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Forsmark site investigation

Supplementary hydraulic tests in Quaternary deposits

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Abstract

Supplementary hydraulic tests in Quaternary deposits were performed in the Forsmark area during the period May 18 to July 7, 2006. The tests consist of slug test in 11 monitoring wells, pumping tests in three wells and permeameter tests in situ in seven BAT filter tips. The specific objective of the tests was to obtain data for the estimation of the hydraulic properties (hydraulic conductivity, K, and storativity, S) in (i) Quaternary deposits in assumed groundwater discharge areas (lakes and wetlands), and (ii) local topographically elevated areas, in the vicinity of percussion boreholes.

The objective of the slug tests was to obtain data for the estimation of the hydraulic conductivity and storativity of the till and sand layers in the immediate vicinity of the well screen. The data from the tests were evaluated by using three methods, the Cooper et al. method, the Hvorslev method and the Bouwer & Rice method.

The three pumping wells are placed in till, in the contact zone between Quaternary deposits and bedrock. Unconfined conditions prevail at two of these locations. In one well (SFM0103) the till is overlain by clay, gyttja and peat, which means that semi-confined to confined conditions prevail. The screens of the monitoring wells are placed in till or in sandy layers, overlain by layers of clay, gyttja, peat and/or open water. The drawdown and recovery data from the pumping test were evaluated by the Theis method, the Jacob method, and the Theis recovery method. Further, in order to investigate the leakage of water from the layers overlaying the till during the pumping test, drawdown data from one pumping well and two monitoring wells were analysed using the Hantush method.

The BAT filter tips are placed in clay, gyttja or peat at depths between 0.88 and 2.62 m below ground surface.

The evaluation provided values of the hydraulic conductivity (K) in the following ranges:

Slug tests; Cooper et al. method (K):	$5.8 \cdot 10^{-9}$–$3.3 \cdot 10^{-4}$ m/s
Slug tests; Hvorslev method (K):	$8.9 \cdot 10^{-9}$–$1.5 \cdot 10^{-4}$ m/s
Slug tests; Bouwer & Rice (K):	$7.6 \cdot 10^{-9}$–$6.8 \cdot 10^{-5}$ m/s
Permeameter tests (K):	$2.6 \cdot 10^{-7}$–$3.4 \cdot 10^{-7}$ m/s
Pumping tests (K):	$6.3 \cdot 10^{-6}$–$1.8 \cdot 10^{-4}$ m/s

Sammanfattning

Kompletterande hydrauliska tester i jord bestående av slugtester i elva observationsbrunnar, provpumpningar i tre pumpbrunnar och slutligen permeametertester in situ i sju BAT-spetsar genomfördes under perioden den 18 maj–7 juli, 2006. Syftet med de genomförda hydraultesterna var att erhålla data för utvärdering av hydrauliska egenskaper (hydraulisk konduktivitet, K, och magasinskoefficient, S) i (*i*) kvartära avlagringar inom förmodade utströmningsområden (sjöar och våtmarker) och (*ii*) lokala höjdområden i närheten av hammarborrhål.

Syftet med de genomförda slugtesterna var att erhålla data för utvärdering av hydraulisk konduktivitet och magasinskoefficient för morän och sandlager i närheten av observationsbrunnarna. De erhållna datamängderna utvärderades med hjälp av tre metoder; Cooper et al. Hvorslev och Bouwer & Rice.

De tre pumpbrunnarna är placerade i morän där filterdelen sitter i kontaktzonen mellan morän och berg. Öppna magasinsförhållanden råder vid två av dessa platser. Vid en pumpbrunn (SFM0103) är moränen överlagrad av lera, gyttja och torv vilket medför att halvslutna till slutna förhållanden råder vid denna brunn. Observationsbrunnarnas filter är placerade i morän eller sandiga lager vilka ofta är överlagrade av lera, gyttja, torv och/eller öppet vatten. Avsänknings- och återhämtningsdata från provpumpningarna är utvärderade i enlighet med Theis, Jacob och Theis recovery. För att utvärdera eventuellt läckage från överliggande lager ner till den pumpade formationen utvärderades avsänkning från en pumpbrunn och två observationsbrunnar i enlighet med Hantush.

BAT-spetsarna sitter i torv, gyttja eller lera på ett djup varierande från 0,88 till 2,62 meter under markytan.

Utvärderingarna av den hydrauliska konduktiviteten gav följande resultat

Slugtest; Cooper et al. (K):	$5{,}8\cdot10^{-9}$–$3{,}3\cdot10^{-4}$ m/s
Slugtest; Hvorslev (K):	$8{,}9\cdot10^{-9}$–$1{,}5\cdot10^{-4}$ m/s
Slugtest; Bouwer & Rice (K):	$7{,}6\cdot10^{-9}$–$6{,}8\cdot10^{-5}$ m/s
Permeametertest (K):	$2{,}6\cdot10^{-7}$–$3{,}4\cdot10^{-7}$ m/s
Provpumpningen (K):	$6{,}3\cdot10^{-6}$–$1{,}8\cdot10^{-4}$ m/s

Contents

1 Introduction

This document reports the results obtained from the activity *Supplementary hydraulic tests in Quaternary deposits*, which is one of the activities performed within the site investigations at Forsmark. The work was carried out in accordance with activity plan AP PF 400-06-015. In Table 1-1 controlling documents for performing the activity are listed. Both the activity plan and the method descriptions are SKB's internal controlling documents.

The hydraulic tests consist of slug tests in 11 monitoring wells, pumping tests in three wells, and permeameter tests in situ in seven BAT filter tips. The tests have been performed during the period May 18 to July 7, 2006.

The screens of the three pumping wells are installed in the contact zone between Quaternary deposits and bedrock. Unconfined conditions prevail at two of these locations. In one pumping well (SFM0103) the till is overlain by clay, gyttja and peat, which means that semi-confined to confined conditions prevail.

The screens of the monitoring wells are installed in till or in sandy layers and are generally overlain by layers of clay, gyttja, peat and/or open water. The BAT filter tips are installed in layers of clay, gyttja or peat.

Figure 1-1 shows the locations of the monitoring wells, pumping wells and BAT filter tips.

The permeameter tests were performed by Golder Associates' sub-consultant, GeoNordic AB. Their report (in Swedish) is attached in Appendix 3 and the results are presented in Chapter 6.

The results are stored in SKB's data base SICADA, and are traceable by the activity plan number.

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Kompletterande hydrauliska tester i jord	AP PF 400-06-015	1.0
Method descriptions and instructions	**Number**	**Version**
Metodbeskrivning för slugtester i öppna grundvattenrör	SKB MD 325.001	1.0
Instruktion för rengöring av borrhålsutrustning och viss markbaserad utrustning	SKB MD 600.004	1.0
Instruktion för användning av kemiska produkter och material vid borrning och undersökningar	SKB MD 600.006	1.0

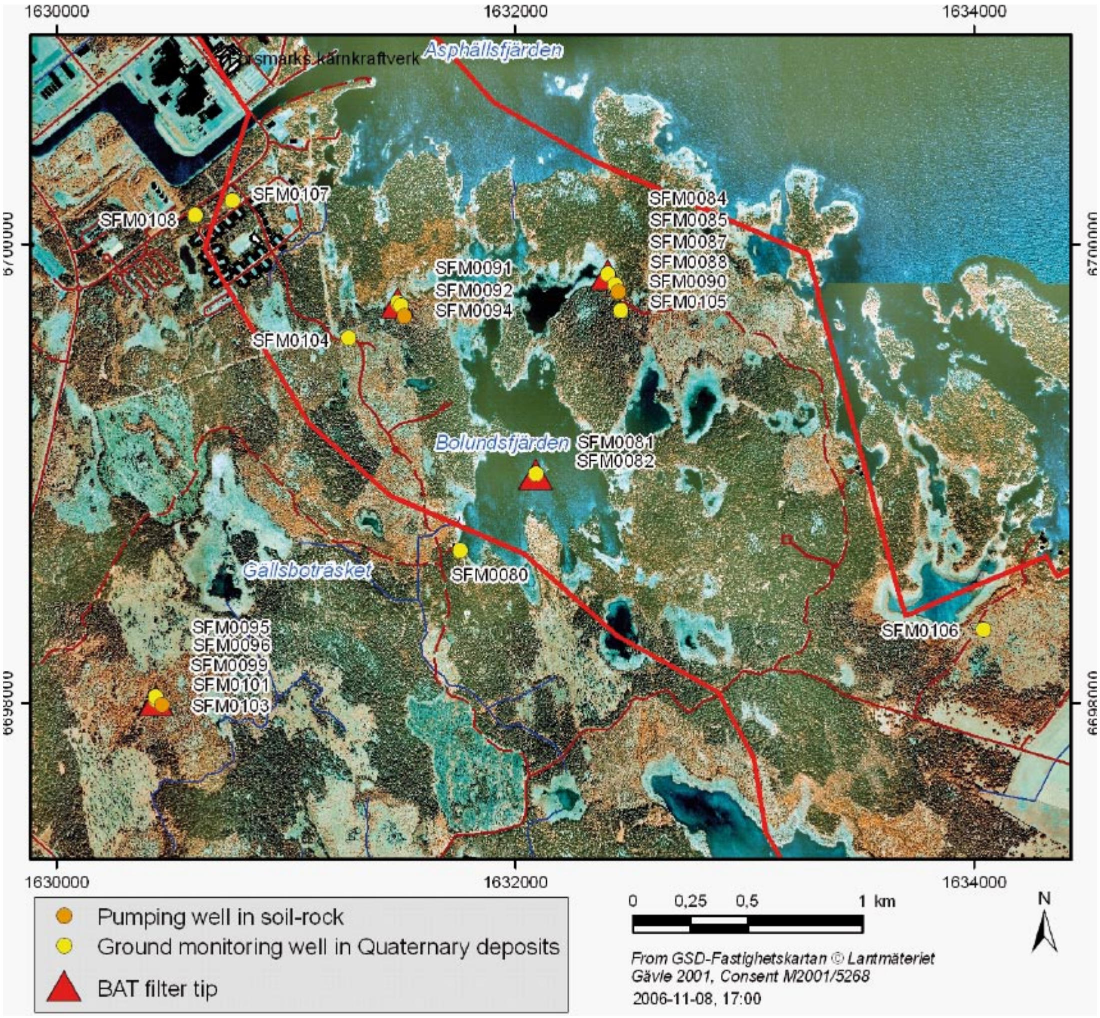

Figure 1-1. *Locations of the tested monitoring wells, pumping wells and BAT filter tips.*

2 Objective and scope

The overall objectives of the hydrogeological investigations in the Forsmark area are described in /1/ and /2/. The specific objective of the performed hydraulic tests is to obtain data for the estimation of the hydraulic properties (hydraulic conductivity (K) and storativity (S)) in (i) Quaternary deposits in assumed groundwater discharge areas (lakes and wetlands), and (ii) local topographically elevated areas, in the vicinity of percussion boreholes. Table 2-1 lists the tested boreholes.

Table 2-1. Coordinates (coordinate system RT 90 2.5 gon W 0:-15 for X and Y, and RHB70 for Z) and type of borehole. Z is measured from the top of stand pipe.

ID	X	Y	Z	Type
SFM0080	6698658.524	1631719.097	4.359	Groundwater monitoring well
SFM0081	6698999.907	1632093.487	1.308	Groundwater monitoring well
SFM0082	6699000.136	1632093.965	1.387	BAT filter tip for pore pressure and permeability measurements
SFM0084	6699868.483	1632405.985	1.230	Groundwater monitoring well
SFM0085	6699868.905	1632405.793	1.674	BAT filter tip for pore pressure and permeability measurements
SFM0087	6699868.143	1632406.371	1.309	Groundwater monitoring well
SFM0088	6699868.154	1632405.592	1.096	BAT filter tip for pore pressure and permeability measurements
SFM0090	6699824.641	1632437.560	1.638	QD-rock pumping well
SFM0091	6699745.569	1631490.633	1.414	Groundwater monitoring well
SFM0092	6699746.063	1631490.713	1.414	BAT filter tip for pore pressure and permeability measurements
SFM0094	6699731.624	1631506.647	1.365	QD-rock pumping well
SFM0095	6698014.752	1630437.616	12.099	Groundwater monitoring well
SFM0096	6698014.587	1630436.941	11.637	BAT filter tip for pore pressure and permeability measurements
SFM0099	6698014.138	1630437.490	11.559	BAT filter tip for pore pressure and permeability measurements
SFM0101	6698014.510	1630437.853	12.040	BAT filter tip for pore pressure and permeability measurements
SFM0103	6698029.589	1630435.231	11.797	QD-rock pumping well
SFM0104	6699591.792	1631275.359	3.545	Groundwater monitoring well
SFM0105	6699710.161	1632464.596	3.618	Groundwater monitoring well
SFM0106	6698321.312	1634043.400	4.693	Groundwater monitoring well
SFM0107	6700187.423	1630769.188	3.148	Groundwater monitoring well
SFM0108	6700126.451	1630609.465	4.213	Groundwater monitoring well

3 Equipment

3.1 Description of equipment

3.1.1 Slug tests

For the slug tests, the following equipment was used:

- Portable PC.
- Van Essen Instruments Diver® with built-in pressure transducer and temperature sensor, with connecting cable.
- Pressure transducer, Keller (0–100 kPa).
- Data logger, Datataker DT50.
- Temperature sensor, Pt-100.
- Elwa PLS 50A water-level meter, with light and sound indicator.
- Folding rule.
- Slug and wire in stainless steel.
- Conductivity meter.

