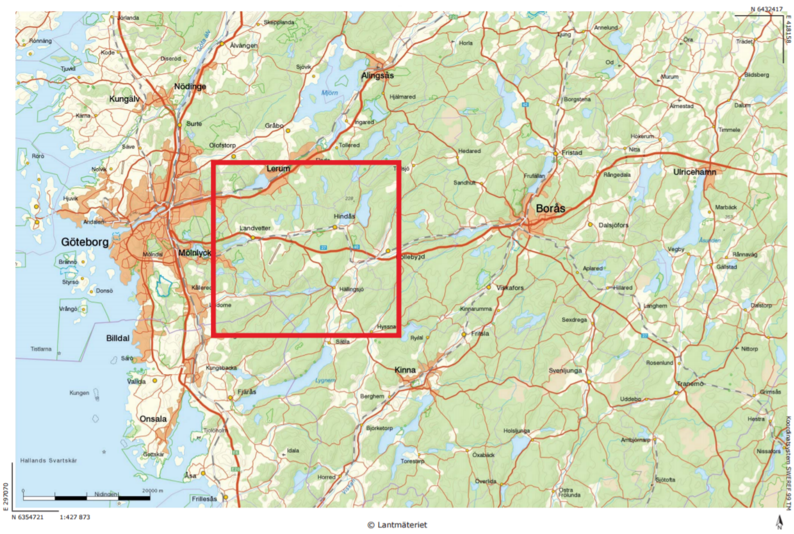

Figure 1.1: Map showing the area between Mölnlycke and Bollebygd were the studied boreholes are located, see fig 1.2. (Lantmäteriet, 2017)

Figure 1.1 Shows the area in which the planned stretch where the 17 boreholes are distributed. The locations of the boreholes are marked by the blue squares in figure 1.2 below.

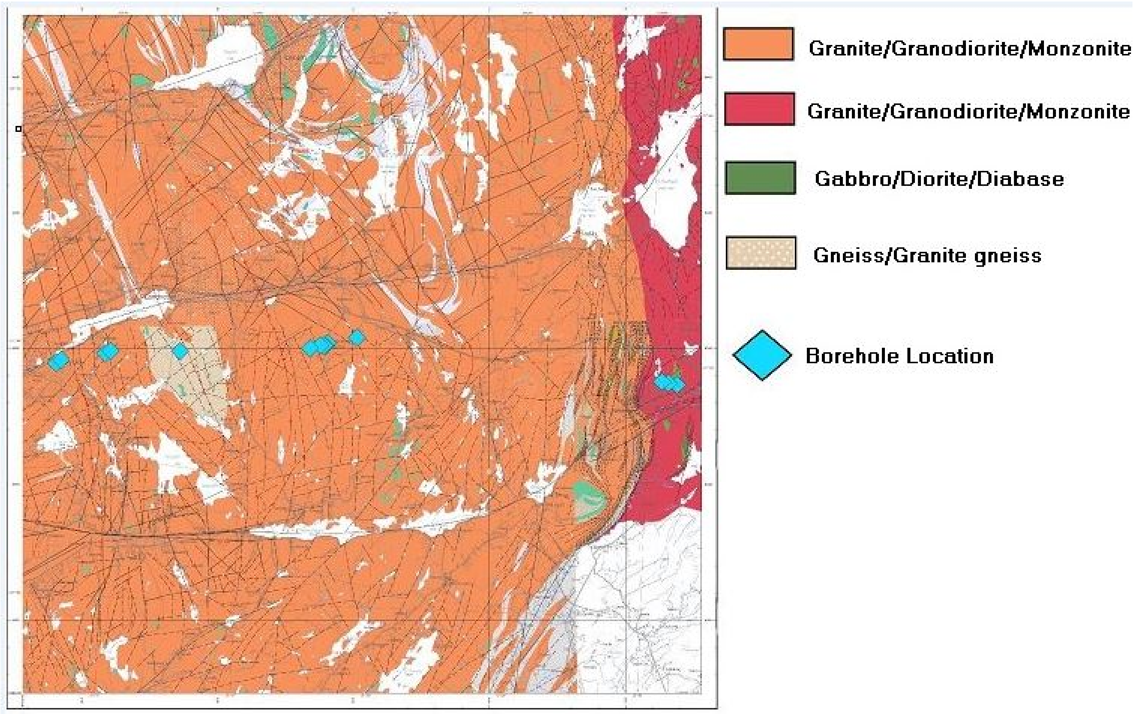

Figure 1.2: Map of the different rock types in the area (SGU, 2017). Blue squares indicate location of boreholes.

Figure 1.2 also shows the rock types in the area as well as the deformation zones (the lines). The orange and red colours indicates that it is granite/granodiorite which is the majority of the rock and this is also where the majority of the boreholes are located. One borehole is located in a metamorphic rock (gneiss). There are also a few smaller areas of basic rock (gabbro, diorite, diabase) that is represented by green colour. From the figure 1.2 it can be seen that the boreholes furthest to the east is potentially located in the basic rock. Some of the boreholes are also located close to deformation zones which can be very influential on the water inflow to the boreholes. However, it is hard to say at this scale if the boreholes actually penetrates the deformation zones at all. The boreholes were drilled at an angle and depending on the direction they could be facing away from the deformation zones.

The topography in the area varies between 50-150 m above the sea level and that leads to several tunnels have to be made. Along the studied stretch there are 7 planned tunnels and because it is in the tunnels the transmissivity of the rock is relevant. It is at the location of the future tunnels the water pressure tests have been performed. The topography and location of the tunnels is shown in figure 1.3 and 1.4 below.

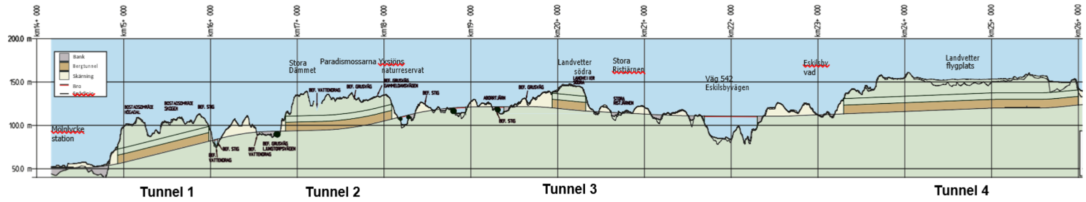

Figure 1.3: Topography of the first half of the stretch (Trafikverket, 2016)

For the future Tunnel 1 two boreholes were made, Tunnel 2 had two boreholes as well and Tunnel 3 one. Tunnel 4 which goes under the Landvetter airport is the longest one and also have the highest number of boreholes distributed along its stretch, which is eight.

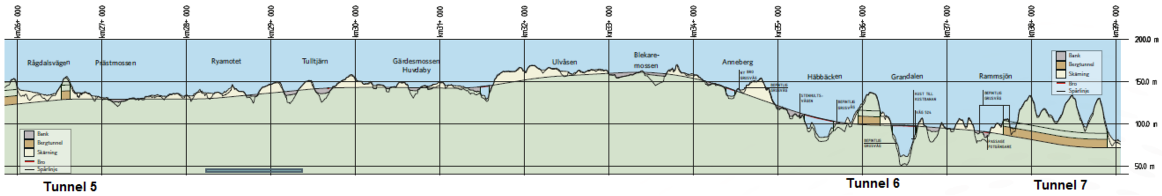

Figure 1.4: Topography of the second half of the stretch (Trafikverket, 2016)

Tunnel 5 is short and only one borehole was made there and Tunnel 7 have three. However, no boreholes were drilled at the location of tunnel 6.

2

Literature review

2.1 Hydraulic properties of an aquifer

An aquifer is defined as a saturated underground layer containing water bearing rocks, sand, silts etc where the hydraulic conductivity is sufficient to extract a reasonable amount of water in wells (Singhal and Gupta, 2010). There is mainly three different types of aquifers, they are confined, unconfined and leaky/semi-confined. A confined aquifer is described as an aquifer with an impermeable layer, for example rock or clay, both under and over it. The water in the confined aquifer occurs under pressure that is greater than the atmospheric pressure. Groundwater in joints and fractures in igneous and metamorphic rock can be under confined conditions (Singhal and Gupta, 2010). The aquifer may be restored by rain water and the age of ground water sometimes is over 1000 years (Government of Tasmania, 2017). Leaky or semi-confined aquifers are similar to confined aquifers with the difference that the confining layers are not completely impervious which leads to leakage between the aquifer and surrounding layers. In reality an aquifer is rarely completely confined and is usually more of a leaky or semi-confined aquifer (Singhal and Gupta, 2010). The unconfined aquifer is not fully saturated and the upper level of saturation that is the upper ground water surface is called the water table which is at atmospheric pressure. In an unconfined aquifer the restorage of water is by rain water which move through the overlying soil (Government of Tasmania, 2017). The storativity of a confined aquifer is less than that of the unconfined aquifer. The aquiclude is shown in the figure below and is an impermeable layer. It cannot transmit water in normal hydraulic conditions. An aquiclude can lie over or under the aquifer (Hall and Chen, 1996).

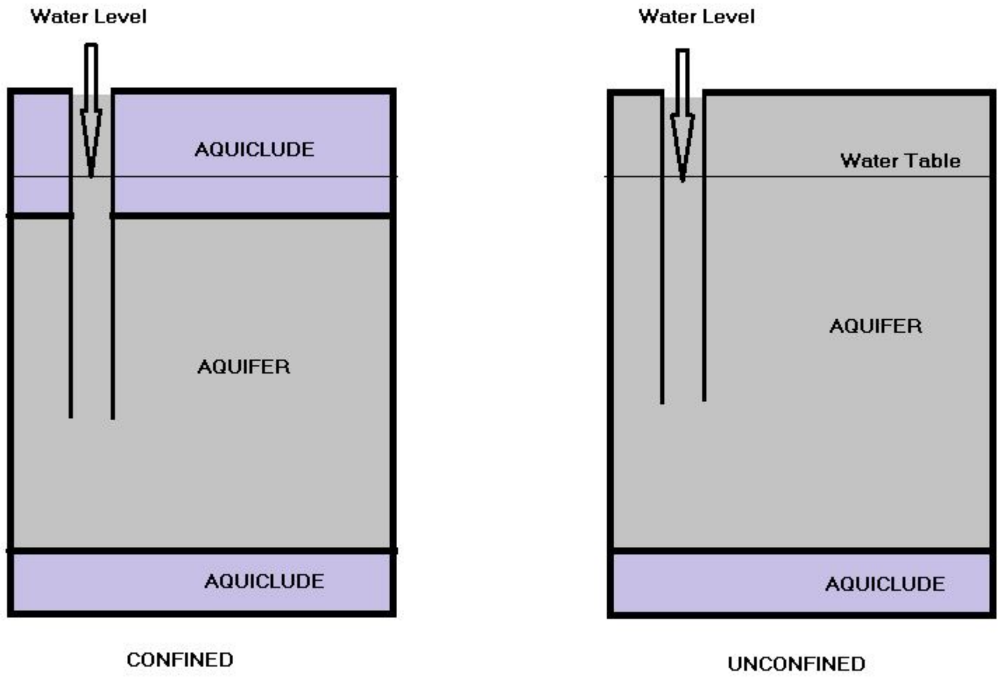

Figure 2.1: Modified image showing a confined and a unconfined aquifer (Lawrence, 1997).

One important hydraulic property of rock is the ability to transmit water. This can be described as hydraulic conductivity K. It can be expressed as :

$$K = \frac{v}{\Delta h/\Delta l} \tag{2.1}$$

v is the groundwater velocity and $\Delta h/\Delta l$ is the hydraulic gradient and K can be expressed in m/s. The properties of the fluid (water) and of the rock is influencing the hydraulic properties. For hard fractured rock K is mainly dependent on fracture properties such as size and inter-connection(Singhal and Gupta, 2010). Another way to describe the aquifer's ability to transmit water is permeability k. It can describe the properties of the medium better as it is not dependant on the fluid properties but on the properties of the medium itself. The relationship between hydraulic conductivity and permeability is:

$$K = \frac{k\gamma}{\mu} \tag{2.2}$$

With Darcy's equation that can be written as:

$$k = \frac{\mu \frac{Q}{A}}{\gamma \frac{\Delta h}{\Delta l}} \tag{2.3}$$

Where μ is the viscosity and γ is specific weight of the fluid.

Transmissivity is related to hydraulic conductivity and permeability and is a measure of the water flow through a vertical strip which extends through the whole saturated thickness of the aquifer, with a unit width. Transmissivity can be expressed in m^2/s. For confined aquifers the saturated thickness is the same as the thickness of the aquifer and the transmissivity can be written as $T{=}Kb$ where b is the saturated thickness (Singhal and Gupta, 2010). However, in unconfined aquifers the saturated thickness can be smaller than the thickness of the aquifer.

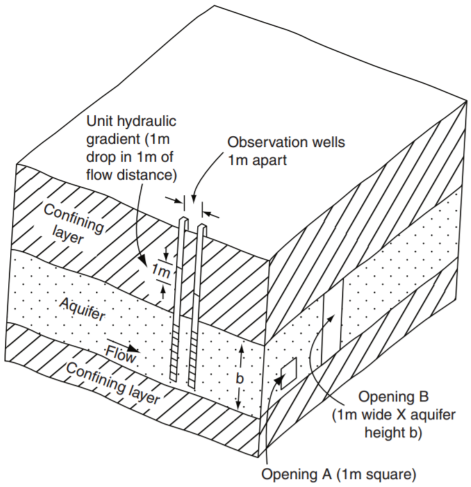

Figure 2.2: Illustration of the hydraulic conductivity K, through opening A, and Transmissivity T, through opening B (Singhal and Gupta, 2010).