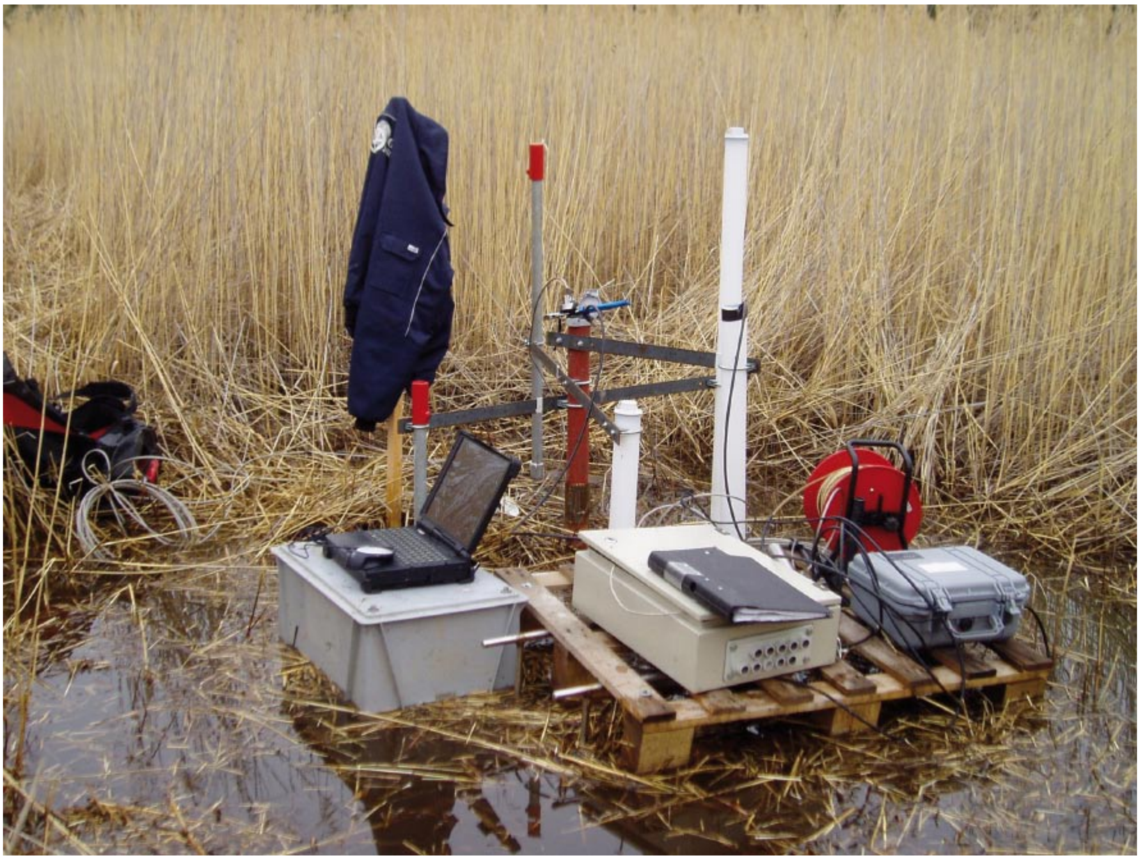

Figure 3-1. *Performance of a slug test in a monitoring well at a wetland (monitoring wells; SFM0084, 85, 87 and 88).*

3.1.2 Pumping tests

For the pumping tests, besides the above mentioned equipment (excluding the slug), the following equipment was used:

- Submersible pump.
- Flow meter.
- Plastic 10 L bucket.

3.1.3 Permeameter tests

The hydraulic conductivity measurements were performed by the GeoN BAT-type permeameter. In Figure 3-2 the principles of the permeameter equipment are illustrated. A thorough description of the principles of the BAT system is given in /3/.

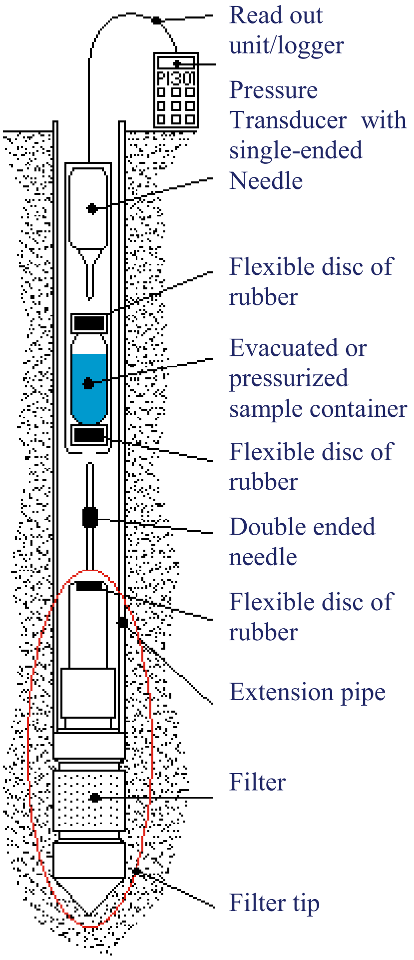

Figure 3-2. *GeoN BAT-type permeameter equipment.*

3.2 Sensors

Basic sensor data of the used equipment are given in Table 3-1.

Table 3-1. Sensor data.

	Sensor	Name	Unit	Value/range
Pressure	Diver	Measurement range Resolution Accuracy	cm wc[1] cm wc % of measurement range	0 to 1,000 0.2 0.1
	Keller	Measurement range Resolution Accuracy	Bar % of measurement range % of measurement range	0 to 1[2] 0.002 0.1
Temperature	Diver	Measurement range Resolution Accuracy	°C °C °C	–20 to +80 0.01 ± 0.1
Conductivity	Hach	Measurement range Resolution Accuracy	μS/cm % of reading % of reading	0–2,000 0.5 2
Water flow	Elfter	Measurement range Resolution Accuracy	L/min L/pulse % of reading	1.20[3] 0.1[4] 0.15

[1] Centimetres water column.
[2] The Keller instrument automatically compensates for the (atmospheric) air pressure.
[3] Calibrated range.
[4] The flow meter gives one electrical pulse/0.1 L.

4 Execution of slug tests in groundwater monitoring wells

4.1 Execution of field work

4.1.1 Test principle

The principle of slug tests is to initiate an instantaneous displacement of the water level in an observation well, and to observe the following recovery of the water level in the well as a function of time. A slug test can be performed by causing a sudden rise (referred to as a falling-head test), or a sudden fall of the water level (rising-head test) /4/. In all boreholes, both falling-head tests and rising-head tests were performed. In the latter case, the slug was withdrawn from the well when the water level had recovered to its initial level, following the falling-head test. Figure 4-1 illustrates the practical performance of a falling-head test.

The time for recovery of the water level in the well depends on the hydraulic contact between the well and the surrounding geological material, the hydraulic conductivity of the material, the displacement of the water level in the well and the screen length. For wells which demonstrate a slow recovery, the test is aborted after a specified maximum period of time. For wells with a very quick recovery, more than one test is recommended. The criteria adopted here for the slug tests, concerning e.g. abortion of falling-head tests and rising-head tests, are described in activity plan AP PF 400-06-015 and in the method description SKB MD 325.001.

Figure 4-1. *Performance of falling-head test in well SFM0108.*

4.1.2 Test procedure

The test procedure is briefly described below:

1. Cleaning of equipment that is lowered into the well according to method description SKB MD 600.004.
2. Measurement of the depth from the top of the stand pipe to the water level and the bottom of the well.
3. Measurement of the electrical conductivity.
4. Determination of the slug and wire length. The objective is to cause as large initial displacement of the water level as possible. In the majority of the present tests, a shallow undisturbed water level implied that the slug length was restricted to 0.25, 0.50, 1.00 or 2.00 m, in order to prevent water from rising above the top of the stand pipe in the falling-head tests.
5. Logging of pressure in air, and at two known depths in the well, with the pressure transducer.
6. Performance of falling-head test: Rapid lowering of slug into the well (fixed with a wire stop). Sampling frequency of the water pressure: one measurement per second.
7. Check of the recovery of the water level in the well using a water-level meter.
8. Change of the sampling frequency of the water pressure for wells with a slow recovery of the water level (see Table 4-1). Before changing the sampling frequency, the Diver®/Keller was stopped with the PC, and data were saved in a separate raw data file.
9. Performance of rising-head test: Withdrawal of the slug from the well when the water level has recovered following the falling-head test. Sampling frequency of the water pressure: one measurement per second.
10. Termination of slug test approximately one hour after start of the rising-head test (according to activity plan AP PF 400-06-015 for performance of supplementary slug tests in Forsmark).

In general, the sampling interval of the water pressure during the slug tests was according to Table 4-1.

4.2 Boreholes tested

Basic technical data of the groundwater monitoring wells in which the slug tests were performed are given in Table 4-2. Note that all boreholes are vertical. For more details see /5/ and /6/.

4.3 Slug tests

Test data from the performed slug tests are summarized in Table 4-3.

Table 4-1. Guidelines for sampling interval for pressure measurements during the slug test.

Time interval from start of test (min)	Sampling interval (s)
–1 to 0	1
0–4	1
4–10	10
10–20	20
20–40	60
40–	180

Table 4-2. Technical data of the tested boreholes.

Borehole	Borehole diameter (mm)	Material of stand pipe and screen	Inner diameter of stand pipe (mm)	Depth to screen secup[2] (m)	Depth to screen seclow[2] (m)	Screen length (m)
SFM0080	194[1]	Steel	72	8.62	9.62	1
SFM0081	60.3	Steel	51.3	4.85	5.25	0.4
SFM0084	60.3	Steel	51.3	3.70	4.10	0.4
SFM0087	63	HDPE	50	2.0	2.20	0.2
SFM0091	60.3	Steel	51.3	1.9	2.3	0.4
SFM0095	122[1]	HDPE	50	5.0	6.0	1
SFM0104	122[1]	HDPE	50	4.0	5.0	1
SFM0105	122[1]	HDPE	50	2.0	3.0	1
SFM0106	122[1]	HDPE	50	3.0	4.0	1
SFM0107	122[1]	HDPE	50	5.0	6.0	1
SFM0108	122[1]	HDPE	50	5.0	6.0	1

[1] Drilling was performed by air-rotary drilling with a casing driver system. The outer diameter of the drill casing was 122 mm (SFM0080: 194 mm). Filter sand was filled between the well casing and the drill casing while the latter was pulled out. The effective borehole diameter used for evaluation of K and S was therefore assumed to be 122 mm (SFM0080: 194 mm).

[2] Depth from the top of the stand pipe.

Table 4-3. Summary of test data from the performed slug tests.

Borehole	Test start[1] (YYYY-MM-DD hh:mm)	tp[2] (s)	tF[2] (s)	Depth to water level in well prior to slug test[3] (m)	Depth to water level in well prior to slug test[4] (m)	Tew[5] (°C)	ECw[5] (mS/m)
SFM0080	2006-07-06 19:00	6,840	2,220	2.99	3.71	9.3	77.5
SFM0081	2006-07-06 12:47	14,119	12,410	0.21	1.06	24.4	694
SFM0084	2006-05-23 09:19	73,321	89,874	0.11	0.66	6.5	119
SFM0087	2006-05-23 09:35	1,182	325	0.10	0.75	7.1	194
SFM0091	2006-05-30 17:22	780	860	0.05	0.85	5.2	107
SFM0095	2006-05-22 16:14	3,027	2,559	0.37	1.37	6.5	154
SFM0104	2006-05-19 09:58	4,462	4,224	1.77	2.37	7.6	121
SFM0105	2006-05-23 15:26	137,229	204,925	1.76	2.46	4.7	152
SFM0106	2006-06-06 06:45	211,774	225,816	2.46	2.86	9.5	98.4
SFM0107	2006-05-22 19:49	6,663	3,852	1.45	2.10	5.4	163
SFM0108	2006-05-18 13:45	3,238	5,103	0.70	1.50	4.5	145

[1] Start of falling-head test in Swedish Standard Time.

[2] tp denotes duration of falling-head test, and tF duration of rising-head test.

[3] The reference point is the ground surface.

[4] The reference point is the top of the stand pipe.

[5] Tew and ECw denote well water temperature and electrical conductivity, respectively.

4.4 Data handling/post processing

Raw data from the pressure transducer were saved on a portable PC. Prior to the data evaluation all files were imported to MS Excel and saved in *.xls format. Data processing was performed in MS Excel, in order to produce data files for the estimation of transmissivity and storativity. The data processing involved correction of the data for barometric pressure and identification of exact starting times of the tests.

4.5 Analyses and interpretations

The following section gives a short overview of the methods used for analysis and interpretation of the slug test data. For a more detailed description of the used methods, see /4/.

All tested wells are only partially penetrating the aquifer. In the evaluation, the aquifer thickness was substituted by the effective well screen length, which was assumed to be equal to the nominal screen length. For the wells where a sand filter is installed, the effective diameter of the well screen and stand pipe were assumed to be equal to the outer diameter of the drill casing, 122 mm (SFM0080, 194 mm). For the wells where no sand filter is installed, the effective well screen and stand pipe diameter were assumed to be the nominal outer diameter of the screen and stand pipe.

4.5.1 Cooper et al. method

The Cooper et al. method is designed to estimate the transmissivity, T (K multiplied by aquifer thickness), and storativity S of an aquifer /7/. The method was originally developed for fully penetrating wells in confined aquifers. By replacing the formation thickness by the effective screen length, the method may be applied also to partially penetrating wells. If a close match can be obtained with a type curve applying a physically plausible α (see below), the method can also be applied in unconfined aquifers, see /4/. The Cooper et al. method is also recommended as "the first choice" method by Butler /4/.

In the method, a plot of the normalized displacement versus the logarithm of $ß = Tt/r_c^2$ (with t and r_c being time and the inner radius of the stand pipe, respectively) forms a series of type curves for different values of $\alpha = r_w^2S/r_c^2$ (where r_w is the well radius). The method involves manual fitting of a curve for a particular α to the measured data. The theory of the method and practical recommendations for its application are given in /7/.

For the present analysis according to the Cooper et al. method, the computer program Aquifer Test Ver. 4.0 was used /8/. The analysis for each observation well according to the Cooper et al. method was performed for two main cases:

1. Curve fitting to the type curve corresponding to an assumed storativity of $S = 10^{-5}$ (see relation between and S and α above).
2. Best fit obtained by allowing variation of α.

As is also discussed in /4/, the sensitivity of T to the curve-fitting procedure is relatively small compared to the sensitivity of S. Hence, the values of S that are obtained by the Cooper et al. method are relatively uncertain, compared to the obtained values of T.

4.5.2 Hvorslev method

The Hvorslev method was designed to estimate the hydraulic conductivity (K) of an aquifer. The method assumes a fully or partially penetrating well in a confined or unconfined aquifer of apparently infinite extent. In the Hvorslev method, a straight-line plot of the logarithm of the normalized displacement versus time is fitted to the measured data. The Bouwer & Rice method (see Section 4.5.3) is based on the same principle. The theory of the Hvorslev method and practical recommendations for its application are given in /4/.

For the present analysis according to the Hvorslev method, the computer program Aquifer Test Ver 4.0 was used /8/. The program allows for both automatic (based on linear regression analysis) and manual fitting of a straight-line plot to the measured data. The principles of both automatic and manual fitting procedures and their implications are presented in /8/. As also discussed and shown in /8/, automatic curve-fitting is inappropriate in some cases, and some manual curve-fitting procedure is required. Guidelines for manual fitting of e.g. upward-concave plots are given in /4/. In particular, for the Hvorslev method it is recommended to fit the straight line for a normalized displacement in the interval 0.15–0.25.

4.5.3 Bouwer & Rice method

The Bouwer & Rice method /4/ was designed to estimate the hydraulic conductivity (K) of an aquifer. The method assumes a fully or partially penetrating well in an unconfined or leaky confined aquifer of apparently infinite extent. As for the Hvorslev method, the Bouwer & Rice method involves the fitting of a straight-line plot of the logarithm of the normalized displacement versus time to the measured data. The theory of the Bouwer & Rice method and practical recommendations for its application are given in /4/.

For the present analysis according to the Bouwer & Rice method, the computer program Aquifer Test Ver 4.0 was used /8/. As for the Hvorslev method, the program allows for both automatic (based on linear regression analysis) and manual fitting of a straight-line plot to the measured data. The principles of both automatic and manual fitting procedures and their implications in the Bouwer & Rice method are presented in /8/. As also discussed and shown in /8/, for the Bouwer & Rice method it is recommended to fit the straight line to upward-concave plots for a normalized displacement in the interval 0.20–0.30 /4/.

5 Execution of pumping tests in wells in soil-rock

5.1 Execution of field work

The principle of a pumping test is to abstract groundwater from a pumping well, and to observe the decline of the water level in the pumping well and the surrounding groundwater monitoring wells as a function of time. The recovery of the water level in the wells can also be observed following termination of the pumping /9/, /10/. The practical arrangement of a pumping test is illustrated in Figure 5-1.

The decline (or recovery) of the water level as function of time depends on the pumping rate, the hydraulic contact between the well and the surrounding geological material, the hydraulic properties (hydraulic conductivity and storativity) of the geological formation, and the boundary conditions for groundwater flow. In each of the pumped wells, the pumping was terminated after 3–7 days, and the recovery of the water level was observed for 2–5 days after pump stop (see Table 5-2).

Figure 5-1. *Pumping well (SFM0103), flow meter, and hose for discharge of water from the well to the recipient.*

Step-drawdown pumping tests were performed prior to the pumping tests. The purpose of the step-drawdown pumping tests was to determine the proper pumping rates for the subsequent pumping tests. The intention was to keep the flow constant during the test. However, due to the influence of boundary conditions constant flow could not be maintained throughout the test periods in two of the pumping tests, see Section 7.2

The test procedure is briefly described below:

1. Function checks and cleaning of pump, pressure transducer and all other equipment that is lowered into the wells according to SKB MD 600.004, level one.
2. Installation of the pump in the pumping well and connection to a water-flow meter.
3. Connection of the pump to an electrical supply and installation of a plastic hose for discharge of the pumped water to a recipient.
4. Manual measurements of the water level in the pumping well and the monitoring wells. Measurements of the depths of the wells.
5. Emptying of the water in the monitoring well (SFM0084, -0087, -0091 and -0095) three times followed by water sampling.
6. Installation of pressure transducers in the wells.
7. Performance of step-drawdown pumping test. Manual measurements of the water level in the pumping well (i) prior to the test, and (ii) immediately prior to the termination of each pumping step.
8. Termination of step-drawdown pumping test, recovery of the water level in the pumping well. Determination of proper pumping rate during the pumping test in consultation with the Activity Leader.
9. Performance of the pumping test. Manual measurements of the water level in the pumping well and the monitoring wells as a backup and check of the automatic recordings.
10. Sampling of water from the pumping well during the pumping test. Water sampling in the monitoring wells after the stop of recovery measurements.
11. Check at several occasions during the pumping test of the pumping/discharge rate from the pumping well by (i) the water-flow meter and a stop watch at the pumping well, and (ii) at the discharge point using a plastic 10 L bucket and a stop watch.
12. Termination of pumping (pump stop) after 3 to 7 days.
13. Continued measurements of pressure, temperature and electrical conductivity in the pumping well and the monitoring wells for approximately 2 to 5 days after pump stop.

5.2 Boreholes tested

Basic technical data of the pumping wells, BAT tips and groundwater monitoring wells of the pumping tests are given in Table 5-1. All boreholes are vertical. For more details see /5/.

5.3 The pumping tests

Test data from the performed pumping tests are summarized in Table 5-2.

Table 5-1. Technical data of pumping wells, BAT tips and monitoring wells grouped according to location.

Borehole	Type	Borehole diameter (mm)	Material	Inner diameter of stand pipe (mm)	Depth to screen secup[2] (m)	Depth to screen seclow[2] (m)	Screen length (m)
SFM0090	Pumping well	125[1]	Steel	101	3.07 (2.44)[3]	5.57 (4.94)[3]	2.5
SFM0084	Monitoring well	60.3	Steel	51.3	3.70 (3.15)[3]	4.10 (3.55)[3]	0.4
SFM0085	BAT filter tip	32	HDPE	25.6	3.18 (2.18)[3]	3.22 (2.22)[3]	0.04
SFM0087	Monitoring well	63	HDPE	50	2.00 (1.35)[3]	2.20 (1.55)[3]	0.2
SMF0088	BAT filter tip	32	HDPE	25.6	1.18 (0.80)[3]	1.22 (0.84)[3]	0.04
SFM0094	Pumping well	125[1]	Steel	101	2.24 (1.44)[3]	4.74 (3.94)[3]	2.5
SFM0091	Monitoring well	60.3	Steel	51.3	1.9 0 (1.1)[3]	2.30 (1.05)[3]	0.4
SFM0092	BAT filter tip	32	HDPE	25.6	1.73 (0.95)[3]	1.77 (0.99)[3]	0.04
SFM0103	Pumping well	125[1]	Steel	101	4.90 (4.14)[3]	7.40 (6.64)[3]	2.5
SFM0095	Monitoring well	122[1]	HDPE	50	5.0 0 (4.0)[3]	6.0 0 (5.00)[3]	1.0
SFM0096	BAT filter tip	32	HDPE	25.6	3.18 (2.54)[3]	3.22 (2.58)[3]	0.04
SFM0099	BAT filter tip	32	HDPE	25.6	2.18 (1.69)[3]	2.22 (1.73)[3]	0.04
SMF0101	BAT filter tip	32	HDPE	25.6	2.18 (1.15)[3]	2.22 (1.19)[3]	0.04

[1] Drilling was performed by air-rotary drilling with a casing driver system. The outer diameter of the drillcasing was 125 mm (SFM0095: 122 mm). Filter sand was filled between the well casing and the drill casing while the latter was pulled out. The effective borehole diameter used for evaluation of T and S was therefore assumed to be 125 mm (SFM0095: 122 mm).

[2] The reference point is the top of the stand pipe.

[3] The reference point is the ground.

Table 5-2. Summary of test data from the three pumping tests performed in SFM0090, SFM0094 and SFM0103.

Well	Test start[1] YYYY-MM-DD hh:mm:ss	tp[2] (s)	tF[3] (s)	Depth to water level in well prior to test[4] (m)	Tew[5] (°C)	ECw[5] (mS/m)	Qp[6] (L/min)
SFM0090	2006-06-30 09:42:00	262,319	170,940	1.12	6.5	136	4.8
SFM0084	–	–	170,940	0.26			
SFM0085	–	–	170,940	–			
SFM0087	–	–	170,940	0.18			
SMF0088	–	–	170,940	–			
SFM0094	2006-06-17 14:48:38	338,214	438,022	0.37	10.4	75.9	35.5
SFM0091	–	–	442,653	0.15			
SFM0092	–	–	451,786	–			
SFM0103	2006–06–05 13:01:00	615,970	239,750	0.47	5.4	60.8	60.0
SFM0095	–	–	239,750	0.38			
SFM0096	–	–	239,750				
SFM0099	–	–	239,750				
SFM0101	–	–	239,750				

[1] Swedish Standard Time.

[2] tp denotes duration of pumping phase of the test. Tp is from pump start to pump stop.

[3] tF denotes duration of recovery phase. tF is from pump stop to the stop of the logger. At two of tests the loggers turned off simultaneously.

[4] Depth from the ground.

[5] Tew and ECw denote well water temperature and electrical conductivity, respectively.

[6] Qp denotes the pumping rate.

5.4 Data handling

Raw data from the pressure transducers and flow meter were saved on a portable PC. Prior to the data evaluation all files were imported to MS Excel and saved in *.xls format. Data processing was performed in MS Excel, in order to produce data files for the estimation of transmissivity and storativity. The data processing involved correction of the data for barometric pressure and identification of exact starting time of the test.

5.5 Analyses and interpretations

The following sections provide a short description of the methods used for analysis and interpretation of the data obtained during the pumping tests. For a more detailed description of the methods used, see /9/ and /10/.

5.5.1 Theis method

The Theis method was designed to estimate the transmissivity (T) and storativity (S) of an aquifer /9/, /10/. The method was originally developed for fully penetrating wells in confined aquifers. In the method, the measured data of the drawdown $s(t) = h_0 – h(t)$, where s is the drawdown, t denotes time and h is the hydraulic head, are plotted in a diagram with a logaritmic scale on both axes. Subsequently, a so-called type curve of W(1/u) (or W(u)) versus 1/u is plotted in the same diagram, and the mesasured data curve is fitted to the type curve. In the type curve, the parameter u is defined as

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

where r is the radial distance from the pumping well to the observation well, and the well function W(u) is defined as

$$W(u) = \int_u^{\infty} \frac{\exp(-x)}{x} dx$$

After the two curves are fitted to each other, the coordinates of a so-called match point are used to obtain T and S. The theory of the method and practical recommendations for its application are given in /9/ and /10/.

For the present analysis according to the Theis method, the computer program Aquifer Test Ver 4.0 was used /8/. The program allows for both automatic and manual fitting of the type curve to the measured data.

5.5.2 Jacob method

The Jacob method utilizes the fact that the well function W(u) in Section 5.5.1 can be developed as the series

$$W(u) = -0.5772 + -\ln u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{2 \cdot 3!} - \frac{u^4}{2 \cdot 4!} + \ldots$$

According to the definition of the parameter u (see Section 5.5.1), the approximation is valid for u < 0.01 (i.e. for a small distance r from the observation well to the pumping well and/or for large times, t). The theory of the Jacob method and practical recommendations for its application are given in /9/ and /10/.

For the present analysis according to the Jacob method, the computer program Aquifer Test Ver 4.0 was used /8/. The program allows for both automatic and manual fitting of the type curve to the measured data.

5.5.3 Theis recovery method

The Theis recovery method was designed to estimate the transmissivity T of an aquifer, using data from the recovery phase following the pump stop /9/, /10/. The method can be used to analyse recovery data from both monitoring wells and pumping wells, but it is best suited for cases where stationary conditions have been attained during pumping. In the method, the measured data of the residual drawdown s(t'/t) = h_0–h(t'/t) is plotted in a diagram with a logarithmic scale on the time axis. s is the residual drawdown and h_0 is the water level at pump start. For the ratio t'/t (dimensionless time), t' is the sum of elapsed times from pump start and pump stop; the latter is denoted t. Subsequently, a straight line is fitted to the measured data in order to provide T. The theory of the method and practical recommendations for its application are given in /9/ and /10/.

For the present analysis according to the Theis recovery method, the computer program Aquifer Test Ver 4.0 was used /8/. The program allows for both automatic and manual fitting of a straight line to the measured data.

5.5.4 Walton (Hantush & Jacob) method for leaky aquifers

In order to investigate possible leakage of water into the pumped aquifer during the pumping tests, the Walton (Hantush & Jacob) method was used /11/, taking into account leakage from an upper to a lower aquifer.

Similar to the Theis method (see Section 5.5.1), the method involves fitting of measured drawdown data to a type curve. However, the type curve is now plotted as W(1/u, r/L) (or W(u, r/L)), where the parameters u and r have the same definitions as in the Theis method. The parameter L is defined as

$$L = \sqrt{Kb\frac{b'}{K'}}$$

where b is the saturated aquifer thickness, and b′/K′ denotes the thickness of the low-permeable layer divided by its hydraulic conductivity. The well function W(u, r/L) is given as

$$W(u, r/L) = \int_u^\infty \frac{\exp\left(-xr^2\right)}{4L^2x}dx$$

The theory of the method and practical recommendations for its application are given in /9/ and /10/. For the present analysis according to the Walton method, the computer program Aquifer Test Ver 4.0 was used /8/. The program allows for both automatic and manual fitting of the type curve to the measured data.

5.6 Nonconformities

- Due to logger problems, the pumping test in SFM0103 had to be restarted, delaying the time schedule one week.
- The estimated pumping rate (estimated by a short step-drawdown pumping test) for the pumping test in SFM0090 was too high and the test had to be restarted with a lower pumping rate.
- At the slug test in SFM0105, only a rising-head test was possible to perform, since the initial water level was at the middle of the well screen.

6 Execution of permeameter tests in situ

The performance of the permeameter tests as well as calibration and function tests of the equipment for measurements of hydraulic conductivity were carried out by GeoNordic AB.