The storativity of an aquifer can also be of importance, it is described as the volume of water that is released from storage as the average head declines. This is defined for a column with a unit cross sectional area, the average head is also in unit length and therefore the storativity is dimensionless. In unconfined aquifers the water release from storage is mainly due to gravity drainage and the storage is usually considered to be equal to the specific yield or effective porosity. However, in confined aquifers the water released is due to compressibility of the rock and water (Singhal and Gupta, 2010). The storativity of a confined aquifer is $S = bS_s$, where S_s is the specific storage. The specific storage is the volume of water released due to compression of the aquifer and the expansion of water when the average head decline and is only used for confined aquifers. S_s can be written as $S_s = \gamma(\alpha + \eta\beta)$. Where α is the compressibility of the rock and η is the porosity (Singhal and Gupta, 2010). In reality the water flow in hard rock is mainly in the fractures of the rock and it is therefore the properties of the fractures that will determine the hydraulic properties of the rock mass. However, on a large scale the rock could be seen as an equivalent continuum with a hydraulic conductivity K (Gustafson, 2012). In this case the properties are regarded as the same everywhere in the rock mass. When evaluating hydraulic tests for example this assumption is advantageous as it allows for the use of common differential equation with analytical solutions. A description of the fractures as two parallel planes with a certain aperture where the water is conducted is closer to reality. The hydraulic conductivity would in this case be $K_f = T/b$, where T is transmissivity and b the hydraulic aperture (Gustafson, 2012). The rock mass can then be seen as a network of this fractures where the groundwater is conducted. Looking even closer at the fracture it can be seen that the aperture of the fractures varies a lot across the fracture plane. The flow can then be estimated as a network of different channel flows that are linked together (Gustafson, 2012). With the conductance C_c the channel flow can be written as:

$$Q_C = C_C \frac{\Delta h}{\Delta l} \tag{2.4}$$

2.2 Description of fractures

The most important part of geological structures are fractures and discontinuities. The presence of these kinds of fractures and discontinuities allows the storage and movement of fluids. The main factors which control the groundwater flow through fractures are stress, temperature, geometry etc. A single fracture can be considered as a smooth planar surface and it shows the discontinuity such as foliation, shear zone, joints etc.(Singhal and Gupta, 2010).

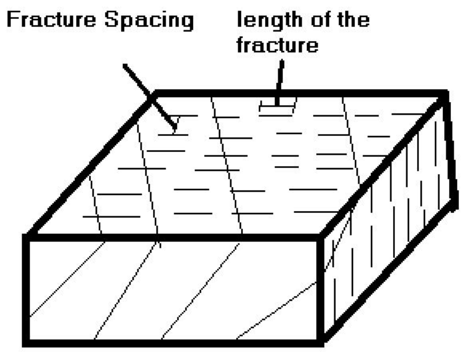

Figure 2.3: Modified fracture characterization (Singhal and Gupta, 2010).

Fracture spacing is the distance between individual fractures. The spacing of the fractures have a great influence on both the flow of groundwater and the permeability of rock mass. The spacing of the fracture bearing the density of the linear fracture and it can also corresponds to the frequency of the fracture (Singhal and Gupta, 2010). The fracture length is also called its persistence. The quantification of the fracture length is very difficult and it can measured by considering the trace length of the discontinuity. The fracture length have great influence on the interconnectivity and it can show different patterns. The influence of fracture length on discontinuity shows in the figure 2.4. The interconnected fracture length is represented by the strong fracture where the trace length can be recognized. Whereas when the fracture length is short the fractures interconnect poorly and that is represented by a weak fracture. In a weak fracture it is difficult to recognize the trace length. The intermediate of these two are represented by a moderate fracture (Singhal and Gupta, 2010).

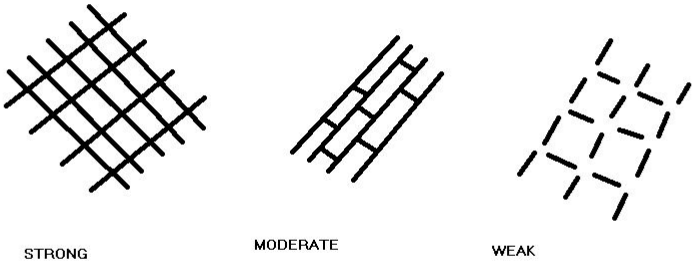

Figure 2.4: Modified influence of fracture length (Singhal and Gupta, 2010).

From the trace length of both the strike and dip it is possible to determine the area of the fracture. The area of the fracture can be circle, elliptical etc. Suppose the area of the fracture resembles the circular disc then the area is equal to

$$A = \frac{\pi}{4}(D^2 + S_D^2) \tag{2.5}$$

Where D is the diameter and S_D is the standard deviation (Singhal and Gupta, 2010). The fracture have to show a visible movement and it have to be parallel to the fracture surface.
The occurrence of fractures is due to the effect of stresses in different ways. Some of them are due to the effect of the tectonic actions, some of them are due to weathering or due to the effect of some natural phenomenon like landslides etc. A fracture can be classified into three types these are shear fractures, dilation fractures and hybrid fractures. Here, a shear fracture have a dihedral angle 2i>45°, the dihedral angle is considered as the angle between two fractures, and it exhibits shear displacement. Whereas a dilation fracture acts as an open fracture with no shear movement. This open fracture is created because of the movement of planar surface at an angle perpendicular to the fracture surface. Hybrid fractures have a dihedral angle of 2i<45° and the fracture is partly filled with veins and a vein is considered as a filled fissure. The shear and dilational origin where featured by the hybrid fracture and it can also exhibits the shear displacement (Singhal and Gupta, 2010).

2.2.1 Parallel plate model

The cubic law is derived from a simple model called parallel plate model. In that model it is assumed that the fracture consists of two parallel smooth walls that are separated by an aperture b (e.g Zimmerman and Bodvarsson (1996)). This model is very commonly used in flow modeling in rock even though it is based on a very simplified fracture geometry assumptions. It is also the only geometrical fracture model where an exact calculation of hydraulic conductivity is possible to achieve (Zimmerman and Bodvarsson, 1996). Other models exists that take in to consideration wall roughness and asperity contacts etc, however, most of them are refinements on parallel plate model. The transmissivity can be described with the cubic law which can be written as (Snow, 1968):

$$T = \frac{\rho g}{\mu}\frac{b^3}{12} \tag{2.6}$$

The T is the transmissivity, b is the aperture, μ is the viscosity and ρ is the density of water. As can be seen in the cubic law the transmissivity is very dependent on the aperture and small variations of the aperture can have a big impact on transmissivity. To get a slightly better representation of the reality the aperture can be replaced with a mean aperture. This is because in reality the fractures are rough and therefore the aperture varies.

Furthermore the fractures are in contact with each other in some points which cause obstacles that the water have to flow around and due to water tends to follow the path of least resistance the water will flow where the aperture is greater. The parallel plate model can be used to investigate the aperture effect due to the flow rate and it is determined by considering all the parameters such as inlet/outlet pressure, length etc which helps to arrange or determine different models having different aperture and aperture flow. The flow is in between two parallel plates and the surface for the model is smooth, also a pressure gradient is formed which is constant through out the planes. This leads the flow to move in an unidirectional way (Sarkar et al., 2004).

2.2.2 Two apertures

The potential flow through a fracture is dependent on the aperture of the fracture. A larger aperture will yield a higher transmissivity. The fracture transmissivity can be calculated with the equation 2.6. The equation shows that even if a small change in the aperture b can change the transmissivity a lot as b is raised to the power of 3. In reality a fracture do not have the same aperture everywhere, it is varying and is contact in some places and more open at other locations. It can also be clogged with particles at some places (Gustafson, 2012). Therefore to describe the fractures more accurately a model with varying aperture is needed. One simple model is described by Fransson (1999) where the aperture close to the borehole is different from the aperture further away and is described by the equation:

$$\Delta h = \frac{Q}{2\pi T_{A0}} ln\frac{R_0}{r_w} = \frac{Q}{2\pi T_1} ln\frac{r_1}{r_w} + \frac{Q}{2\pi T_0} ln\frac{R_0}{r_1} \tag{2.7}$$

Here T_1 is the local transmissivity close to the borehole that extends to the radius r_1 and T_0 is the transmissivity further away with the radius of influence, R_0. This equation for varying aperture is basically the same equation that is usually used for drawdown and is similar to equation 2.8. The drawdown is calculated for each part of the fracture and is then added together, just as for the equation including skin factor (equation 2.9). Two basic types of fractures that can occur and can be described with this equation is shown in the figures 2.5 and 2.6, where figure 2.5 is the case with a locally small aperture close to the borehole and 2.6 is the reverse with a locally large aperture.

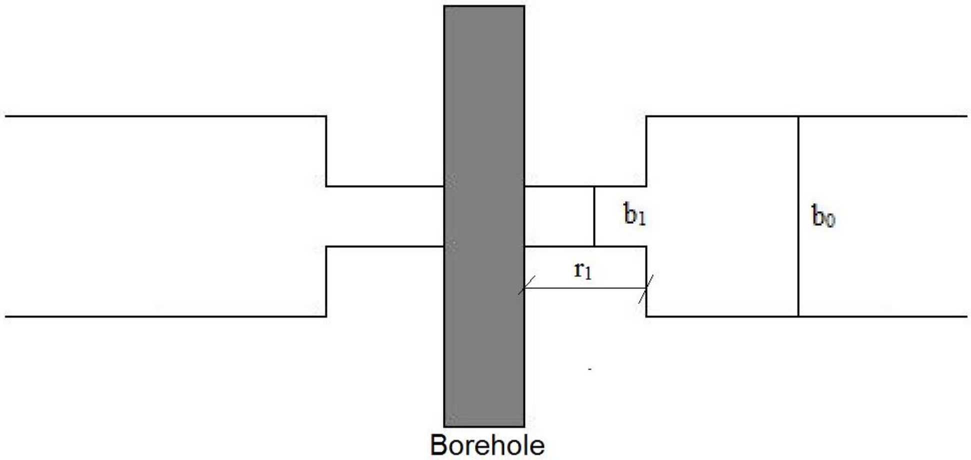

Figure 2.5: Aperture with varying radial extension $b_1 < b_0$

If the transmissivity would be estimated with steady state analysis for this case with a locally small aperture at the borehole it would reflect the transmissivity close to the borehole. This is because the smaller aperture hinders the water flow and it is what would be seen if the measurement is done in the borehole (Fransson, 1999) and (Gustafson, 2012). Potentially this would mean that if the overall transmissivity for the rock is represented by the larger aperture the transmissivity can be underestimated.

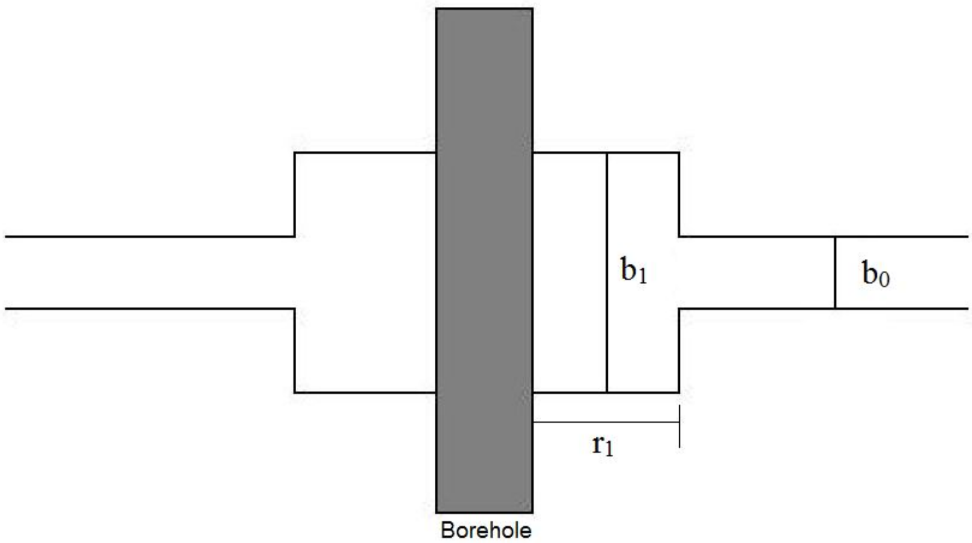

Figure 2.6: Aperture with varying radial extension $b_1 > b_0$

In the other case in figure 2.6 the borehole is located in a part of the fracture where the aperture is locally larger. If a steady state analysis is made in this borehole the transmissivity for the local part of the fracture would barely affect the result (Fransson, 1999) and (Gustafson, 2012). This is because the smaller aperture at a distance limits the water flow and if it is this tighter section that corresponds with the overall transmissivity for the rock mass then this transmissivity would be a good representation of the whole fracture.

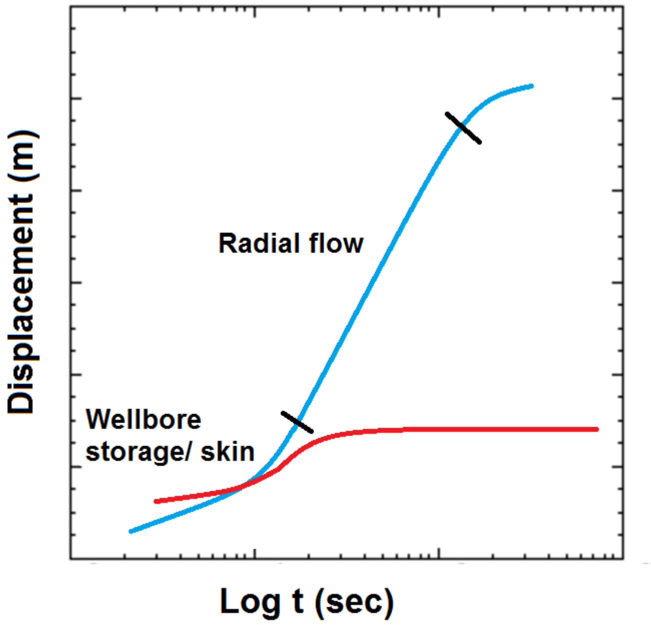

Figure 2.7: Typical transient data plot modified (Duffield, 2017), blue line is drawdown and red line is the derivative.

The figure above shows how a typical transient analysis plot might look. As the transient data shows how the pressure varies over time it is possible to see the effects of skin and wellbore storage. The early part is usually not a good representation of the rock mass as a whole as it is dominated by wellbore storage and skin effects (Bourdet et al., 1989). By analysing the derivative of the transient plot it is possible to see what flow regime that is existent at a particular time. If the derivative is constant then it means that the flow has reached a infinite acting radial flow. In figure 2.7 this would occur at the straight part and it is this part of the graph that a Cooper and Jacob solution can be fitted to, see section 2.3.1. The transmissivity achieved for analyzing that part would then represent the transmissivity of the aquifer that is not affected by the skin or local conditions as it would for steady state. Therefore the transient analysis can potentially see the conditions further away from the borehole. In the case of a locally small aperture as in figure 2.5 the transient transmissivity would then be higher than the one obtained from steady state analysis but with a high skin. For the other case in figure 2.6 then the transient and steady state transmissivity should show similar results, the difference being a smaller skin factor.

2.2.3 Skin factor

If the aquifer is completely homogeneous then standard equations for the drawn-down can be used. However, sometimes the fractures can be clogged with particles close to the borehole. This would then lead to a greater inflow resistance and therefore an additional drawn-down in the borehole/well (Gustafson, 2012). This effect of a pressure change that only occurs close to the borehole is commonly known as skin effect. The agreement between theoretical pressure in a well with constant outflow and the actual performance is not always sufficient. Van Erdinger observed this and made the assumption that the permeability is not equal everywhere and instead assumed that the permeability is reduced close to the borehole, due to damage from production of the well (Van Everdingen, 1953). To take this in to consideration the dimensionless skin factor was introduced to the pressure equation (Hawkins, 1956). The simple drawdown equation without skin is:

$$s = \frac{Q}{2\pi T} ln \left(\frac{R_0}{r_w} \right) \tag{2.8}$$

Where R_0 is the radius if influence at the time t, where the extrapolated drawdown curve crosses the zero line (Gustafson, 2012). By introducing the skin factor the drawdown equation would then be:

$$s_w = \frac{Q}{2\pi T} \left(ln \left(\frac{R_0}{r_w} \right) + \xi \right) \tag{2.9}$$

The skin factor affects pressure readings by deforming the shape of transient readings during early times and shifts the readings by an amount Δh (de Swaan, 1990).
As mentioned earlier the skin factor can be due to damage or clogging of the borehole, however, the same response would be expected if the fracture width closer to the borehole is smaller than further away. Furthermore the opposite condition can also occur, where for example the borehole passes through a very conductive fracture in an otherwise low permeability rock mass (Gustafson, 2012). It can then be assumed that if the fracture width close to the borehole is greater than it is further away it would give a similar response. This would show as a negative value of the skin factor.

2.3 Pumping test

A pumping test is a field test where water is pumped at a controlled rate out of a well and the drawdown is measured (Duffield, 2017). The main principle behind the pumping test is to find the reaction of aquifer due to the applied stresses, the applied stress means that the extraction of the groundwater from the well. The reaction due to this stress is measured by determining the drawdown with respect to the time (Driscoll, 1986). The drawdown can either be measured in one or several observational wells or in the pumped well. The data obtained can be used to estimate hydraulic properties of the aquifer. Usually it is the transmissivity, hydraulic conductivity, specific yield and storativity that are estimated with pumping tests. This is done with a method called curve matching, where type curves are fitted to the plotted drawdown data (Duffield, 2017). Three common types of pumping tests are:

- **Constant-rate test**- The control well is pumped at a constant rate and the drawdown is measured in observational wells or in control well.
- **Step-drawdown tests** - The discharge rate is initially low and constant and is then increased through several pumping intervals of continuously increasing constant discharge rates. The duration of each interval is usually equal and ranging from 30 minutes to 2 hours (Kruseman and De Riddler, 1994). Step-drawdown test is a single-well pumping test that in addition to estimating transmissivity and hydraulic conductivity also can be used to evaluate well loss, well efficiency, effective well radius and wellbore skin factor.
- **Recovery tests** - After a constant-rate or step-drawdown pumping test has ended a recovery test can be conducted. The residual drawdown is measured in either surrounding observational wells or in the control well.

The equipments used for the tests are flow meter, water level indicator and logger. Each part of the equipment has its own importance to obtain good results. The flow meter is used to measure the flow rates such as determining weather it is high flow rate or low flow rate. The water level indicator is used to measure the water level that is used to determine the static or dynamic water level. In order to record the data from the aquifer a logger is used. There are some transient solution methods that are used for determining the properties of aquifers such as Cooper-Jacob solution method and Theis solution method (Driscoll, 1986).

2.3.1 Transient test analysis

Cooper-Jacob method of analyzing pumping tests is based on a straight-line approximation of the Theis equation for unsteady flow to a fully penetrating well in a confined aquifer (Duffield, 2017). This method can be used to evaluate variable-rate tests as well as drawdown of the first recovery period (if the observation data contains recovery measurements)(Duffield, 2017). However, it can not be applied to multiple pumping wells.

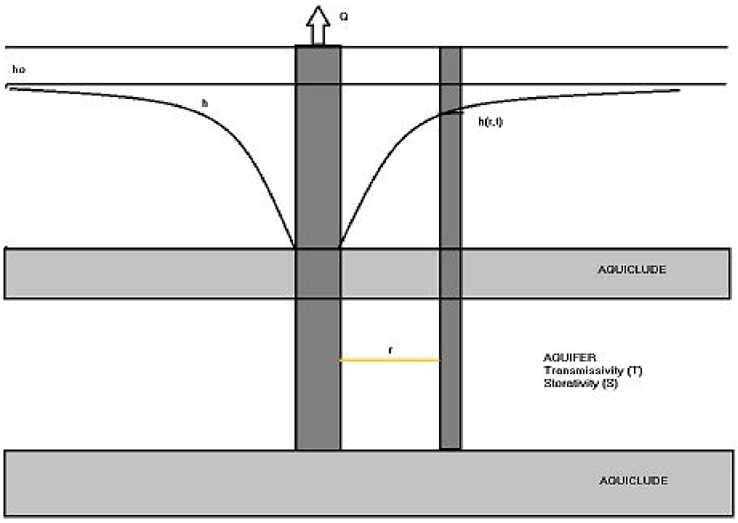

Figure 2.8: Modified well configuration- Cooper-Jacob test solution method for confined aquifer (Duffield, 2017)

For a non leaky confined aquifer of infinite extent and uniform thickness the Theis equation (which Cooper-Jacob is a modified form of) for drawdown (s) is:

$$s = \frac{Q}{4\pi T} W(u) \tag{2.10}$$

$$u = \frac{r^2 S}{4Tt} \tag{2.11}$$

Where Q=pumping rate, r=radial distance, t=time, s=drawdown, S=storativity, T=Transmissivity and *W(u)* is theis well function for non leaky confined aquifers. The well function, *W(u)*, can be evaluated with the expression below:

$$W(u) = -0.5772 - ln(u) + u - \frac{u^2}{2*2!} + \frac{u^3}{3*3!} - \frac{u^4}{4*4!} + ... \tag{2.12}$$

However, for small values of u the well function can be approximated with only the two first terms. To be able to achieve a good accuracy with this approximation then the critical value of u should either $u \leq 0.05$ or $u \leq 0.01$ (depending on what source is used)(Duffield, 2017). According to this it is very important to find the values for both *W(u)* and u. In order to find the values for these equations it is necessary to follow the curve matching method. It is performed by plotting a graph between displacement and time in a semi-logarithmic plot, where the time axis is logarithmic (Carlsson and Gustafson, 1997). A straight line is then obtained and by calculating the slope of the straight line the transmissivity can be found. If the pumping rate show some variation during the test the recovery data can be used. The Cooper-Jacob solution can be written as (Carlsson and Gustafson, 1997):

$$s = \frac{Q}{4\pi T}(-0.5772 - ln(u)) \tag{2.13}$$

Then the transmissivity can be calculated by first plotting s as a function of log t on a semi-logarithmic axis and using the following equation:

$$T = \frac{Qln(10)}{4\pi\Delta s} \tag{2.14}$$

where s is the change of displacement per log cycle time. Then S can also be calculated as:

$$S = \frac{2.25Tt_0}{r^2} \tag{2.15}$$

where t_0 is the point where the line intercept the x-axis. Many assumptions are taken into consideration while using Cooper-jacob solution method. Some of them are related to the aquifer. The aquifer is considered to be confined having no leakage. The thickness of the aquifer is uniform and considered as homogeneous. Another assumption is related to the flow which is taken as unsteady.

Dougherty- Babu is another method used, it is a mathematical solution. By using this method the hydraulic properties can also be determined. The effect of wellbore storage and the effect of skin is included in this method which helps to expand the solution compared to that obtained from the Theis solution method. Also here the curve matching method is used to analyze the data obtained from the pumping test. According to the Dougherty-Babu method some basic assumptions are related to the aquifer such as it has to aswell be homogeneous. It has to be confined and there will be no leakage in the aquifer. Here aswell it is assumed that the flow have to be unsteady (Duffield, 2017).

One useful tool for interpreting and analyzing well pressure data is the pressure derivative. This is usually done by plotting the logarithmic derivative versus time and its corresponding drawdown in a scatter plot (Renard et al., 2009). The derivative curve comes from deriving the pressure with respect to the logarithmic time and that can be done numerical with the Bourdet derivative (Bourdet et al., 1989). The main reason to use this method to analyze well data is to be able to detect different flow regimes. Knowing what flow regimes are occurring is important to better choose which curve matching method should be used.

One example of a flow regime is that shown during early time is wellbore storage. This is shown as the drawdown and derivative follows the same straight line with a unit (1:1) slope (Duffield, 2017). The transmissivity can't be estimated during this early time as the effect of stored water in the well affects the data more than the properties of the aquifer (Renard et al., 2009). If instead the drawdown and derivative curves at an early time have a 1:2 slope and a separation of roughly a factor 2, it would indicate a linear flow from an vertical fracture (Duffield, 2017).

Furthermore, one flow regime that can be observed during late time is infinite acting radial flow. This flow regime occurs when the pressure derivative in a log-log plot change in proportion to the logarithm of time and is indicated by the derivative becoming constant (horizontal line in the plot) (Spane and White, 1993). For infinite acting radial flow it is possible to analyse the data with a confined, semilog straight-line method such as Cooper and Jacob (Spane and White, 1993). It is common that the derivative cause a hump at indermediate time, after wellbore storage effects and before late times where a radial flow can be observed. This hump is caused by the wellbore storage effect but it has also been shown that the same shape occurs when there is a skin effect present in the borehole (Renard et al., 2009). Therefore the hump is a function of the combined wellbore storage effect and the skin effect.

2.3.2 Constant Head test

The constant head test is a test where the head of the well remain constant whereas the discharge is controlled with respect to time. The main aim of the constant head test is to estimate the hydraulic properties such as transmissivity T, storativity S and hydraulic conductivity K (Duffield, 2017). The properties of the aquifer were estimated by using mathematical models.

One solution for Constant-Head test is Jacob-Lohman (1952). The solution is obtained by assuming a fully penetrating well in a homogenous and isotropic confined aquifer (Duffield, 2017). Also a straight line method is developed and by that method the aquifer coefficients can be determined. An illustration for this Jacob-Lohman solution is shown below.

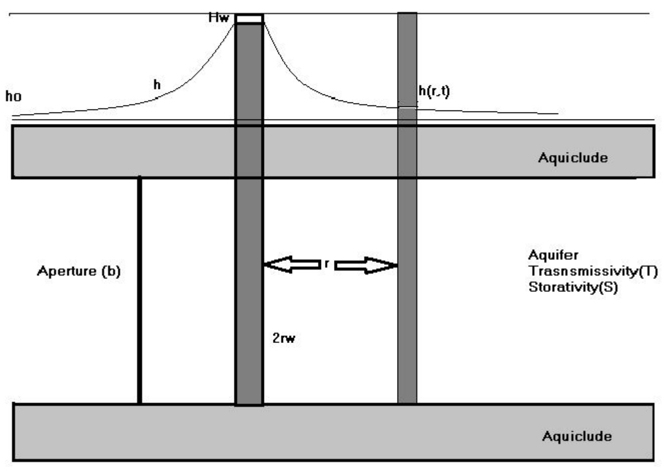

Figure 2.9: Modified picture of Well configuration nonleaky confined aquifer (Duffield, 2017).

The H_w is considered as the constant head in the test well. The test well width above the aquiclude is equal to two times r_c where r_c is the radius of the casing. Whereas the test well width between two aquiclude is given as two times r_w where the r_w is the radius of the well. Here the b is the distance between two aquicludes and r is the center to center distance between the test well and observation well. The main parameters obtained from the tests are transmissivity, storativity, well radius and nominal casing radius.

Some of the assumptions were followed by the Jacob-Lohman solution for constant head test are that the flow is considered to be not constant. The solution which is applicable to the confined aquifer where the thickness of the aquifer is taken as uniform. This solution were performed in fully penetrated well (Duffield, 2017). The transmissivity and storativity are estimated using a straight line method.