6.1.1 Execution of field work

The key constituents of the GeoN BAT-type equipment for water measurement of hydraulic conductivity are a filter tip (pore size: 20 micron), an adapter pipe, and an evacuated or pressurized sample container, see Figure 3-2. The filter tip and the sample container are sealed with flexible rubber discs. During the tests a connection is established between the filter tip and the sample container by a doubled-ended needle /3/.

The tests can be conducted as an inflow test or an outflow test /3/. In the inflow test the sample container is filled with gas (partly evacuated) while in the outflow test the container is partly filled with water and partly with compressed air. All permeameter tests were conducted as outflow tests.

6.1.2 Analyses

The permeameter tests start with a measurement of the equilibrium pore water pressure in soil. The initial pressure in the gas/water container is chosen based on the type of test to be performed and the equilibrium pore water pressure. The container is lowered down inside the adapter pipe and temperature equilibrium should be reached before the container is connected to the filter tip by the double-ended needle. After connection the change in the pressure in the container is automatically recorded.

The pressure change in the container is analyzed by the falling head theory as defined by Hvorslev /12/.

7 Results and discussion

7.1 Slug tests

As mentioned in Section 4.1.1, both falling-head and rising-head tests were performed at each slug test, i.e. from each test, two independent tests are obtained.

Table 7-1 presents the results of the slug test analysis according to the Cooper et al. method. The left and right main columns present the obtained values of transmissivity, T, and storativity, S, for the falling-head tests and the rising-head tests, respectively. In each major column, the first two minor columns ("best fit") give the results for the case when both T and S are varied. The third minor column gives the value of T when the storativity, S, is fixed ($S = 1.0\cdot10^{-5}$).

The slug tests were performed during the summer and the groundwater level was lower than normal. As a consequence the groundwater level was below the bentonite sealing in two of the wells, SFM0105 and SFM0106. This made the evaluation problematic for these wells and the results obtained can be questioned. Under these conditions, when the slug is lowered into the groundwater the water will rise within the gravel pack. During the recovery, the groundwater table will descend, still within the gravel pack, and the main part of the water will discharge from the well above the original groundwater table into the unsaturated zone (see Figure 7-1, part A and Figure A1-61 to A1-68 in Appendix 1). After the slug has been removed, the groundwater probably recharges from the sand/gravel pack, flowing back into the stand pipe (see Figure 7-1, part C). Because of the differences in hydraulic conductivity between the gravel and soil surrounding the well there will be a time delay before the groundwater from the soil reaches the screen. During the time delay the recovery slows down, and after the delay the recovery will increase, now representing the soil formation (see Figure A1-57, -58, -59 and -60 in Appendix 1). In the evaluation work with the computer program Aquifer Test Ver 4.0 the full screen length was used which probably not is correct according to the discussion above. In SFM0105 the falling-head test is excluded since it was judged impossible to evaluate.

As can been seen in Table 7-1 there is generally a good correlation between the T-values evaluated from the falling-head test and the rising-head test. In one case, SFM0106, there is a big difference (10^{-5}–10^{-8}). This is probably due to that the evaluated result from the rising-head test represent the gravel according to the discussion above.

Table 7-1. Parameters evaluated by the Cooper et al. method. Underlined values are reported to the SICADA database as best estimate.

Borehole	Falling-head test				Rising-head test			
	Test no.	T (m²/s), best fit	S(–), best fit	T (m²/s), S = 10^{-5}	Test no.	T (m²/s), best fit	S(–), best fit	T (m²/s), S = $^{10-5}$
SFM0080	1	$6.1\cdot10^{-6}$	$3.8\cdot10^{-5}$	$7.8\cdot10^{-6}$	1	$7.3\cdot10^{-6}$	$5.7\cdot10^{-5}$	$8.5\cdot10^{-6}$
SFM0081	1	$1.4\cdot10^{-6}$	$1.2\cdot10^{-8}$	$9.2\cdot10^{-7}$	1	$9.3\cdot10^{-7}$	$1.3\cdot10^{-7}$	$6.5\cdot10^{-7}$
SFM0084	1	$3.2\cdot10^{-7}$	$2.6\cdot10^{-8}$	$2.0\cdot10^{-7}$	1	$1.7\cdot10^{-7}$	$4.4\cdot10^{-7}$	$1.3\cdot10^{-7}$
SFM0087	1	$1.2\cdot10^{-4}$	$9.6\cdot10^{-11}$	$6.3\cdot10^{-5}$	1	$1.5\cdot10^{-4}$	$4.8\cdot10^{-10}$	$7.8\cdot10^{-5}$
SFM0091	1	$5.5\cdot10^{-5}$	$8.4\cdot10^{-4}$	$9.0\cdot10^{-5}$	1	$8.5\cdot10^{-6}$	$5.0\cdot10^{-1}$	$8.5\cdot10^{-5}$
SFM0095	1	$5.8\cdot10^{-6}$	$2.3\cdot10^{-1}$	$3.4\cdot10^{-5}$	1	$1.1\cdot10^{-5}$	$9.3\cdot10^{-8}$	$6.7\cdot10^{-6}$
SFM0104	1	$3.5\cdot10^{-6}$	$2.3\cdot10^{-4}$	$4.5\cdot10^{-6}$	1	$3.5\cdot10^{-6}$	$2.3\cdot10^{-4}$	$4.5\cdot10^{-6}$
SFM0105		–	–	–	1	$1.0\cdot10^{-5}$	$3.9\cdot10^{-3}$	$2.9\cdot10^{-5}$
SFM0106	1	$4.8\cdot10^{-8}$	$1.3\cdot10^{-7}$	$2.0\cdot10^{-8}$	1	$9.4\cdot10^{-6}$	$1.4\cdot10^{-2}$	$1.1\cdot10^{-5}$
SFM0107	1	$2.3\cdot10^{-6}$	$1.1\cdot10^{-3}$	$3.9\cdot10^{-6}$	1	$2.3\cdot10^{-6}$	$1.0\cdot10^{-5}$	$2.3\cdot10^{-6}$
SFM0108	1	$7.9\cdot10^{-6}$	$5.9\cdot10^{-6}$	$7.5\cdot10^{-5}$	1	$3.5\cdot10^{-6}$	$8.7\cdot10^{-3}$	$1.9\cdot10^{-6}$

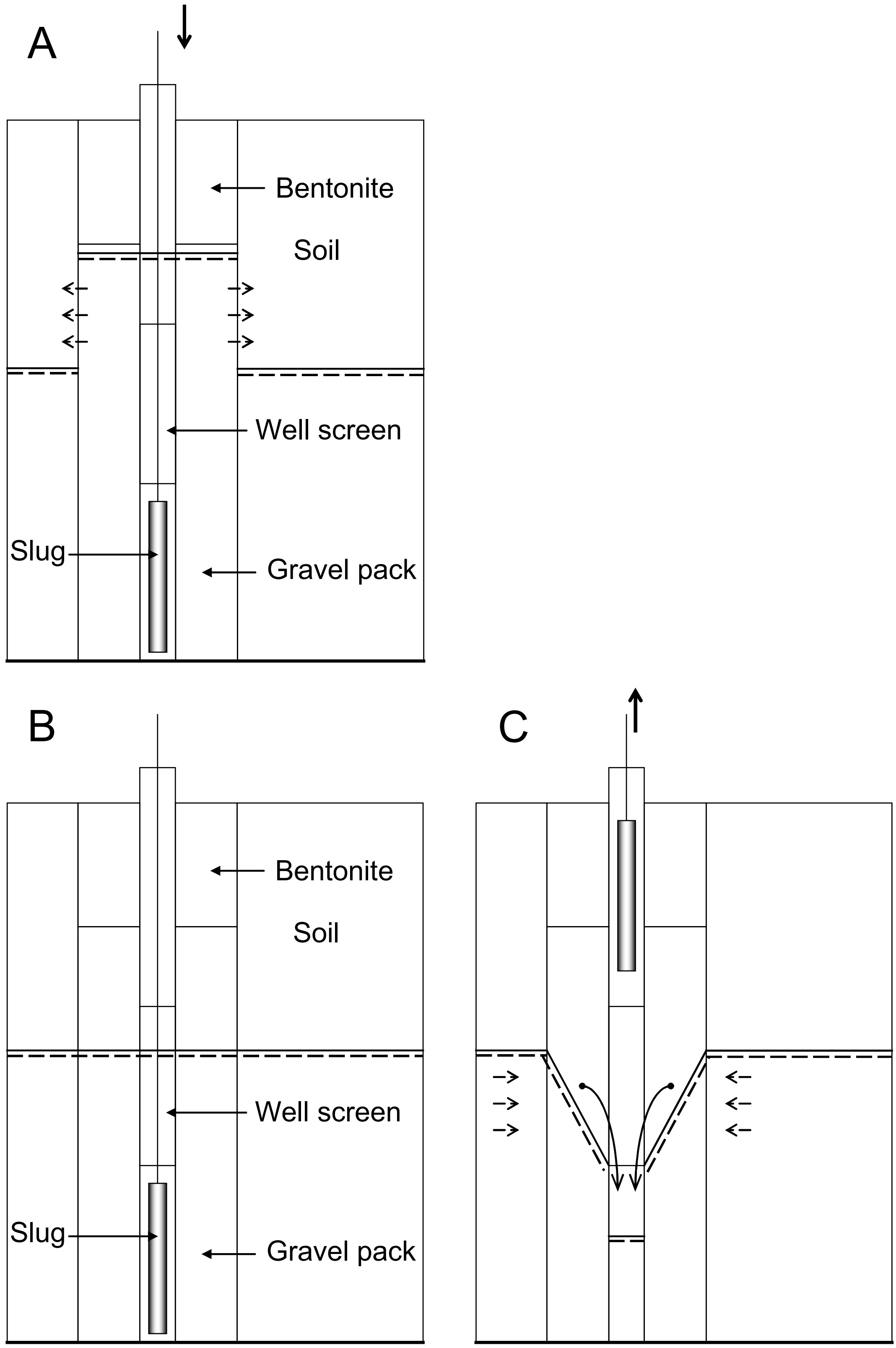

Figure 7-1. A schematic figure of the performed falling-head and rising-head test in SFM0105 and SFM0106.

When comparing rising-head and falling-head tests, one must be aware of that the mechanism behind them is different. During the falling-head test the volume of water is forced to flow out of the well, whereas during the rising-head the flow direction is opposite. Butler /4/ explains the difference caused by mobilization of near-well fine material. The fine material can originate from either the geological material or from a biochemical action on or in the vicinity of the well screen. This near-well effect is normally termed the well skin. During the pumping tests lot of fine material was observed in the abstracted groundwater. This implies that the well skin may be higher during a rising-head test compared to a falling-head test. This effect has not been observed during the evaluation work.

For most wells an acceptable fit was obtained for the Cooper et al. method applying a fixed S. For some wells a somewhat better fit was obtained by varying S. For some wells it was, however, not possible to obtain an acceptable fit. The reason to the bad fit can, for example, be skin effects due to incomplete well-development. Or, the assumption of substituting the aquifer thickness by the effective well screen length, put equal to the nominal screen length, may also be invalid for some wells. Furthermore, for many wells it was difficult to determine if confined, semi-confined or unconfined conditions prevailed. There are also a number of other pre-requisites for the application of the equations on which the method is based, like homogeneity, radial flow and so on, which can explain the difficulties to fit measured values to the type curves.

During the analyses with varying S, the aim has been to fit the curve even if the value of the storativity has been unrealistic. In Table 7-1 values less than $1 \cdot 10^{-6}$ can be questioned. According to Section 4.5.1 the values of S that are obtained by the Cooper et al. method are relatively uncertain, compared to the obtained values of T.

In view of the paragraph above the values obtained with the fixed $S = 10^{-5}$ were used for reporting to the SICADA database as best estimate. The selection of the T-value to be reported was based on which of the falling- or rising-head tests that gave the best fit to the type curves. In Table 7-1 selected values are underlined.

The values of hydraulic conductivity evaluated by the Hvorslev method and Bouwer & Rice method are presented in Table 7-2 and Table 7-3, respectively. Selected values for the SICADA database are underlined.

Table 7-2. Values of hydraulic conductivity, K (m/s), evaluated by the Hvorslev method. Underlined values are reported to the SICADA database.

Borehole	Falling-head test		Rising-head test	
	Test no.	K (m/s).	Test no.	K (m/s).
SFM0080	1	<u>$2.8 \cdot 10^{-6}$</u>	1	$3.5 \cdot 10^{-6}$
SFM0081	1	<u>$7.1 \cdot 10^{-7}$</u>	1	$7.1 \cdot 10^{-7}$
SFM0084	1	$1.7 \cdot 10^{-7}$	1	<u>$1.1 \cdot 10^{-7}$</u>
SFM0087	1	$1.2 \cdot 10^{-4}$	1	<u>$1.2 \cdot 10^{-4}$</u>
SFM0091	1	<u>$6.3 \cdot 10^{-5}$</u>	1	$2.5 \cdot 10^{-5}$
SFM0095	1	$3.1 \cdot 10^{-6}$	1	<u>$5.7 \cdot 10^{-6}$</u>
SFM0104	1	<u>$2.0 \cdot 10^{-6}$</u>	1	$2.0 \cdot 10^{-6}$
SFM0105		–	1	<u>$1.4 \cdot 10^{-6}$</u>
SFM0106	1	<u>$8.9 \cdot 10^{-9}$</u>	1	$4.7 \cdot 10^{-5}$
SFM0107	1	$1.7 \cdot 10^{-6}$	1	<u>$1.1 \cdot 10^{-6}$</u>
SFM0108	1	<u>$2.9 \cdot 10^{-6}$</u>	1	$2.9 \cdot 10^{-6}$

Table 7-3. Values of hydraulic conductivity, K (m/s), evaluated by the Bouwer & Rice method. Underlined values are reported to the SICADA database.