2.3.3 Equalent time (Agarwal method)

When doing a pumping test water is either injected or pumped out a borehole at a certain rate, often constant. After the pumping stops the water level will start to recover to the initial level. Which means that for injection it will decrease and if water was pumped out the level will increase. In figure 3.5 a schematic description of how the water flow can be simulated after the pump stop can be seen.

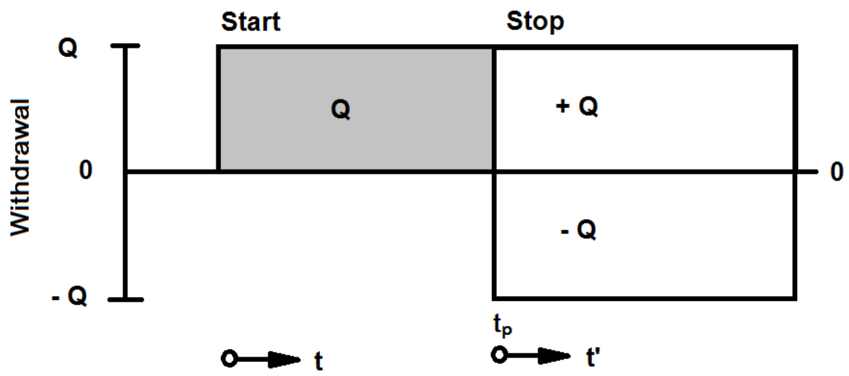

Figure 2.10: How the withdrawal after pump stop can be simulated, conceptual figure modified from (Carlsson and Gustafson, 1997).

In this description the pumping with the capacity Q starts at t=0 and stops at $t = t_p$. The pump stop is then simulated by introducing an equal but negative capacity, -Q, which then leads to a total capacity of zero. The figure describes if the water is withdrawn but the same principle works with injection of water. The only difference is that the withdrawal capacity is negative instead of positive (Carlsson and Gustafson, 1997).

A constant pumping rate can be difficult to maintain during a pumping test while the recovery is always at a constant rate (Thomas Franz, 2017). Because of this the recovery drawdown data can be more reliable (Agarwal, 1980). Agarwal proposed a method to analyze the recovery data where the time axis is replaced by an equivalent time. With this approach the recovery drawdown is the difference between the head at any level and the head when the pumping stops. The time since the pumping started or recovery time can be written as : $t' = t - t_p$. In figure 3.6 it is shown how this parameters are defined in a sample of the data used in this project.

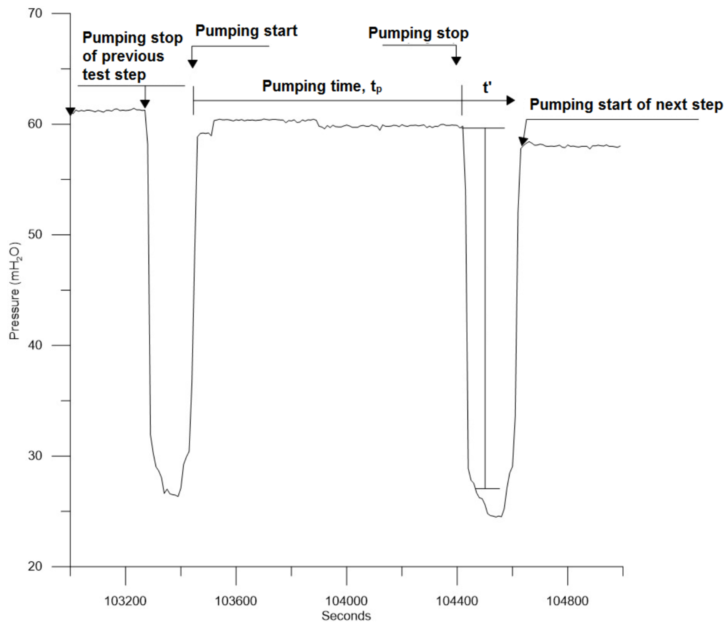

Figure 2.11: Example of the Pressure data from borehole MB04KBH.

By using this new time definitions and consider recovery test with a Cooper-Jacob approximation of the recovery can be written as:

$$s = \frac{Q}{4\pi T} ln\left(\frac{4Tt't_p}{r^2S(t'+t_p)}\right) = \frac{Q}{4\pi T} ln\left(\frac{4Tt_e}{r^2S}\right) \tag{2.16}$$

The only difference between this equation and the Cooper-Jacob one is that t_e (equivalent time) is used instead of the normal time. Equivalent time can be written as :

$$t_e = \frac{t't_p}{(t'+t_p)} \tag{2.17}$$

The assumptions that was made by Agrawal when deriving this solutions are a two dimensional radial convergent flow field, a fully penetrating well, an infinite confined aquifer, no well-bore storage. It also assumes that the Cooper-Jacob approximation is valid.

2.3.4 Steady state analysis

The steady state analysis is a mathematical analysis which includes different types of conceptual models and corresponding equations to calculate transmissivity if steady state conditions are reached or assumed. One model is the Theim's well equation is defined as (see e.g. Gustafson (2012)):

$$T = \frac{Q}{2\pi\Delta h} ln\left(\frac{R_0}{r_w}\right) \tag{2.18}$$

The T=transmissivity ,Q=flow rate (m^3/s), Δh=Pressure in meter head, R_0 = radius of influence, r_w =radius of the well. Another method that is shown in Gustafson (2012) is called Packer test and is basically the same as the Theim's well equation with the only difference is that the radius of influence is replaced by the length of the packer interval. The equation used for finding the transmissivity for packer test is:

$$T = \frac{Q}{\Delta h}\frac{1}{2\pi} ln\left(\frac{L}{r_w}\right) = \frac{Q}{\Delta h} * F \tag{2.19}$$

Moye's formula can be use to find the transmissivity and it is also comparable to the packer test formula. The Moye's formula can be denoted as:

$$T = \frac{Q}{2\pi\Delta h}\left[1 + ln\left(\frac{L}{2r_w}\right)\right] = \frac{Q}{\Delta h} * F \tag{2.20}$$

The F can be estimated by using the available datas. According to Gustafson (2012) the difference in the value are roughly a factor of 0.7 for Packer test and 0.75 for Moye's formula, therefore there is a small difference in results from them. The Thiem's well equation has slightly higher with a factor of 1.07. Some of the assumptions for Thiem's solution method are here in this method which follows the Darcy's law. The flow is horizontal and is in steady state. Its pumping rate is constant and the well is fully penetrated. The Thiem solution method is used to find the transmissivity and hydraulic conductivity. The main drawback for Thiem's solution method is in order to get solution two observation wells are required and there is no storage or extraction hence there is no storativity S.

According to the practical reasons the well discharge can be calculated by using the formula (Kruseman and De Riddler, 1994):

$$Q = \frac{2\pi T(sm_1 - sm_2)}{ln(r_2/r_1)} \tag{2.21}$$

Here sm_1 and sm_2 are the steady state drawdowns and r_2 and r_1 are the distance from piezometer to the well and in meters. In order to find the transmissivity by using the steady state analysis there are two procedures.

In the studied boreholes in this thesis r_w = 0.03 (see section 3.1) and L=5m. F would in this case be roughly 0.81 for the packer test (equation 2.19) and 0.86 for Moye's formula (equation 2.20).

3

Method and material

3.1 Boreholes and water pressure measurements

There are 17 boreholes available that are spread along 6 planned tunnels. The radius of the boreholes are 0.03 m. The pumping tests were carried out in these boreholes. Hence the pressure measurement data and pumping rate data were obtained. The tests were mostly made with a double packer with a distance of 5 m between the packers. There were also two measurements done for each borehole with a single packer for a full borehole measurement and one for half the borehole. For both the single and double packer tests only one pressure step was recorded. The undisturbed groundwater level was measured before any tests could be conducted. All tests were done under the groundwater level. For the single packer it should be atleast one meter under the rock surface and one meter under the groundwater level. In table 3.1 data for the boreholes is shown, including borehole length, packer level and location. Packer level in this case means the depth in the borehole at which the water pressure tests were conducted. For example in borehole RB01KBH the packer level was 35-129.15 m, which would then mean that the greatest depth the packer was placed was at 129.15 m and the shallowest was 35 m below ground level. In the single packer test in this borehole the packer was placed at 35 and the water pressure test was then conducted from 35 m to the bottom of the borehole (129.15m). One reason for the start level is as mentioned above, the test have to be conducted under the ground water level. Table 3.1 also shows a rough location of the borehole, in which of the planned tunnels it is located.

Before starting the test the clock of the pressure sensors was synchronized with the provided stopwatch. In a double packer test the pressure sensor should be placed between the packers and for a single packer it is placed under it. The flow measurement equipment should be able to measure flows between 0.1 and 100 l/min and have an accuracy of $\pm5\%$. Furthermore, the tests were performed with a overpressure of around 3 bars until a constant flow was achieved. In this case a constant flow is defined as the change in the flow is less than 0.1 l/min for flows smaller than 5l/min and for flows larger than 5l/min the change should be less than 1 l/min.

Borehole	borehole length (m)	Packer level (meters from ground level)	Location
RB01KBH	129.15	35-129.15	Tunnel 7
RB02KBH	97	18-97	Tunnel 7
RB03KBH	139	59-139	Tunnel 7
MB04KB	120	29-120	Tunnel 1
MB05KBH	122	41-122	Tunnel 1
LB06AKBH	155	44-155	Tunnel 4
LB06BKBH	152	20-152	Tunnel 4
LB07KBH	169	23-169	Tunnel 4
LB08KBH	170	19-170	Tunnel 4
LB09KBH	164	18-164	Tunnel 4
LB10KBH	122	16-122	Tunnel 4
LB11AKBH	122	5-122	Tunnel 4
LB11BKBH	150	4-150	Tunnel 4
PB13KBH	130	65-130	Tunnel 2
PB16KBH	150	36-150	Tunnel 2
SB17KBH	145	19-145	Tunnel 3
LB18KBH	140	10-140	Tunnel 5

Table 3.1: Borehole data

The table 3.1 shows the borehole data which includes the informations regarding borehole length (meter), packer level and locations. The borehole RB02KBH is located at a position Tunnel 7 where the rock type is gabbro,diorite or diabase. For borehole SB17KBH located at a position Tunnel 3 the rocktype is gneiss. Moreover all the other available borehole locations shows same rock type that is granite or granodiorite.

3.2 Data definition

To be able to make a good analysis of the data it must first be properly understood and variances and deviations need to be explained. The raw data gathered from the water pressure test is pressure at a certain time. This pressure is then plotted against time as can be shown in figure 3.1 below. In the beginning of the curve there was a relative constant pressure of approximately 10 mH_2O, this is the measured atmospheric pressure that shows up before the equipment is lowered into the borehole. When the equipment was then lowered into the borehole the pressure would start to rise due to the water pressure. At the desired depth the packer was expanded and the injection of water was initiated which will cause a very rapid increase in pressure. The pressure was then kept at a constant level for several minutes before the packer was deflated and the pumping stops, this would cause a sudden drop in pressure. The process was then repeated for all the sections in the borehole. The Δh in figure 3.1 is the difference in pressure between the pressure before the pumping starts and during pumping, this is also the overpressure from the pump and is used in the calculation for the steady state analysis.

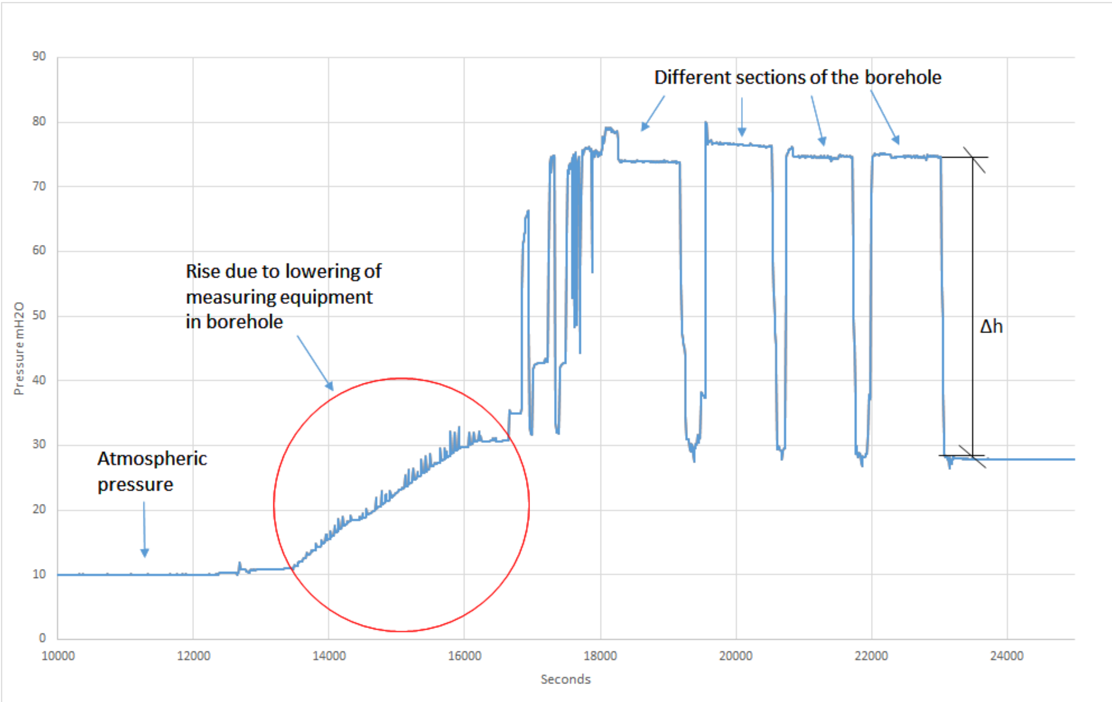

Figure 3.1: The figure is modified from pressure data for borehole LB11KBH.