Borehole	Falling-head test Test no.	K (m/s).	Rising-head test Test no.	K (m/s).
SFM0080	1	$2.2\cdot10^{-6}$	1	$\underline{3.1\cdot10^{-6}}$
SFM0081	1	$\underline{7.4\cdot10^{-7}}$	1	$7.0\cdot10^{-7}$
SFM0084	1	$1.5\cdot10^{-7}$	1	$\underline{1.0\cdot10^{-7}}$
SFM0087	1	$6.6\cdot10^{-5}$	1	$\underline{6.8\cdot10^{-5}}$
SFM0091	1	$3.0\cdot10^{-5}$	1	$\underline{1.7\cdot10^{-5}}$
SFM0095	1	$\underline{2.6\cdot10^{-6}}$	1	$4.6\cdot10^{-6}$
SFM0104	1	$1.5\cdot10^{-6}$	1	$\underline{1.6\cdot10^{-6}}$
SFM0105		–	1	$\underline{1.0\cdot10^{-6}}$
SFM0106	1	$\underline{7.6\cdot10^{-9}}$	1	$8.6\cdot10^{-6}$
SFM0107	1	$\underline{1.3\cdot10^{-6}}$	1	$9.4\cdot10^{-7}$
SFM0108	1	$\underline{2.7\cdot10^{-6}}$	1	$2.4\cdot10^{-6}$

7.2 Pumping tests

The performed pumping tests were evaluated according to the Theis method, the Jacob method, the Hantush method, and the Theis recovery method.

When the results of the pumping tests are plotted in lin-lin, lin-log, and log-log diagrams it is obvious that all three aquifers differ from a "theoretical" aquifer, i.e. an aquifer that is infinite, strictly horizontal, homogenous, etc. The groundwater reservoirs supplying the wells turned out to be quite small, so it was not possible to maintain a constant flow rate during the tests and the decrease of the groundwater level was very fast. As a result it has been difficult to evaluate the hydraulic properties with confidence.

The curve fitting process starts with an analysis of the diagnostic plot in order to point out parts of the plot that are suitable to use in the fitting process. For example, it is important to know when/if the water table reaches the screen or if the water table is at the same level as the water intake of the pump. These parts are not suitable for the fitting process.

Table 7-4 shows the parameters (T, S and in two cases b'/K') evaluated by the different methods. Graphical outputs from the analyses are shown in Appendix 2.

Table 7-4. Parameters evaluated from the pumping tests. Underlined values are reported to the SICADA database.

Borehole	Method	T (m^2/s)	K(m/s)	S (–)	b'/K' (s)
SFM0090 (pumping well)	Theis	$2.5\cdot10^{-4}$	$6.3\cdot10^{-6}$	$6,6\cdot10^{-2}$	
	Jacob	$2.1\cdot10^{-4}$	$5.4\cdot10^{-5}$	$1.3\cdot10^{-1}$	
	Theis Recovery	$\underline{1.4\cdot10^{-5}}$	$3.6\cdot10^{-6}$	$\underline{1.5\cdot10^{-1}}$	
SFM0094 (pumping well)	Theis	$\underline{1.8\cdot10^{-4}}$	$6.7\cdot10^{-5}$	$\underline{1.5\cdot10^{-1}}$	
	Jacob	$3.5\cdot10^{-4}$	$1.3\cdot10^{-4}$	$4.4\cdot10^{-2}$	
	Theis Recovery	$4.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$5.0\cdot10^{-1}$	
SFM0095 (monitoring well)	Hantush	$\underline{1.8\cdot10^{-4}}$	$7.6\cdot10^{-5}$	$\underline{3.1\cdot10^{-4}}$	5.5·108
	Jacob	$4.2\cdot10^{-4}$	$1.8\cdot10^{-4}$	$5.7\cdot10^{-4}$	
	Theis Recovery	$2.1\cdot10^{-4}$	$9.3\cdot10^{-5}$	$9,6\cdot10^{-3}$	
SFM0103 (pumping well)	Hantush	$\underline{2.1\cdot10^{-4}}$	$9.1\cdot10^{-5}$	$\underline{2.2\cdot10^{-1}}$	9.3·104
	Jacob	$3.1\cdot10^{-4}$	$1.4\cdot10^{-4}$	$3.3\cdot10^{-1}$	
	Theis Recovery	$2.0\cdot10^{-4}$	$8.6\cdot10^{-5}$	$5.0\cdot10^{-1}$	

7.2.1 Pumping test in SFM0090

The pumping was performed in well SFM0090. The response was observed in four monitoring wells (SFM0084, SFM0085, SFM0087 and SFM0088); see Figures 7-2 and 7-3. The monitoring wells are placed in a group within an area of 5 m^2 approximately 50 m from the pumping well, and their screens are installed at different depths and in different geological layers.

The well screen of the pumping well is placed in till and bedrock; the lower 1.25 m of the screen (total length 2.5 m) is installed in bedrock, and the upper 1.25 m in till. One of the monitoring wells (SFM0084) is placed in the same till formation as the pumping well. The other three monitoring wells are placed in different geological formations, overlaying the till (see Figure 7-4).

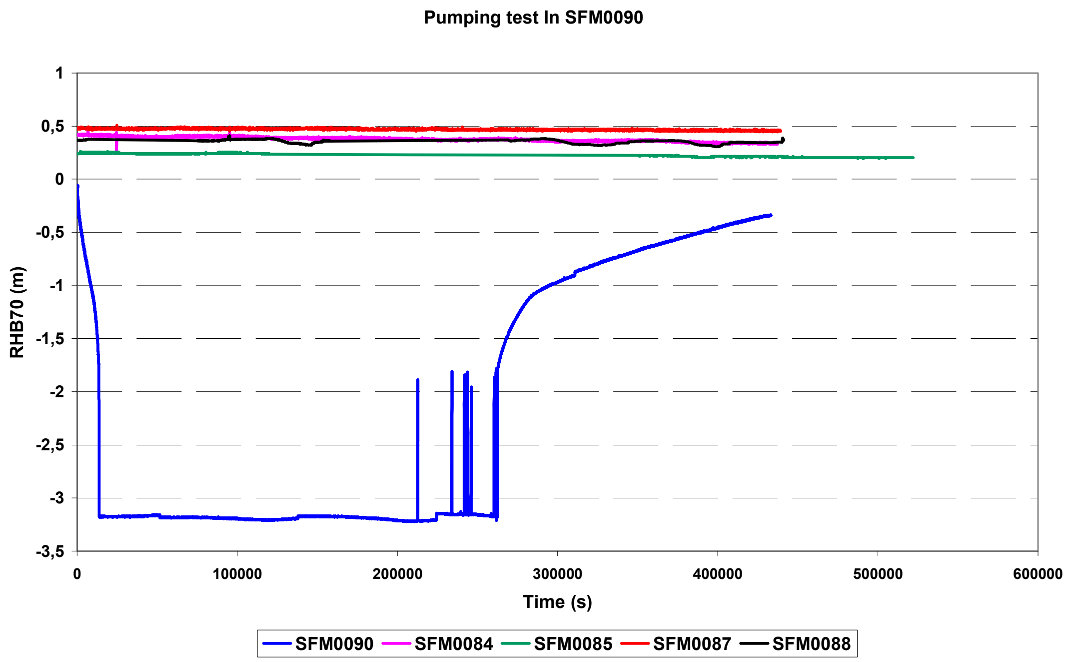

Figure 7-2. *Pumping test in SFM0090. Groundwater level versus time.*

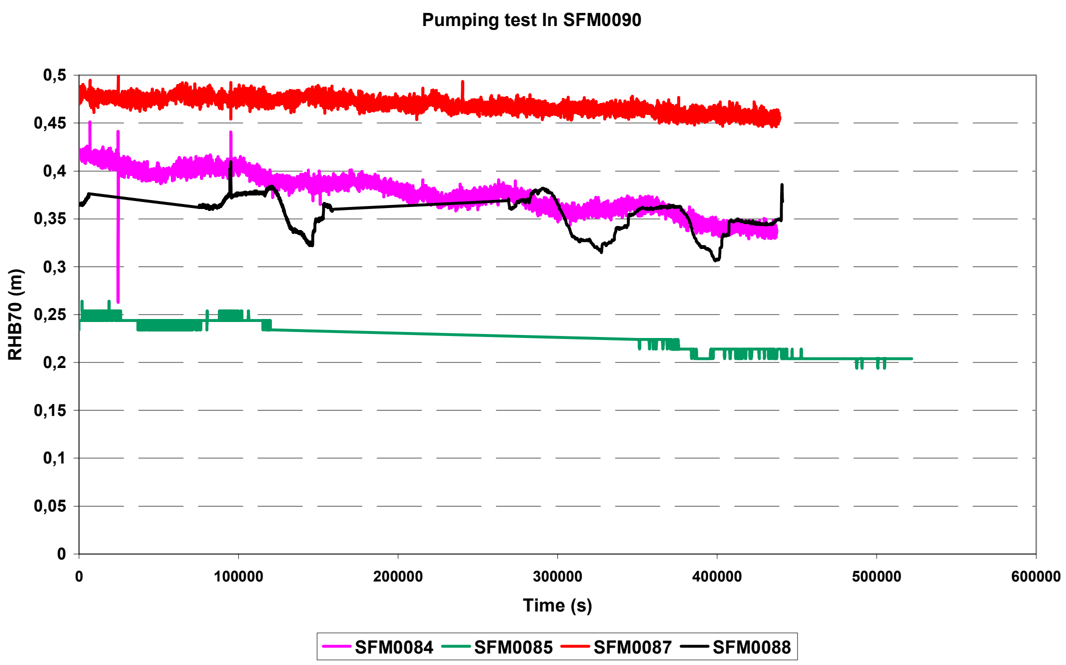

Figure 7-3. *A close-up view of the four monitoring wells.*

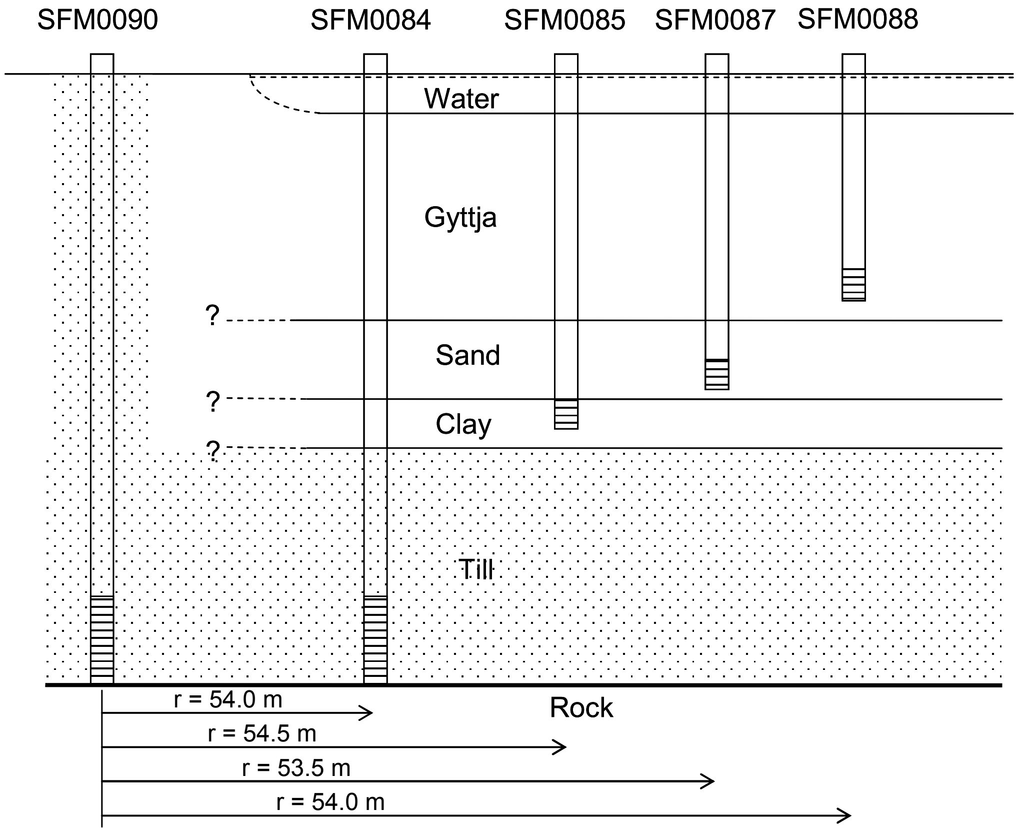

Figure 7-4. *A conceptual model of the pumping well (SFM0090) and the four monitoring wells. Note, not in scale.*

The following remarks can be made concerning the interpretation of the test:

- The lack of any response in the monitoring wells indicates that there is no hydraulic contact between the pumping well and the monitoring wells. Since no response is observed in the till, no conclusions can be drawn concerning the hydraulic contact between the till and the overlaying layers.
- The diagnostic plot (see Figure 7-5) indicates that the local till formation has a limited extension. Between 100 and 10,000 seconds, the drawdown curve for the pumping well has a gradient of 1:2, indicating a 1-dimensional aquifer. 10,000 seconds after pump start, the drawdown curve changes dramatically. The reason for this dramatic change is that the groundwater table at the pumping well first reaches the top of the well screen, and thereafter the bedrock surface. The reduced screen length together with the low conductivity of the rock increase the speed of drawdown.
- The flow rate also indicates that the till formation is surrounded by negative boundaries. During the first approximately five hours the flow rate was 27 L/min, and after that it was a decrease of the flow rate down to 3 L/min. The decrease of the flow rate is a result of a limited reservoir and/or a too high flow rate from the beginning of the pumping test.
- The evaluated storage coefficient is uncertain, since it is evaluated from the pumping well only. The values seem to be too high for a till formation.
- The period that looks like a steady-state condition is a result of that the water level in the pumping well has reached the water intake of the pump.