There is also several deviations or errors in the pressure data that can obscure the results. Therefore it is important to find where this errors are in order to avoid using them for the analysis, as they could influence the calculations and give the wrong result. When the pumping stops the packer should also be deflated, however, sometimes it can be deflated some time after the pumping stops. This can give a similar deviation as in the figure 3.2 below, with a slower pressure drop before the packer is deflated and then a faster drop after. When analysing this part only the part before the packer is deflated can be considered. When the packer is then moved to the next section it will give a small spike in the pressure data. Also when the packer is inflated again it will be seen as a small “hump” before the injection of water begins and a rapid pressure increase can be seen.

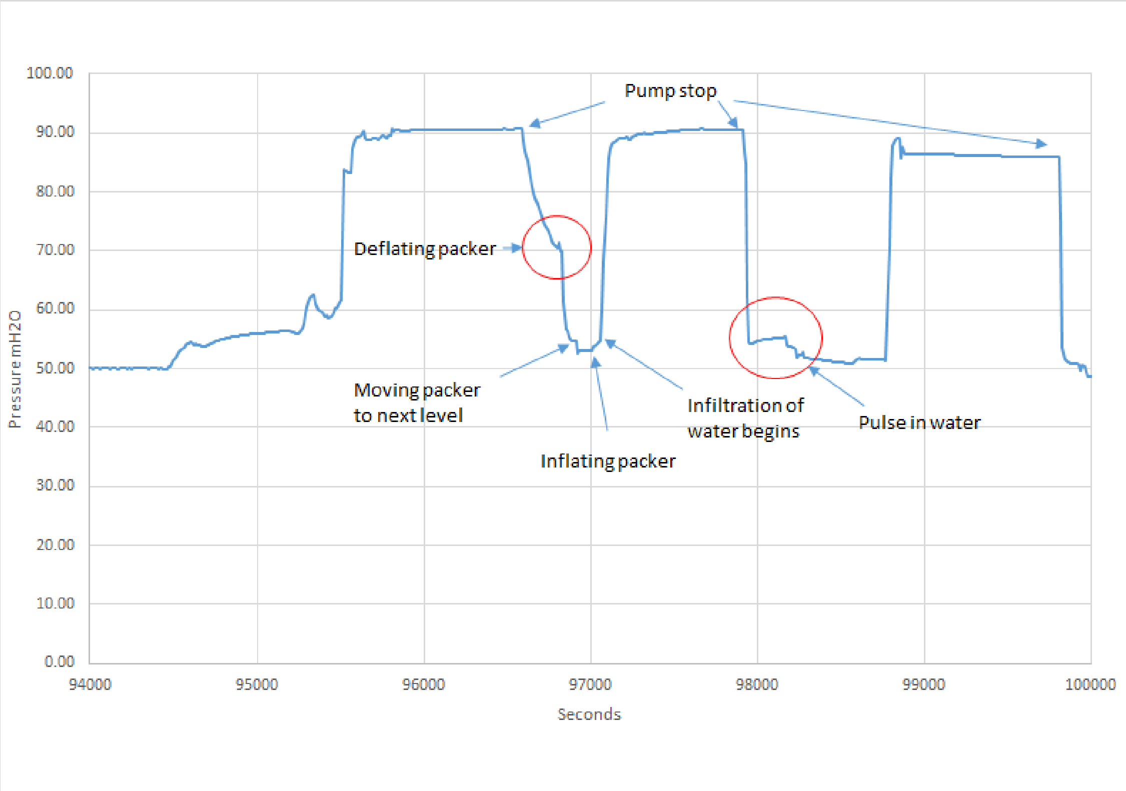

Figure 3.2: The figure is modified from the pressure data for borehole LB11KBH showing the test steps.

In the analysis it is only the values before the packer is moved that can be considered because after that the conditions have been changed and the results will therefore be wrong. In some cases there can occur a larger spike shortly after the pumping stops. One reason for this could be due to the sudden pressure drop causing a pulse in the water. However, there is no available data of exactly when packers are deflated/inflated or moved, only when the pumping starts and stops. The pumping stop time is also when the operator starts to measure the water flow which can be some time after the pump actually starts. The origin of these errors and deviations are therefore based on assumptions about how different actions will affect the pressure.

The amount of data for different sections varies a lot. In some sections there are only 2-3 points that represents the recovery and in others much more. One reason for this is that the time for recovery is fast and due to the pressure being registered every 10 second it will give few points. It can also be due to disturbances in the data making parts of the recovery data unsuitable for analysis. Matching a straight line like in the Cooper-Jacob method to 2 or 3 points will give results that are not reliable. The more data points that is available the more reliable results will be obtained. Therefore the borehole sections will be classified into "high reliability" or "low reliability" depending on how much data is available for the section.

Looking at the borehole RB01KBH it has a section of "higher reliability" at the depth of 128-123 m. Where it has many data points that form a curve with a straight part which the Cooper-Jacob solution can be matched to, as can be seen in the figure 3.3. With the many points with little deviation from the straight line it will give a high reliability of the obtained results.

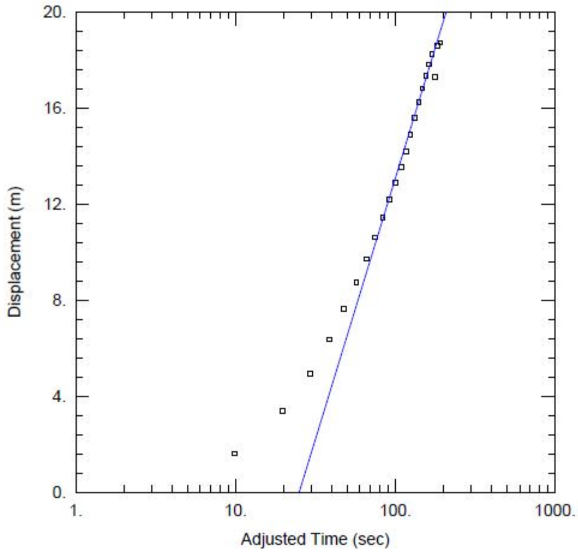

Figure 3.3: Example of borehole RB01KBH , level 128-123 having "high reliability"- Several data points plotted linearly.

However, there is a section with few data points in this borehole which makes it less reliable. In the section 113-108 the points forming the straight line ,that the Cooper-Jacob solution should be matched to, consists of only two points, as can be seen in figure 3.4. To be able to more reliably predict the results more points are needed to confirm that this line is actually the right one.

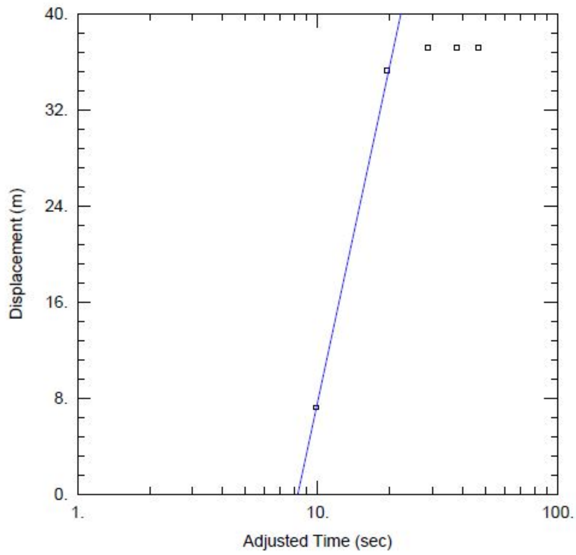

Figure 3.4: Example of borehole RB01KBH , level 113-108 having "low reliability"- few data points plotted.

3.3 Software analysis with AQTESOLV

AQTESOLV version 4.50.002 is a software that uses displacement, pumping and time data to plot the displacement versus time in a graph. The graph is then matched with a curve from one of several available solutions and thereafter a transmissivity and storativity can be obtained. For the evaluation of storativity a interference test is preferable. In order to perform an analysis the displacement at a certain time is needed and depending on the test conducted pumping data is needed. The data that was available for this project was the pressure as a function time. This was then transformed into mH_2O and then by taking the difference from the maximum pressure (the maximum head) and the pressure in a point the displacement was obtained.

The part of the pressure graph that was relevant for the analysis was the pressure drop off after the pumping stopped which is the recovery of the water pressure in the section. This can be done in a few different ways. One way is by considering the whole pumping cycle which means that the pressure and the pumping rate during the whole time the pump is active is considered. The pumping is done in a way so that the pressure is kept at a constant level during the whole pumping cycle. Therefore if the whole cycle is considered it would be more suitable to analyse it as a constant head test with for example the Jacob-Lohman method. Another way is to use the Agarwal method to transform the time into an equivalent time. This way the time starts when the pumping stops, however, the transformation still takes into consideration the pumping. With the equivalent time only the part of the curve that was analyzed was entered in Aqtesolv and was evaluated as a pumping test with for example Cooper-Jacob method.

Which evaluation method that was used depended on what flow regimes that were detected in the data. For the section with a low reliability it was not possible to make any accurate assumptions of the flow regimes from the derivative. Therefore it was assumed that in this sections there is a infinite acting radial flow and that Cooper and Jacob method could be used. With the section with higher reliability there were more data points and was therefore easier to detect patterns from the derivative. If the derivative indicates a infinite acting radial flow the Cooper and Jacob method can be used for the corresponding part of the drawdown curve with good accuracy (Carlsson and Gustafson, 1997).

4

Results and Discussion

From the results obtained from the steady state calculation and the aqtesolv transient analysis the transmissivity versus section level graphs are shown below for the boreholes RB01KBH, LB08KBH, SB17KBH, RB03KBH, LB06AKBH. The steady state transmissivity was obtained for each of the boreholes by solving the packer test (equation 2.19) (Gustafson, 2012). In table 4.1 the number of fractures in some of the relevant sections are shown with comments on characteristics. The fracture data was gathered from photos of the core and borehole images.

Borehole	**Borehole section**	**Comment on core data**
RB01KBH (Fig 4.1)	78-73	13 fractures
RB01KBH (Fig 4.1)	128-123	No visible fractures in the core data but an inflow of 5 l/min
RB03KBH (Fig 4.5)	116-111	7 fractures
RB03KBH (Fig 4.5)	121-116	13 fractures
LB08KBH (Fig 4.4)	104-99	2 fractures
LB08KBH (Fig 4.4)	89-84	No visible fractures in core data but an inflow of 20 l/min
SB17KBH (Fig 4.3)	79-74	6 fractures of which 4 are located very close to each other

Table 4.1: Information about the fractures in some sections of the boreholes.

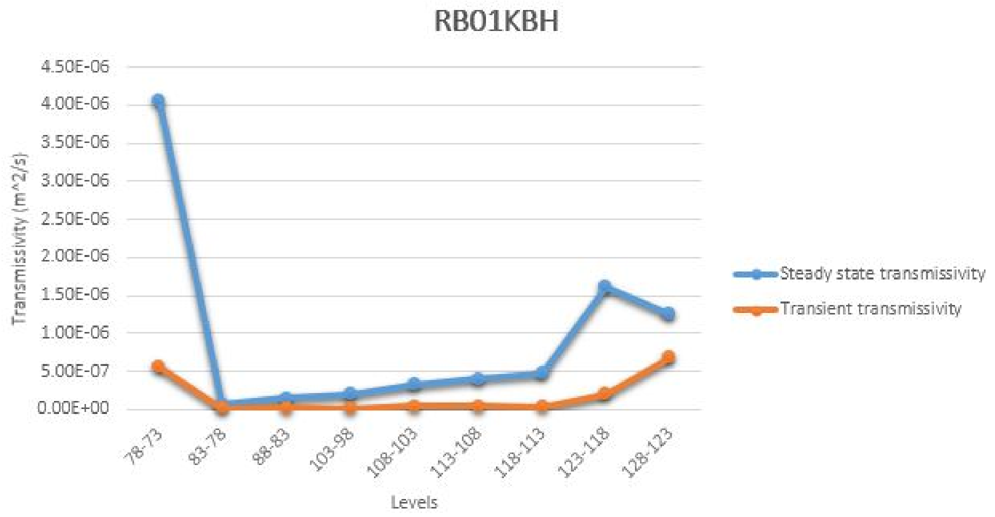

Figure 4.1: Transient and steady state transmissivity for borehole RB01KBH.

In RB01KBH the level 78-73 shows a big difference between the steady and transient transmissivity, this could be due to the presence of multiple fractures which are interconnected to each other are visible, that could be the reason for higher value difference between the transmissivities. However the values are still in the same order of magnitude. In Figure 4.1 where the level 128-123 shows high reliability there is no fracture observed. Moreover all the other levels in each boreholes shows low reliability because of the availability of less number of datas for the sections.

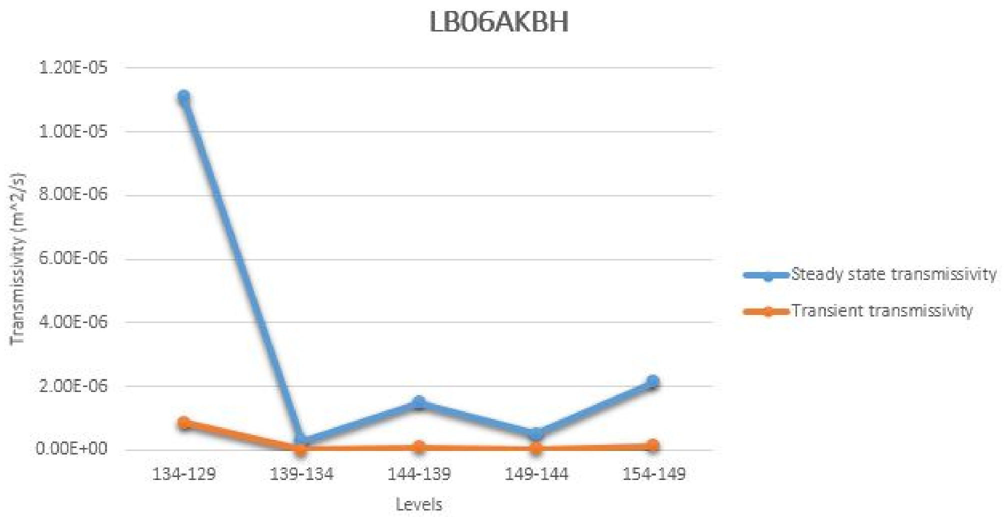

Figure 4.2: Transient and steady state transmissivity for borehole LB06AKBH.

As can be seen in Figure 4.1, Figure 4.2 and Figure 4.3 the transient values are generally lower than the steady state ones for RB01KBH, LB06AKBH and SB17KBH.

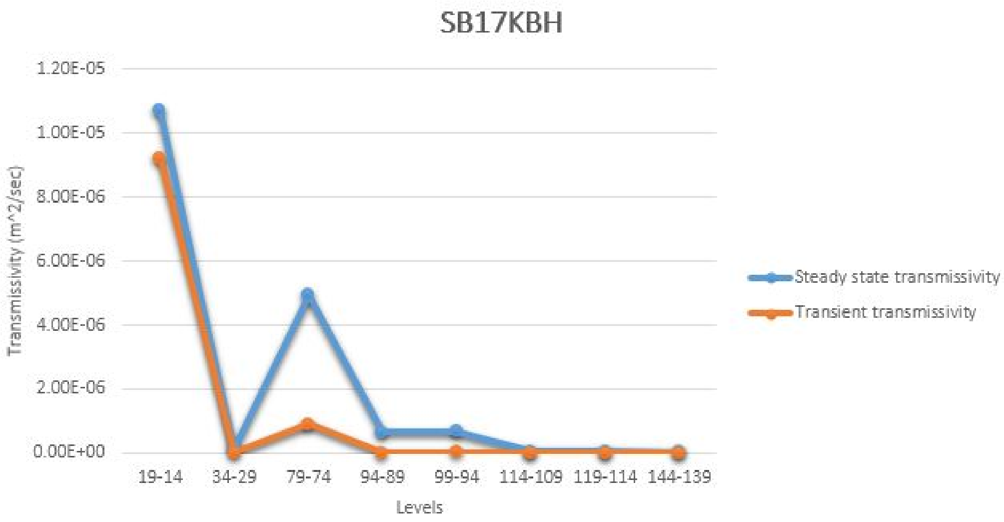

Figure 4.3: Transient and steady state transmissivity for borehole SB17KBH.

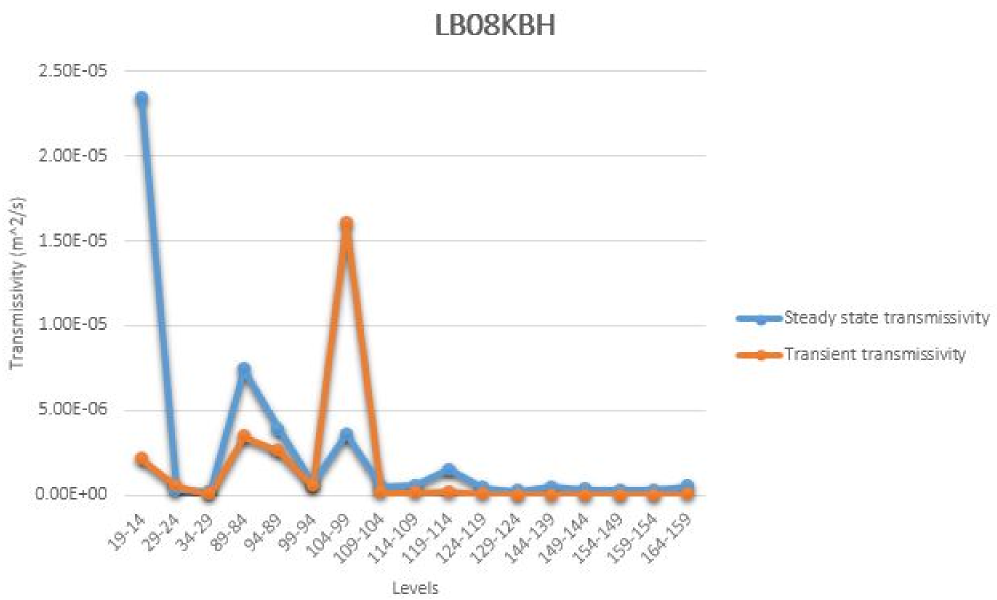

Figure 4.4: Transient and steady state transmissivity for borehole LB08KBH.

In section 104-99 in borehole LB08KBH there is a significantly higher transmissivity evaluated using transient analysis than steady state analysis. This section is not very fractured, only 2 fractures where visible in the core sample. This could indicate that in this section the fracture aperture is locally smaller. However this section is not one of the more reliable sections. There is one section of higher reliability in the borehole which is section 89-84. Here the difference is not as big but there is a slightly higher steady state transmissivity. From the scanning of the borehole there is no visible fracture for this borehole section but examining the core there is at least one potential fracture. The Dougherty-Babu solutions, that is shown in figure A.9 in appendix, gives a slightly higher transmissivity value that is closer to the steady state value, it also gives a skin factor of 1.125.

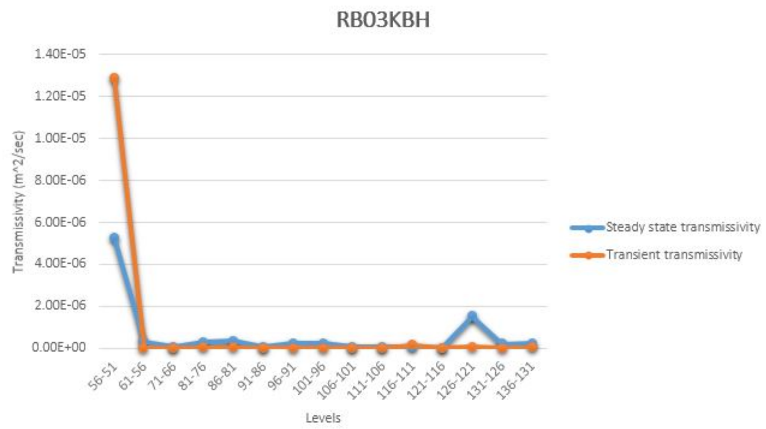

Figure 4.5: Transient and steady state transmissivity for borehole RB03KBH.

In Figure 4.4 and Figure 4.5 the data plotted on the basis of transmissivity values calculated from both the steady state and transient analyses method.
By plotting the values of steady state transmissivity versus the transient transmissivity in a graph it is possible to see how well the transmissivities correspond to each other, see Figure 4.6. Furthermore it is also possible to see if there is any patterns in the agreement of them at low and high transmissivities. This is shown in the graph below where every dot contains the value of transmissivity for steady state and transient analysis in the same borehole section. The green line is a straight line that is the line the dots would follow if there was a 100% agreement.

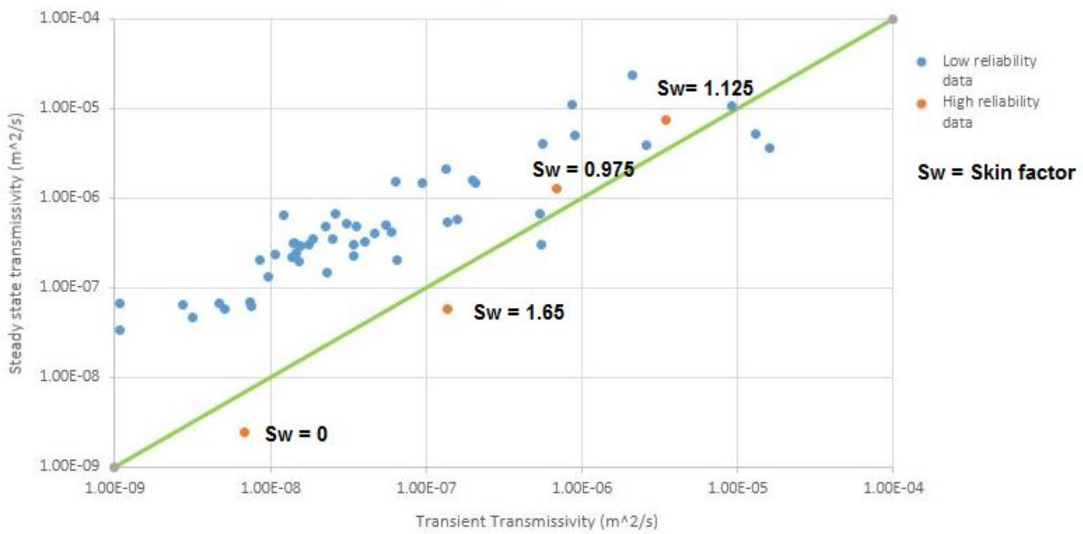

Figure 4.6: Transmissvity comparison for boreholes. Steady state transmissivity based on equation 2.19 and transient transmissivity based on the Cooper-Jacob solution.

The blue dots in Figure 4.6 represents the sections of low reliability and the orange dots are the sections with higher reliability where lower reliability points shows less number of datas for the section and high reliability points shows high number of datas for the section. The majority of data points shows a higher value for the transmissivity estimated with steady state compared to transient data. There are several different equations that can be used to estimate the steady state transmissivity and they differ to each other by a certain factor. Therefore it could be possible that another steady state method could give a better agreement with the transient data. The data points of high reliability all have a good agreement between the steady state and transient data, however, they are few and it is therefore not possible to see any general patterns with certainty.

4.1 Locally small aperture and consequences for grouting

In the case shown in figure 2.5 with a local aperture that is smaller than the aperture at a further distance from the borehole. As was mentioned earlier the flow will be limited by the smaller aperture and it is this aperture that will dominate the transmissivity in a steady state test. This is supported by (Meier et al., 1999) which showed that Q/s values are more dependent on local transmissivites close to the well compared to transmissivity values obtained from Jacob's method. If only a steady state test is made there is a risk that the transmissivity for the aquifer is underestimated. This is because the representative conditions for the aquifer is in fact the bigger aperture and the borehole was drilled in a locally smaller aperture, then the steady state will only show the transmissivity for the smaller aperture. The risk will then be that when for example a tunnel is constructed in the area the estimated water flow to the tunnel will be less than the actual inflow. Designs of grouting can also be wrong if they are based on this steady state test because if a another borehole is drilled close by it might not be in a locally smaller aperture. There would then be higher flow than the grouting was designed for and it could be insufficient in sealing the tunnel.

If instead a transient test is made it would be possible to detect the conditions further away from the borehole. A transmissivity that is higher for a transient test than a steady state test could therefore indicate that there is a smaller aperture locally and that transient transmissivity is a better representation of the aquifer. Estimating a skin factor for the section it can be used for explaining or describe the local conditions of the section. If there is a large skin factor and a low steady state transmissivity while the transient test transmissivity for the same borehole is higher, it could indicate that the aperture of the fractures is smaller locally.

The duration of the steady state test should be of sufficient duration otherwise only the conditions close to the borehole will be taken into consideration. However, if the case is a locally small aperture then the result will not change much if the test is ran for a longer time. It is different for a transient test because the longer the duration the further away from the borehole can be observed. If the duration is too short it will mostly be affected by wellbore storage and skin effects and not show the transmissivity of the aquifer. To be able to make a good prediction from the transient data a duration that is long enough to show clearly what flow regime is present after the skin and wellbore storage effects is needed.

4.2 Locally large aperture

The aperture having a radial dimension which shows a larger aperture closer to the borehole and the aperture far away is smaller shown in the figure 2.6. Lets consider the steady state analysis were the flow is constant and transient analysis were flow is unsteady. The transmissivity through the larger aperture is higher than that of the smaller aperture. Similar to the locally small aperture the flow will be limited by the smaller aperture in the fracture. Hence the steady state test will show the transmissivity for the smaller aperture as long as the flow reach that far. A transient test will show the transmissivity further away from the borehole where the flow is not affected by skin and wellbore storage effects. This means that transient and steady state tests should show similar transmissivity values as they both corresponds to the smaller aperture further away from the borehole. In this case the skin factor corresponds to the locally larger aperture which should give a low skin factor.

When considering a steady state test of long duration the transmissivity will mostly be determined by the smaller aperture due to it limiting the flow through the fracture. The risk with a shorter duration steady state test is that water head might not reach to the smaller aperture. This would lead to overestimating the transmissivity for the aquifer because only the larger aperture close to the borehole is considered.

4.3 Accuracy of results

The results obtained from all the analysis are not fully accurate. Some variations occur due to some small errors, it can be due to technical errors or physical errors. The software AQTESOLV gives transmissivity values for the transient analysis for each method and the possible error occurrence in the software can be due to the wrong input of values and due to the improper curve fitting. The data was also divided into reliable and unreliable data depending on how many data points there was for each section. The unreliable sections had very few data points and are the majority of sections. For this sections the flow regimes had to be assumed as it was not possible to see any distinct flow regimes from the derivative. The reliable sections had more data points so it was possible to see patterns from the derivative and better matching and choice of solution could be made. However, for some of the reliable sections the duration was rather short and it was difficult to see the patterns at late time.

There are some other errors which is obtained from the core drilling. The fractures present in the core sample for some boreholes are not visible in the actual borehole inner wall image. Some confusions obtained due to this unexpected variations. This variation can be visible from the transient transmissivity vs steady state transmissvity plot for borehole LB08KBH and RB03KBH where in some levels the transient transmissvity is higher than the steady state transmissivity.