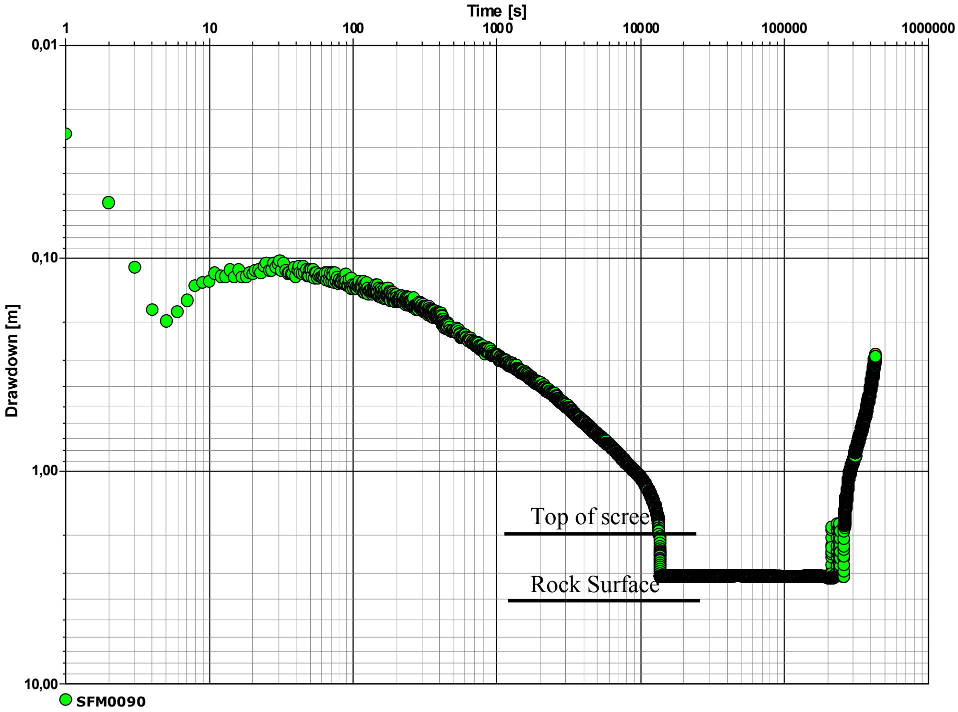

Figure 7-5. *Diagnostic log-log plot of the drawdown in pumping well SFM0090.*

7.2.2 Pumping test in SFM0094

The pumping was performed in well SFM0094. The response was observed in two monitoring wells (SFM0092, and SFM0091), see Figure 7-6 and Figure 7-7. The monitoring wells are placed close to each other, approximately 21 m from the pumping well. The well screens are installed at different depths and in different geological layers (see Figure 7-8).

The well screen of the pumping well is placed in till and bedrock; the lower 1.25 m of the screen (total length 2.5 m) is installed in bedrock, and the upper 1.25 m in till. One of the monitoring wells is placed in the same till formation as the pumping well. The other one is placed in gyttja, overlaying the till and the clayey gyttja (see Figure 7-8).

The following remarks can be made concerning the interpretation of the test:

- The lack of any response in the monitoring wells indicates that there is no hydraulic contact between the pumping well and SFM0091, which is also installed in till. Since no response is observed in the till, no conclusions can be drawn concerning the hydraulic contact between the till and the layers above the till.
- The diagnostic plot (Figure 7-9) indicates that in the beginning, the drawdown curve follows the Theis curve (during 1 minute). Between 60 and 3,000 seconds, the curve has a gradient of 1:2, indicating a 1-dimensional aquifer (gradient 1:2); this is most likely an effect of the reduced screen length. After 10 000 seconds, the groundwater table reaches the bedrock surface.
- The period that looks like a steady-state condition is a result of that the water level in the pumping well has reached the water intake of the pump.
- The flow rate also indicates that the till formation is surrounded by negative boundaries. During the pumping test, the flow rate decreases from 70 L/min to 25 L/min. The average flow rate during the test was 35.5 L/min.
- The evaluated storage coefficient is uncertain, since it is evaluated from the pumping well only.

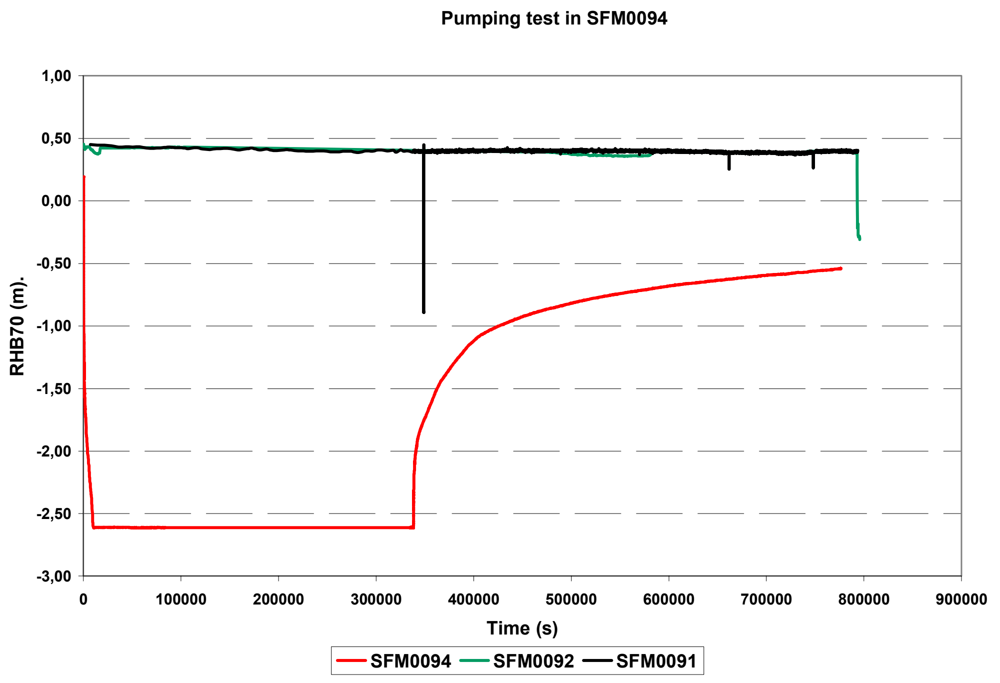

Figure 7-6. *Pumping test in SFM0094. Groundwater level versus time.*

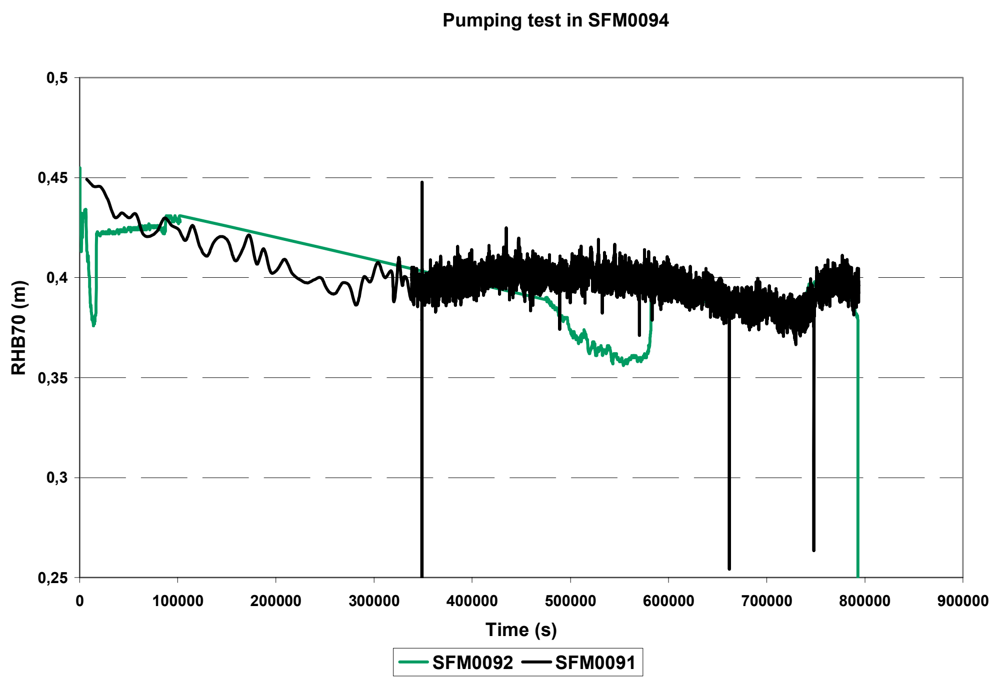

Figure 7-7. *A close-up view of the two monitoring wells.*

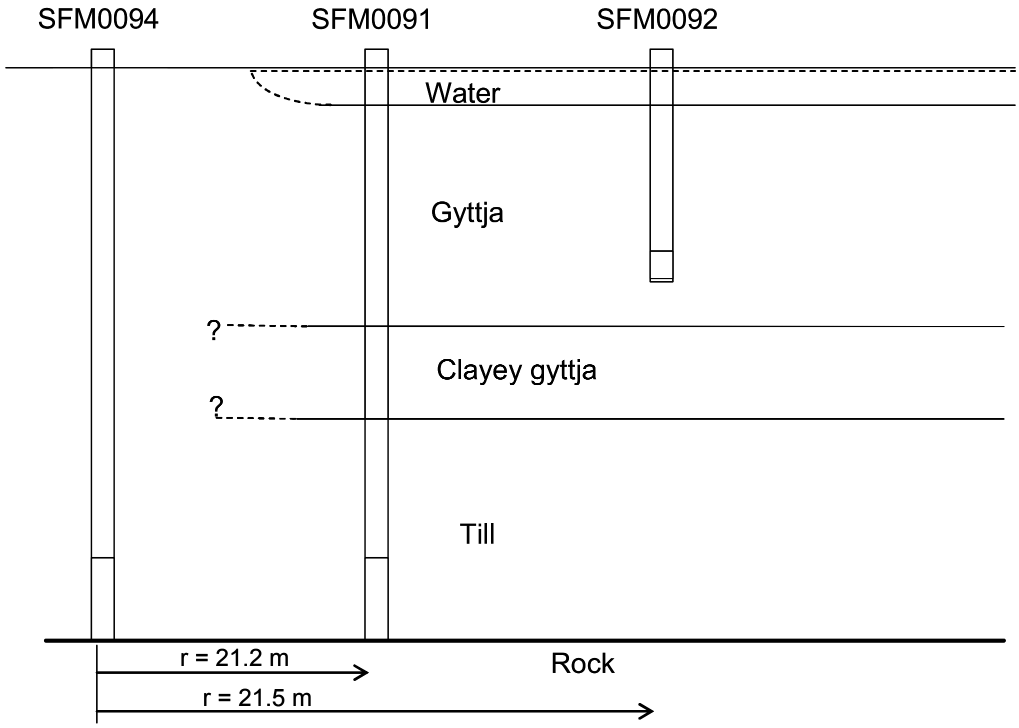

Figure 7-8. *A conceptual model of the pumping well (SFM0094) and the two monitoring wells. Note, not in scale.*

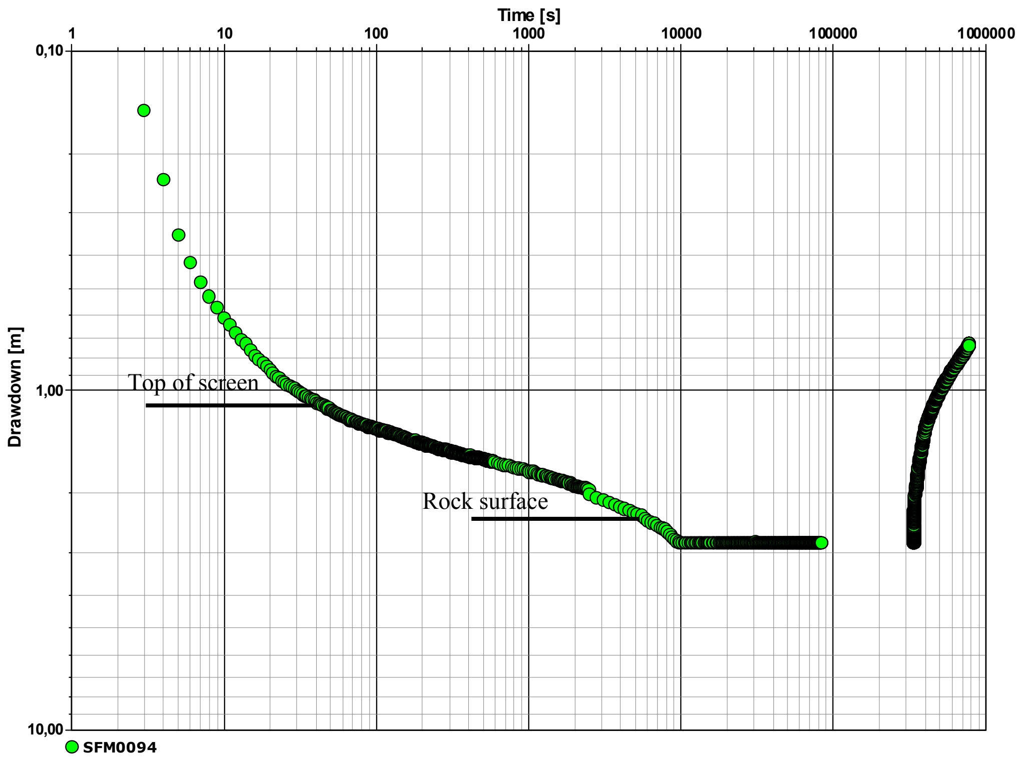

Figure 7-9. *Diagnostic log-log plot of the drawdown in pumping well SFM0094.*

7.2.3 Pumping test in SFM0103

The pumping was performed in well SFM0103. The response was observed in four monitoring wells (SFM0095, SFM0096, SFM0099 and SFM0101), see Figure 7-10 and Figure 7-11. SFM0095 is placed in till, approximately 12 m from the pumping well. The other monitoring wells are installed close to each other, approximately 15 m from the pumping well. The well screens of these three wells are installed at different depths and in different geological layers (see Figure 7-12).