5
Conclusions

In this thesis, the aperture of a fracture is characterized using the transmissivity obtained from transient and steady state analyze. The aperture of the fracture in some of the levels in each boreholes are locally smaller and some of the level doesn't show any fracture presence.

- If there is a locally small aperture close to the borehole then there is a risk if you only do a steady state test that the conditions far away is overlooked. This can give an underestimation of the transmissivity of the aquifer. This is also supported by (Hamm et al., 2005) which shows that specific capacity without considering skin will also lead to the underestimation of the transmissivity of the aquifer. For a tunnel construction application this can lead to bad design as it is designed after smaller flows then what is representative for the aquifer, especially for grouting this means that it might not be designed to seal the larger aperture and higher flows. A transient test can detect the conditions close to the borehole as well as further away and therefore give better representation of the aquifer.
- If there is a locally large aperture close to the borehole and a steady state test is performed the estimated results will be limited by the aperture far away from borehole because the flow is not limited close to the borehole. Moreover, if you do a transient analysis the estimated transmissivity is corresponding to the smaller aperture further away, same as steady state, but by analyzing the skin effect the conditions close to the borehole can be detected. Both steady state and transient tests will give roughly the same transmissivity which should be a general representation of the aquifer, however, even if the flow is corresponding to the smaller aperture, if the fracture is to be sealed then the grout design might have to consider the larger aperture close to the borehole. As this larger aperture could need larger volumes of grout and also a stiffer grout than it would need for a smaller aperture.
- The two different conceptualizations investigated in this report (locally small and large aperture) can be used to describe fractures of varying aperture. There is a few sections where the expected difference of a locally small aperture close to the borehole can be observed, where the transient transmissivity is higher than the steady state. A locally large aperture could not be observed in the investigated boreholes as it can not be seen in a difference of the transmissivity but rather by a negative skin factor, which was not present in any of the sections investigated.
- The transmissivity for steady state were generally higher than for transient test in the investigated boreholes. This is mainly true for the lower reliability

sections while the few sections of higher reliability shows a better agreement.

5.1 Recommendations

The water pressure tests investigated in this report are mainly used for underground construction in rock and the measurements in the boreholes that was used here was made to investigate the properties of the rock in several planned railroad tunnels. The water pressure test can give valuable information for the construction of tunnels, especially when it comes to grouting the fractures in the rock. To be able to make a sufficient sealing of the tunnel the grouting must be properly designed and to do that it is essential to know the geometry and transmissivity of the fractures. As was mentioned before, if the grout is designed for a smaller local aperture then there is a risk that the grout will only seal the fracture close to the borehole. The problem is then that if you continue the tunnel construction you might hit the fracture where the aperture is larger and not sealed and large inflows to the tunnel can occur. Another problem is if the other boreholes of the grouting fans hit the larger aperture while the grout for this boreholes was designed for the smaller aperture, then the designed grout might not be able to seal the fracture.

With a locally large aperture the transmissivity will be represented by the smaller aperture further away. Therefore the grout design will be designed for the smaller aperture, which could lead to a insufficient sealing close to the borehole and underestimation of the grout needed.

Depending on what is prioritized and is most important in each type of construction what is recommended could differ. However, some general recommendations based on the findings in the thesis are:

- Due to the problems and risks that is mentioned earlier it is recommended to use transient test analysis in order to obtain good design of grouting, moreover it is especially important to conduct a transient test when there is a expected fracture zone close to the borehole. This is because a fracture zone can be detected with a transient test and can be planned for in advance.
- A steady state test needs to be of long enough duration for the change in water head to reach a sufficient distance from the borehole. Which should be enough to cover the distance from the borehole where it is desired to study the properties of the fractures in the rock.
- The duration of the transient test need to be long enough that the effects of wellbore storage and skin is no longer affecting the transmissivity and the flow regime after this effects can clearly be seen. An appropriate solution have to be chosen based on what flow regimes can be seen and other available conditions for the aquifer and borehole.
- Future investigations have to be done in more boreholes to obtain more reliable data. By obtaining more reliable data it is possible to see clear correspondences between measured data and conceptual model.

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A

Appendix

A.1 RB01KBH- Level 128-123

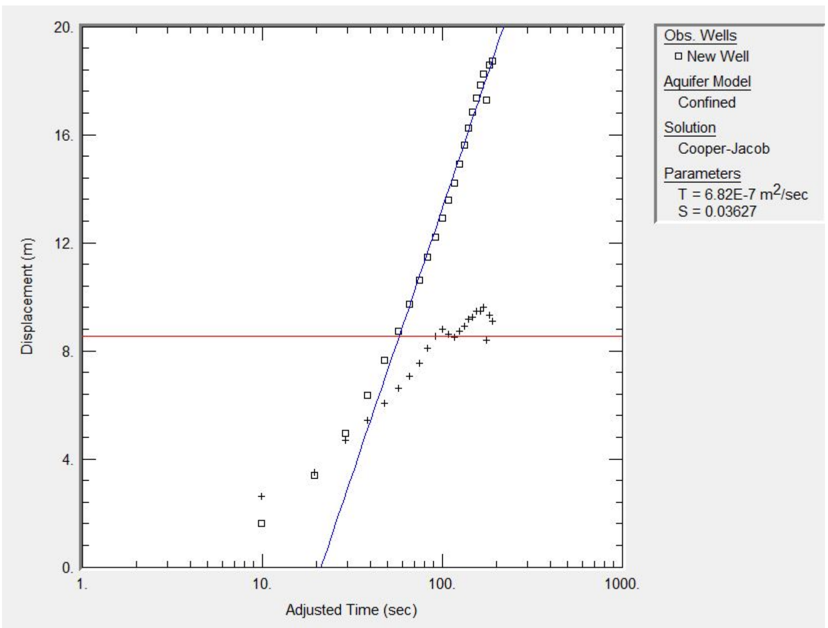

Figure A.1: Cooper-Jacob Solution method 128-123 RB01KBH

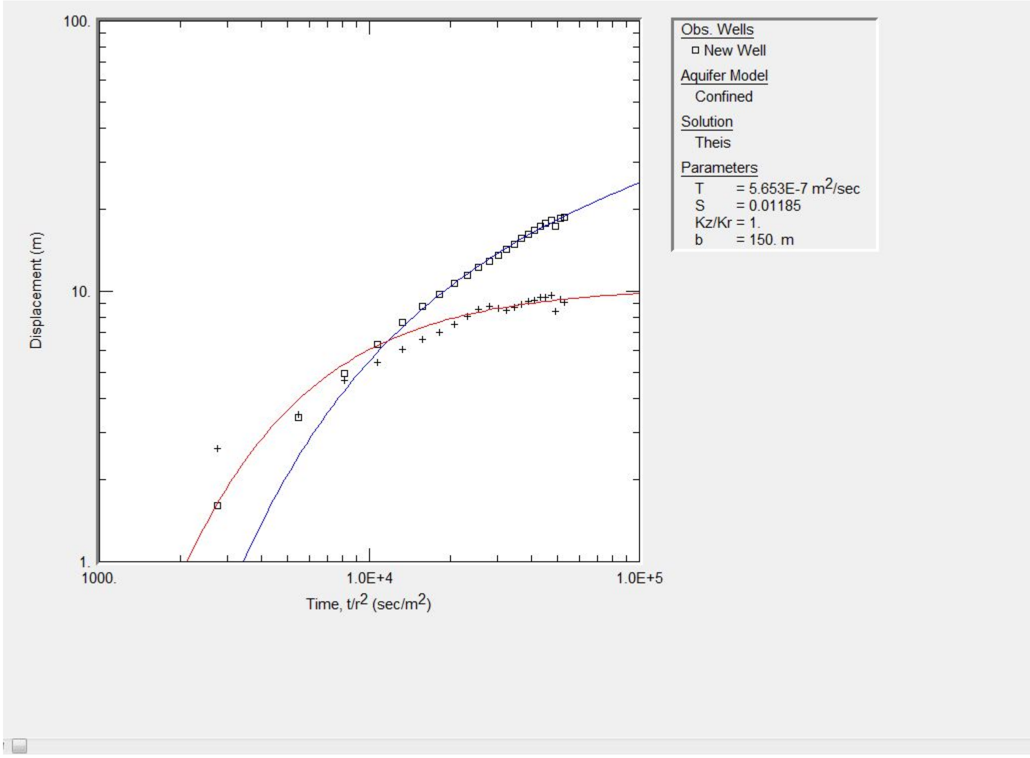

Figure A.2: Theis solution method 128-123 RB01KBH

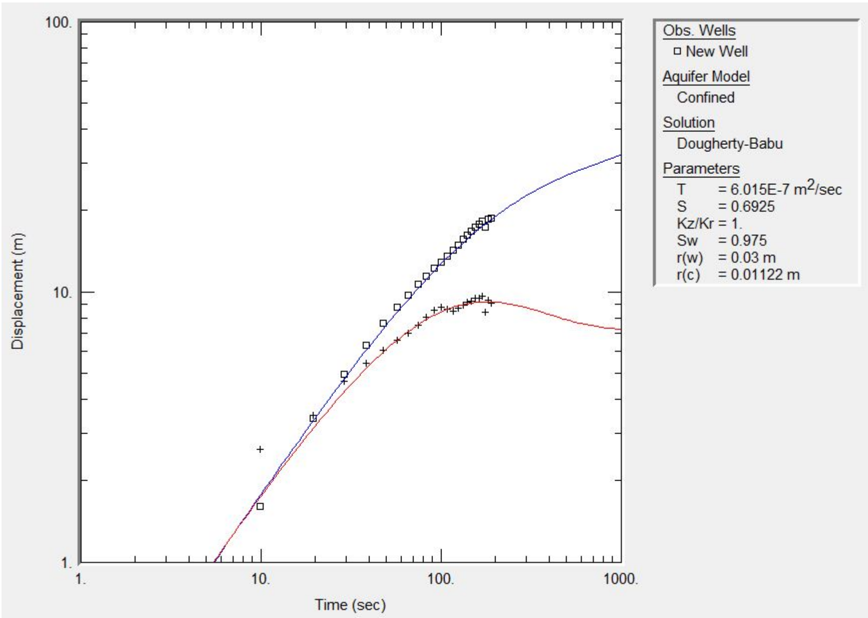

Figure A.3: Dougherty-Babu-RB01KBH 128-123

A.2 LB08KBH- Level 89-84

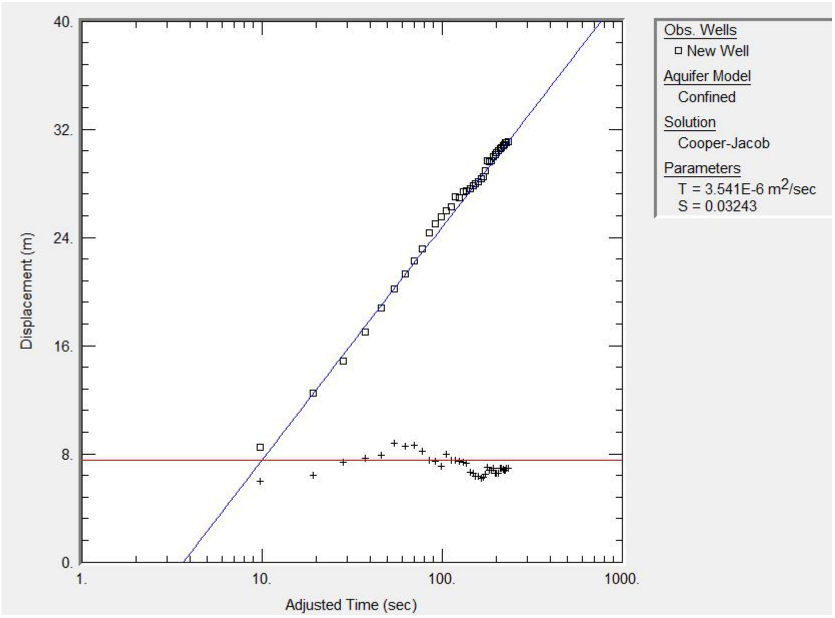

Figure A.4: Cooper-Jacob solution method LB08KBH 89-84

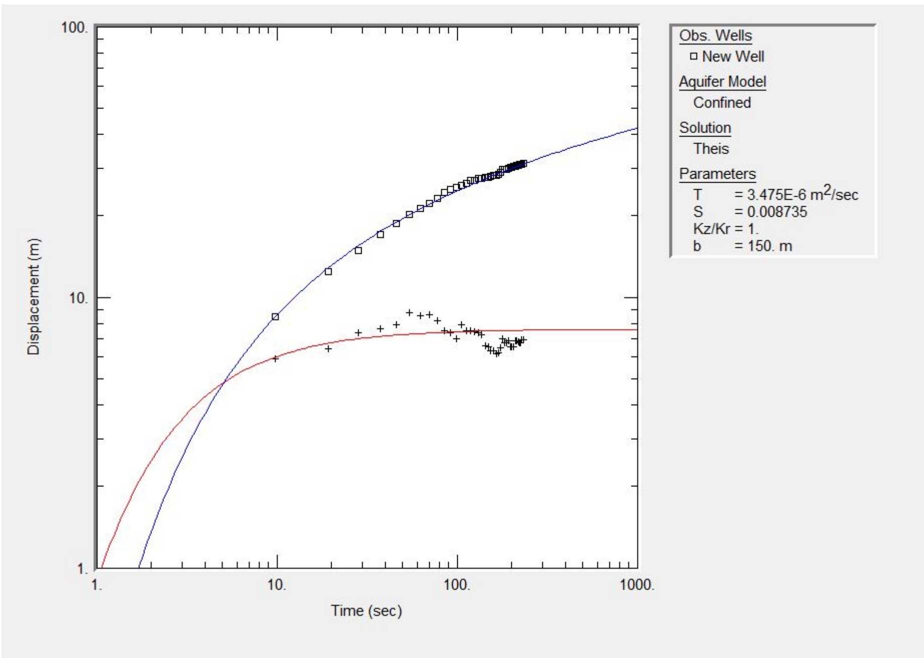

Figure A.5: Theis solution method LB08KBH 89-84

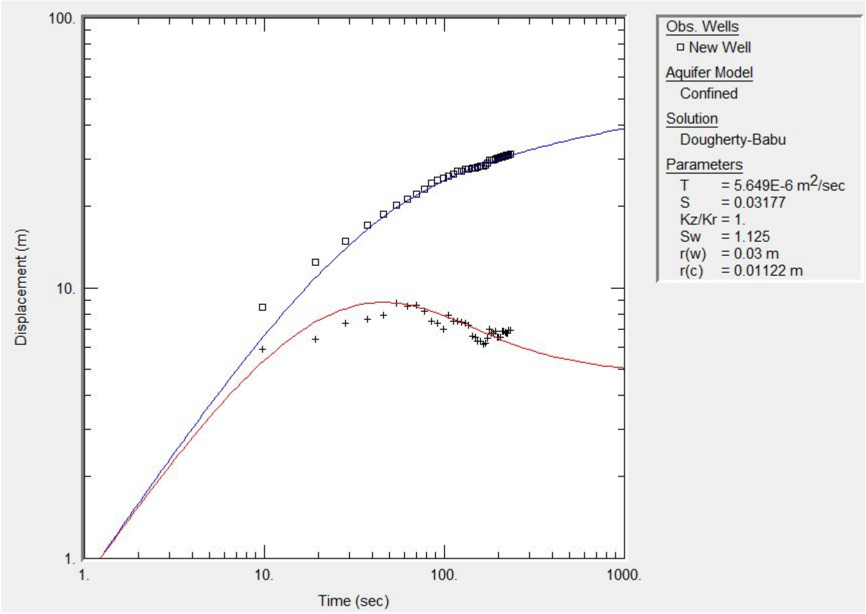

Figure A.6: Dougherty-Babu-LB08KBH 89-84

A.3 RB03KBH-Level 116-111

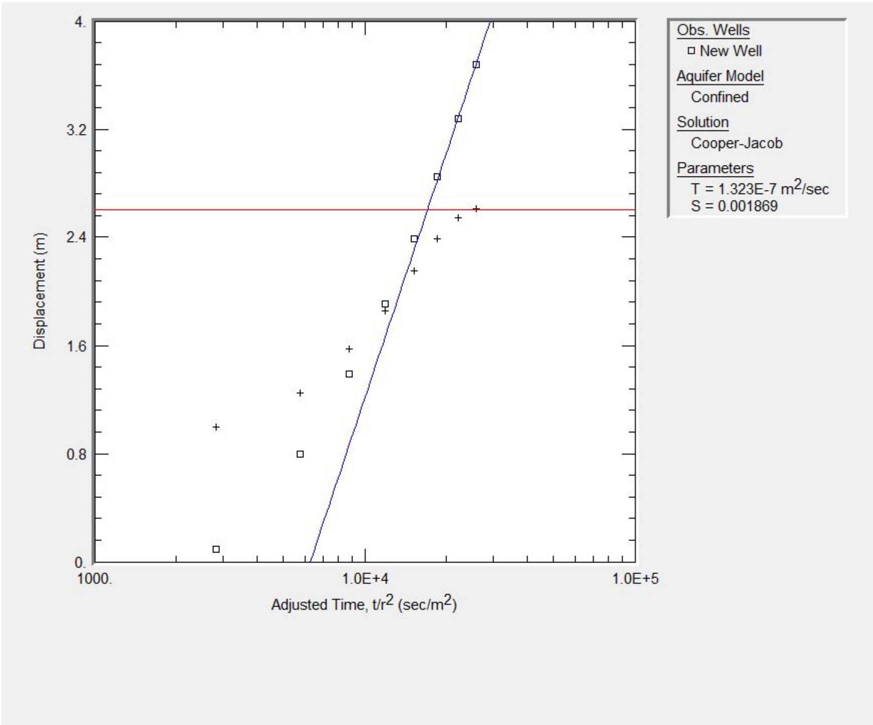

Figure A.7: Cooper-Jacob Solution method RB03KBH 116-111

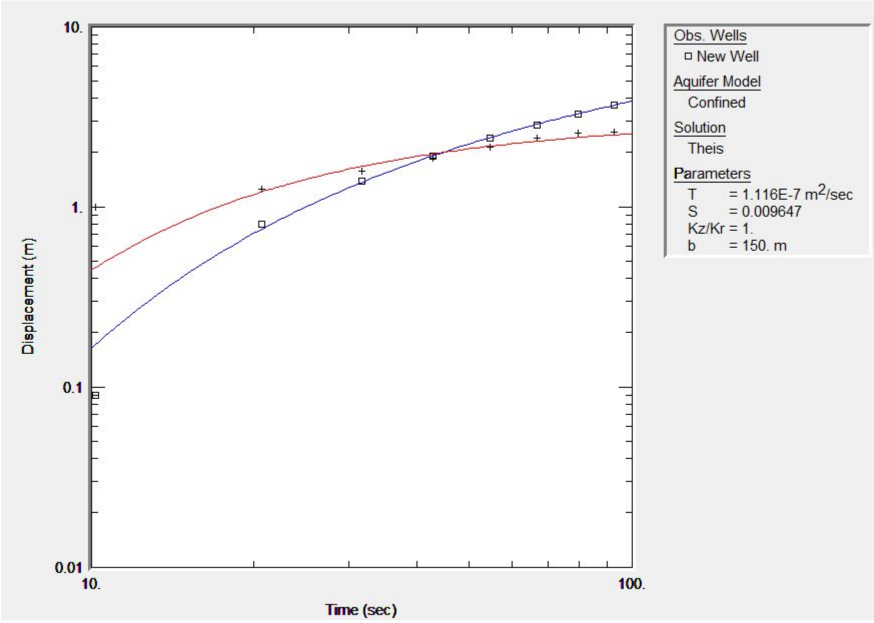

Figure A.8: Theis solution method RB03KBH 116-111

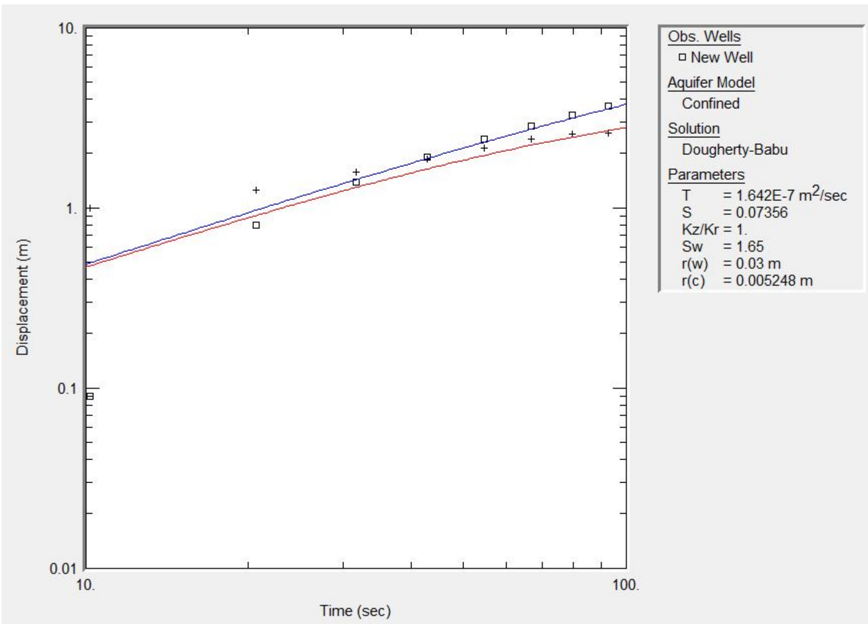

Figure A.9: Dougherty-Babu-RB03KBH 116-111

A.4 RB03KBH- Level 121-116

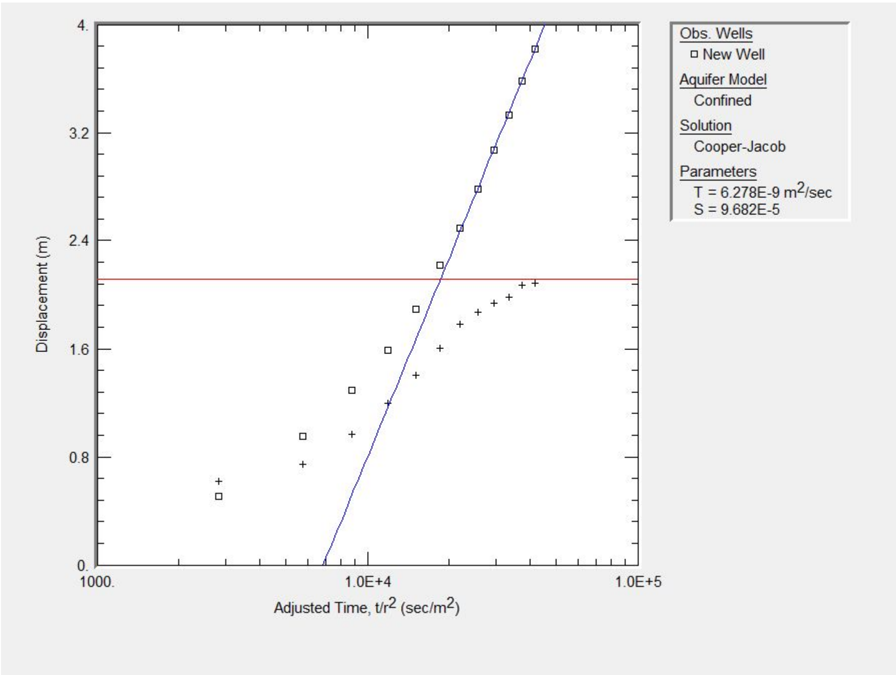

Figure A.10: Cooper-Jacob solution method RB03KBH 121-116

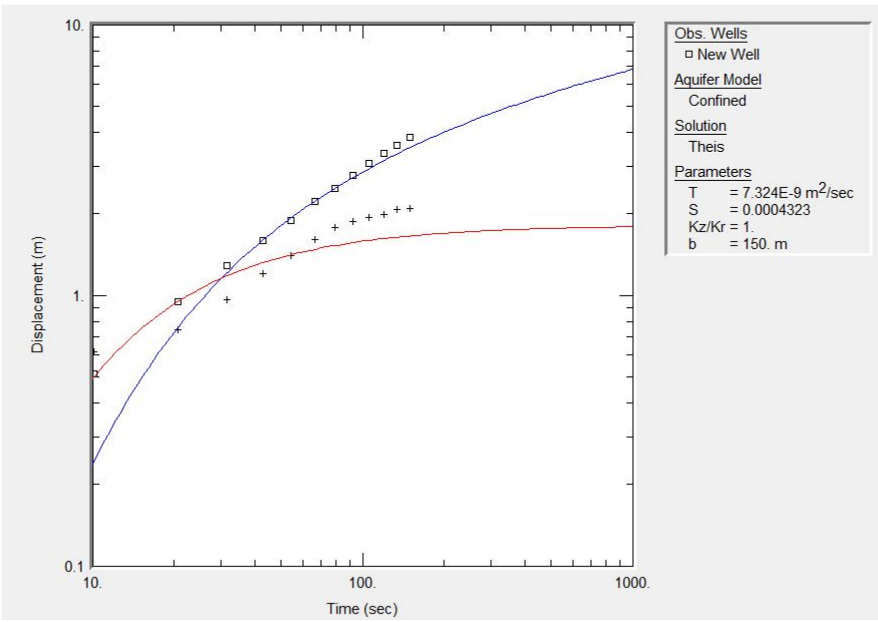

Figure A.11: Theis solution method RB03KBH 121-116

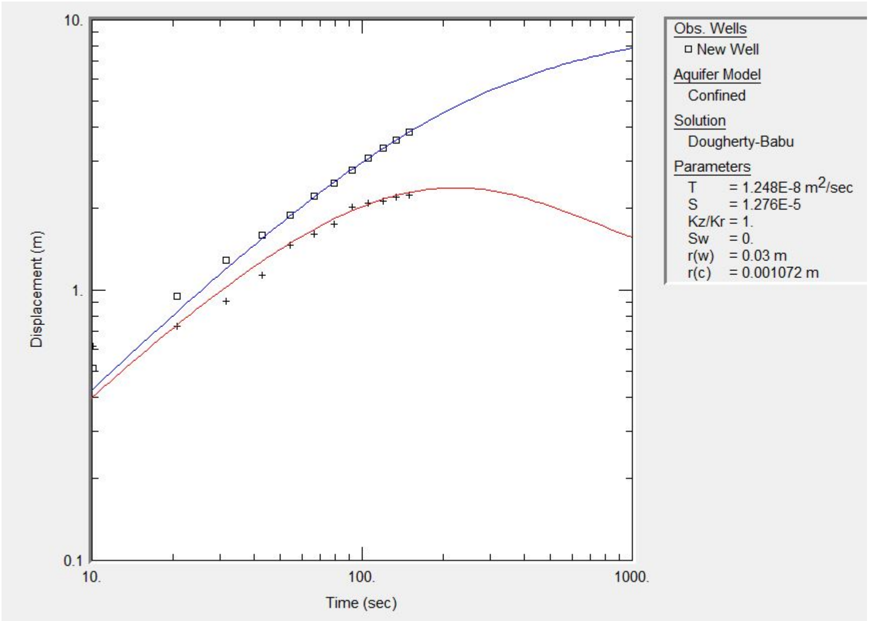

Figure A.12: Dougherty-Babu-RB03KBH 121-116