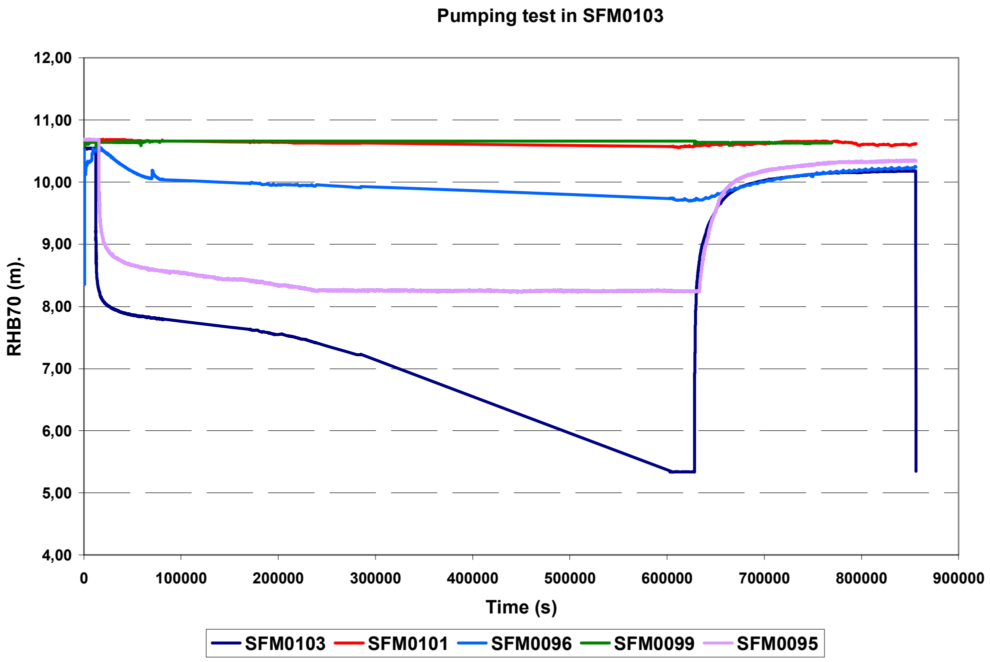

Figure 7-10. *Pumping test in SFM0103. Groundwater level versus time.*

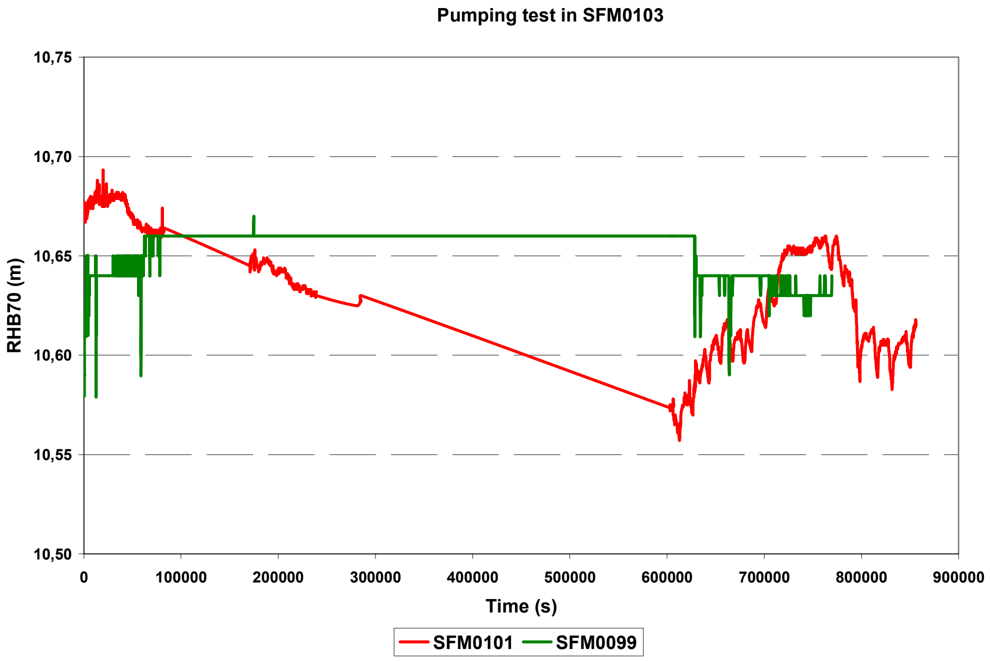

Figure 7-11. *A close-up view of two of the monitoring wells.*

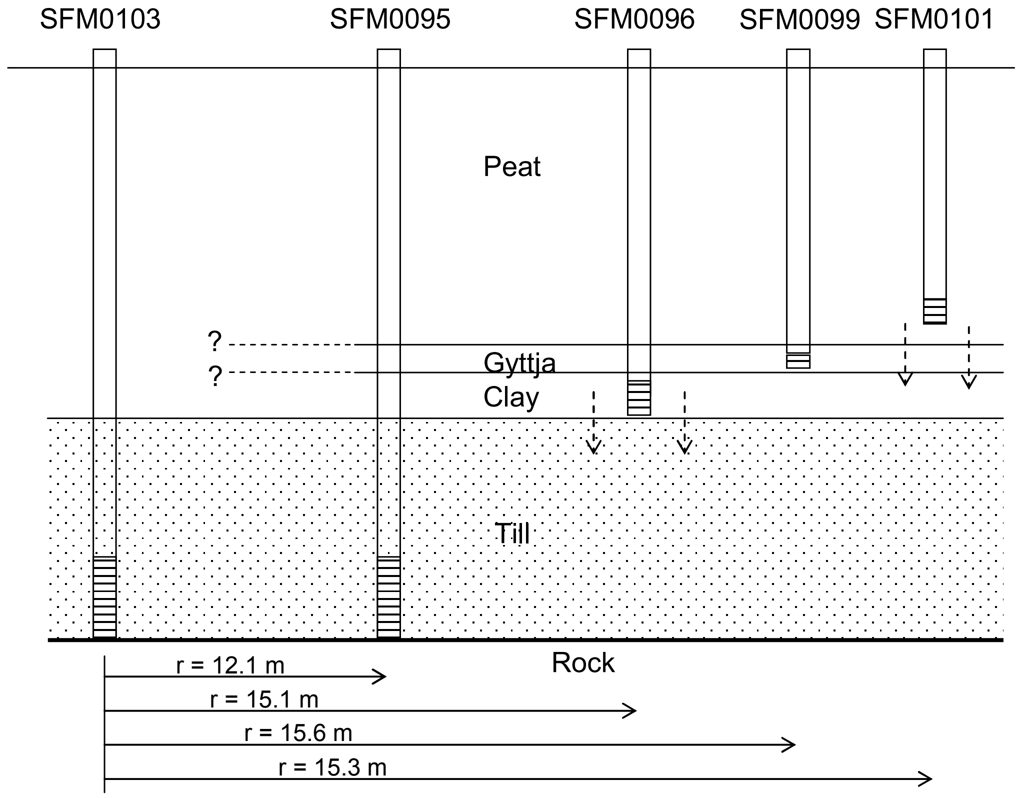

Figure 7-12. *A conceptual model of the pumping well (SFM0103) and the four monitoring wells. Note, not in scale.*

The pumping well is placed in till overlain by clay, gyttja and peat. The well screen of the pumping well is placed in till and bedrock; the lower 1.65 m of the screen (total length 2.5 m) is installed in bedrock, and the upper 0.85 m in till.

One monitoring well has its screen installed in the same till formation as the pumping well. The other three monitoring wells have their screens installed in clay, gyttja and peat that overlay the till (see Figure 7-12).

The following remarks can be made concerning the interpretation of the test:

- Three of the four monitoring wells responded during the pumping test. It is remarkable that the monitoring well that did not respond (SFM0099) has its screen installed in a layer between two other layers that responded (see Figure 7-12).

  A possible explanation is that there may have been some problems with the pressure transducer and/or the data logger in well SFM0099. No errors can be seen in the raw data files, but the lack of response indicates that something is incorrect.

- The test clearly shows that a hydraulic contact exists between the wells in the till formation, and that there is a hydraulic contact between the till and the clay layer on the one hand and between the clay and peat layers on the other. Hence, there is most likely a hydraulic contact across the gyttja layer as well, although this could not be established from the data.
- The diagnostic plot (Figure 7-13) indicates that the drawdown follows the Theis curve during 20 hours after pump start. Subsequently, the curve has a gradient of 1:2. This indicates a 1-dimensional aquifer, but is rather an effect of that the drawdown reaches the boundaries of the pumped formation. At the end of the pumping phase, the groundwater table reaches the screen as well as the bedrock surface.
- The time delay for the pressure response between the different layers is clearly shown in Figure 7-14 and Figure 7-15 (diagnostic plots for SFM0095 and SFM0096).

- In this area there was no major decrease in the flow rate during the pumping test, as was the case in the previously described tests. The average flow rate during the test was 60 L/min.
- By using the leakage coefficient the vertical hydraulic conductivity of the leaky confining layer can be determined. The conductivity is calculated by the following equation:

  K' = (saturated thickness of the leaky confining layer) / leakage coefficient

  $\Rightarrow K' = 2.63 / 5.54 \cdot 10^{8} = 4.75 \cdot 10^{-9}$ m/s

  This value represents a harmonic mean value of the different layers. This vertical hydraulic conductivity value is one order of magnitude lower than the horizontal conductivity evaluated by the permeameter tests (see Section 7.3). Since the texture of the sedimentary deposits often is banded, there might be a difference between the horizontal and vertical conductivity. The vertical hydraulic conductivity for the pumping well SFM0103 is:

  $K' = 2.23 / 9.28 \cdot 10^{4} = 2.40 \cdot 10^{-5}$ m/s

  This value is too high and unrealistic for a peat/gyttja/clay. The reason for the unrealistic value is not clear.
- The evaluated storage coefficient of SFM0103 is uncertain, since it is evaluated from the pumping well only. The values seemed to be too high for a till formation.

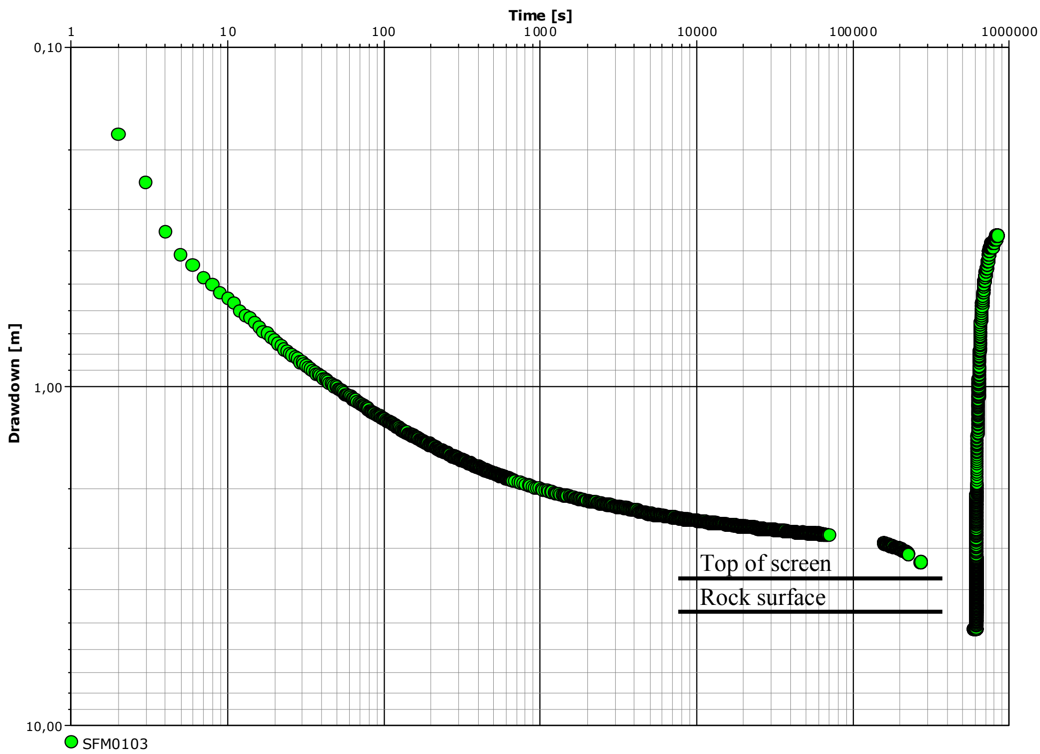

***Figure 7-13.** Diagnostic log-log plot of the drawdown in pumping well SFM0103.*

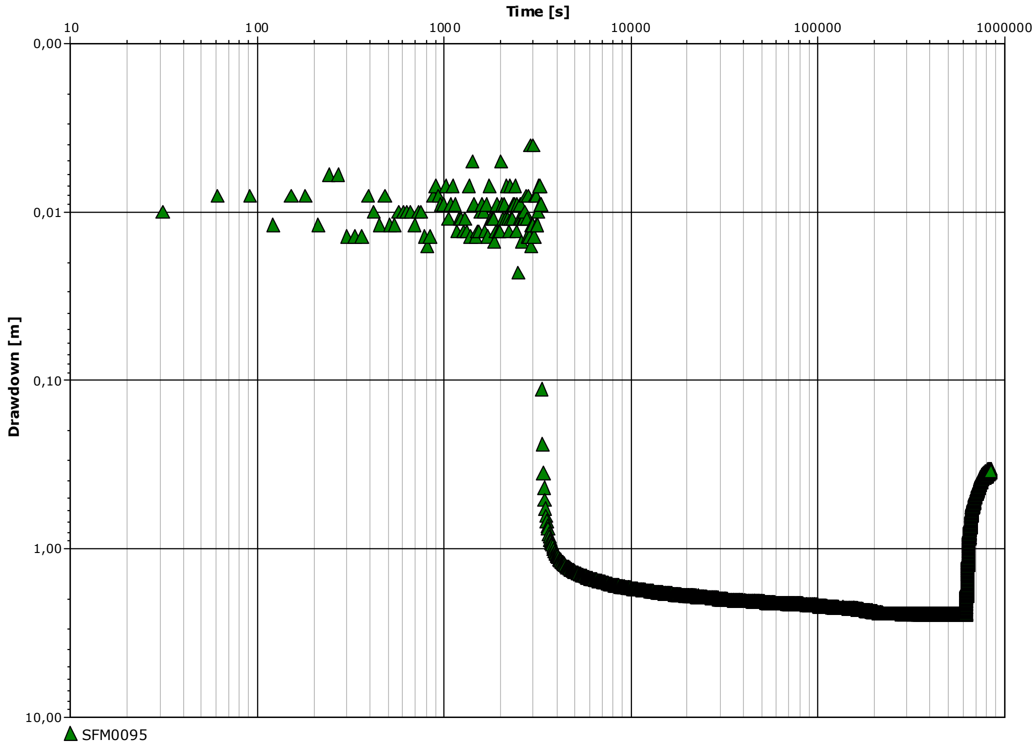

Figure 7-14. *Diagnostic log-log plot of the drawdown in monitoring well SFM0095.*

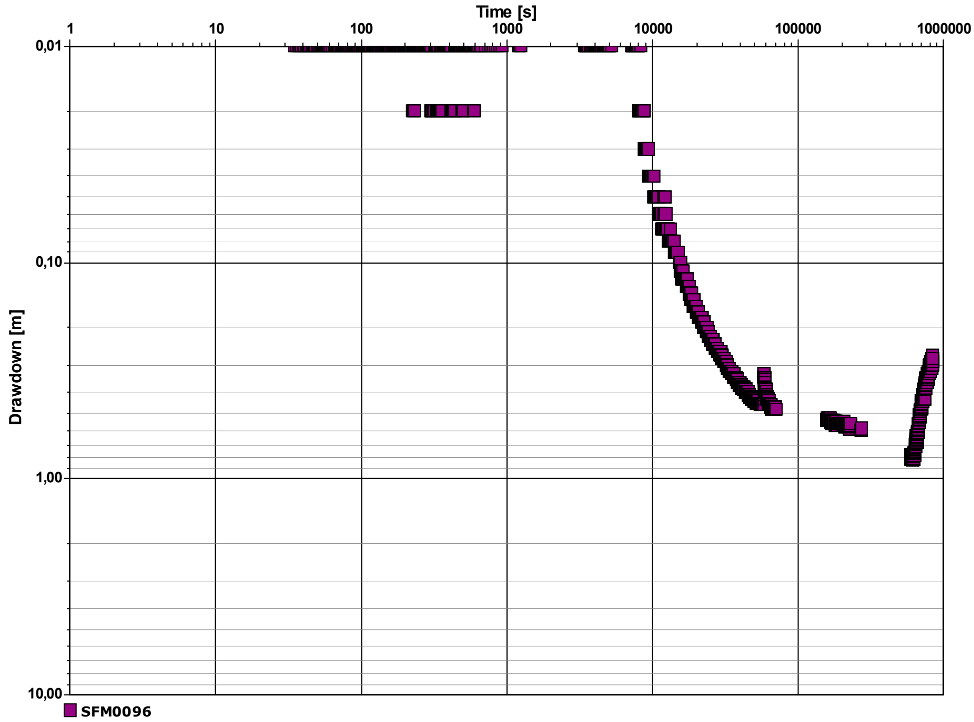

Figure 7-15. *Diagnostic log-log plot of the drawdown in monitoring well SFM0096.*

7.3 Permeameter in situ tests

During the permeameter tests a pressurized specific volume of water is infiltrated into the Quaternary deposits surrounding the filter tip. The change in pressure versus time is continuously registered. Each test generates 24 values of the hydraulic conductivity, in Table 7-5 the mean value is reported. All test results are reported in Appendix 3 (in Appendix 3, which is in Swedish, the hydraulic conductivity is called "permeabilitet" and denoted k). All filter tips are placed in peat, gyttja or clay.

According to the report in Appendix 3, the evaluated conductivities were close to the upper limit of values that can be measured by the equipment. During a test in a soil that is less conductive a stable phase is reached in the middle of the outflow phase. The lack of the stable phase indicated values close to the measurement limit.

Table 7-5. Values of hydraulic conductivity, K (m/s), evaluated by permeameter in situ tests.

Monitoring well	Type of test	Hydraulic conductivity, K (m/s)	Quaternary deposit
SFM0092	Outflow	$3.4 \cdot 10^{-7}$	Gyttja
SFM0082	Outflow	$3.2 \cdot 10^{-7}$	Gyttja
SFM0085	Outflow	$2.6 \cdot 10^{-7}$	Clay
SFM0088	Outflow	$3.3 \cdot 10^{-7}$	Clayey gyttja
SFM0096	Outflow	$2.9 \cdot 10^{-7}$	Clay
SFM0099	Outflow	$3.2 \cdot 10^{-7}$	Gyttja
SFM0101	Outflow	$3.3 \cdot 10^{-7}$	Peat

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Diagrams Slug tests

Appendix 1 contains diagrams of the analysis of the slug tests performed in Aquifer Test. Note that the values on time axes are connected to the curve fitting process, i.e. time/(h/h_0) values should not be compared between the figures.

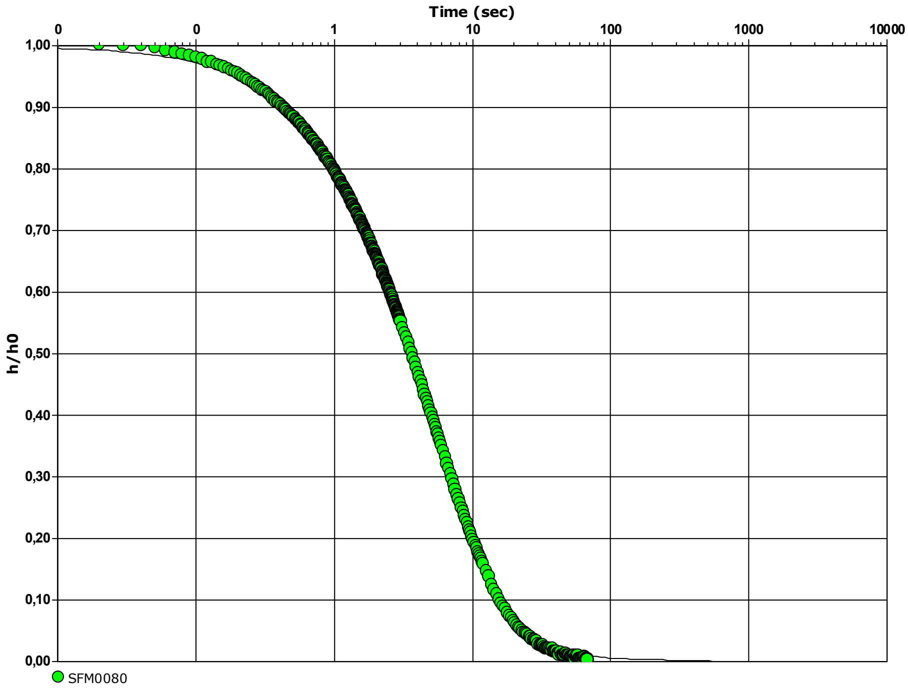

*Figure A1-1. Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0080** (Cooper et al. method).*

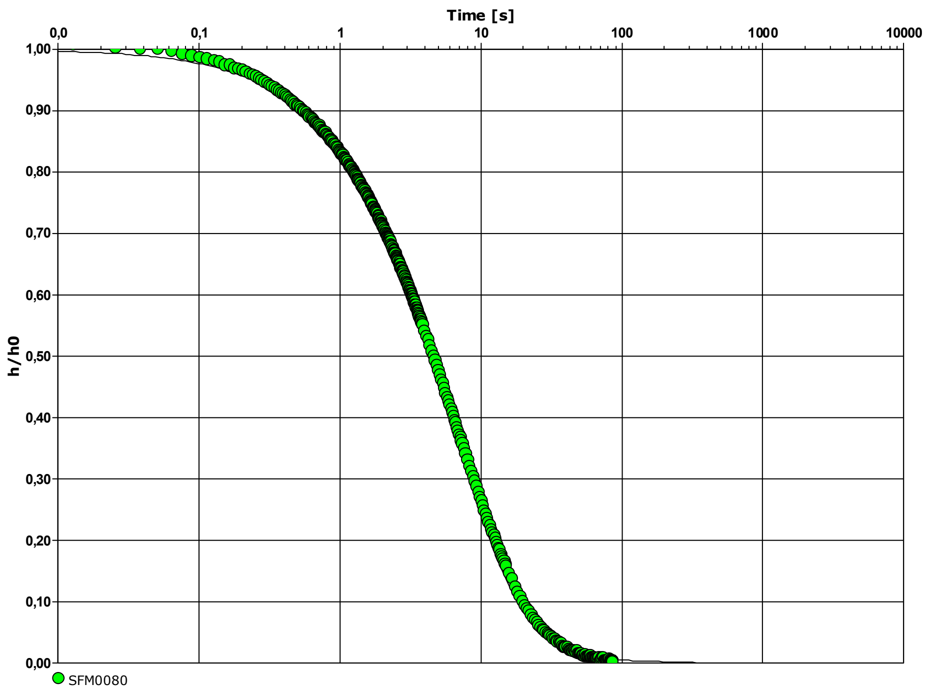

*Figure A1-2. Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0080** (Cooper et al. method, S = 10^{-5}).*

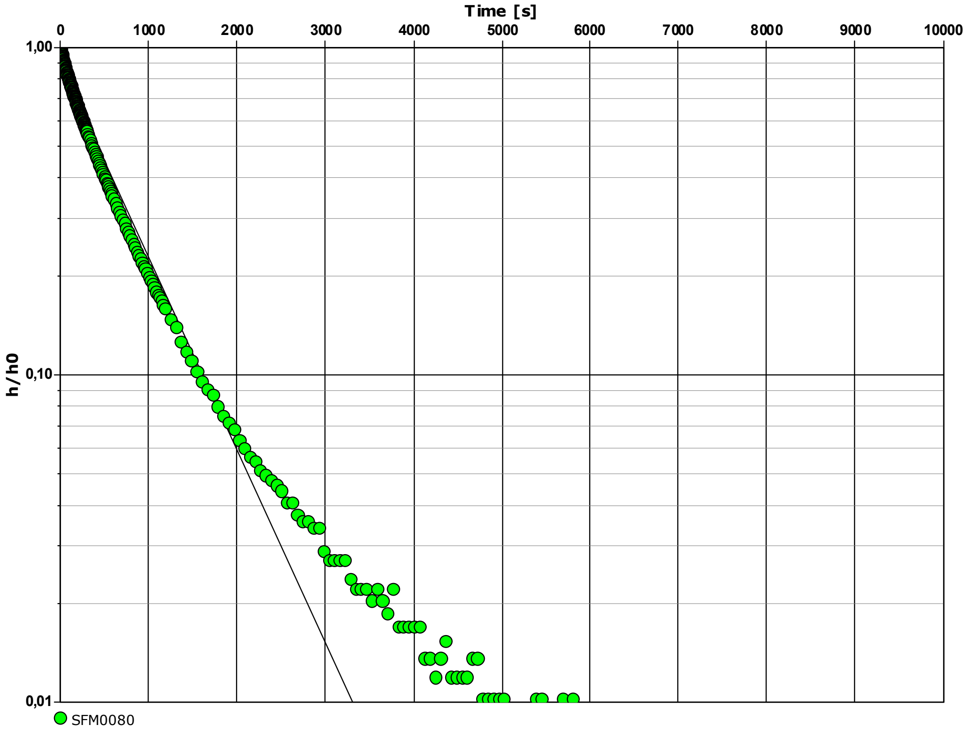

*Figure A1-3. Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0080** (Hvorslev method).*

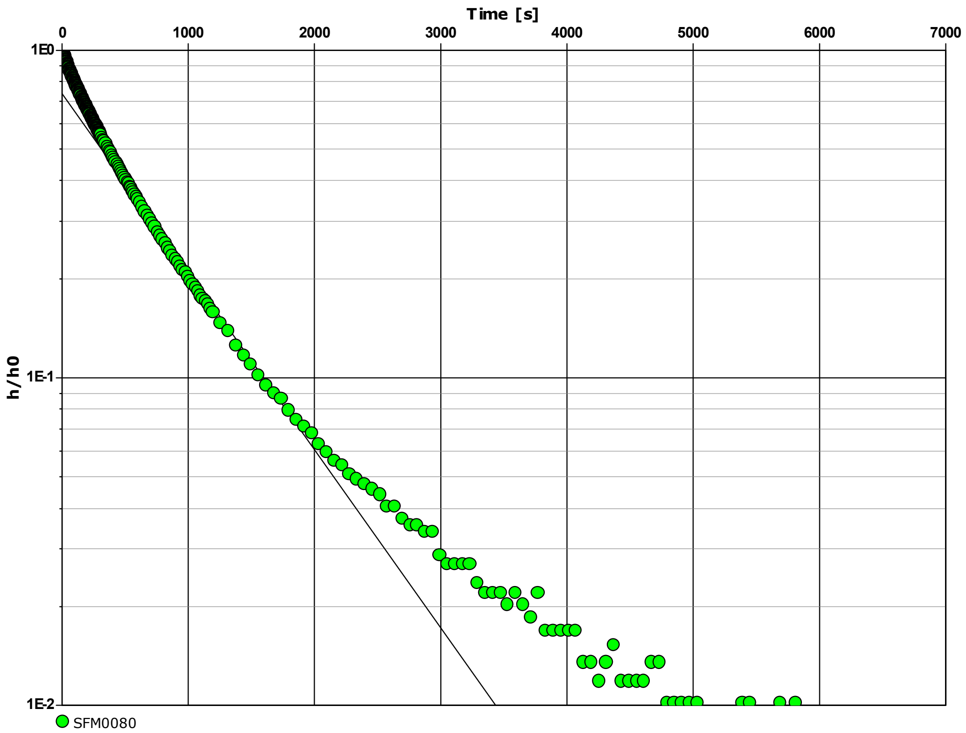

*Figure A1-4. Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0080** (Bouwer & Rice method).*

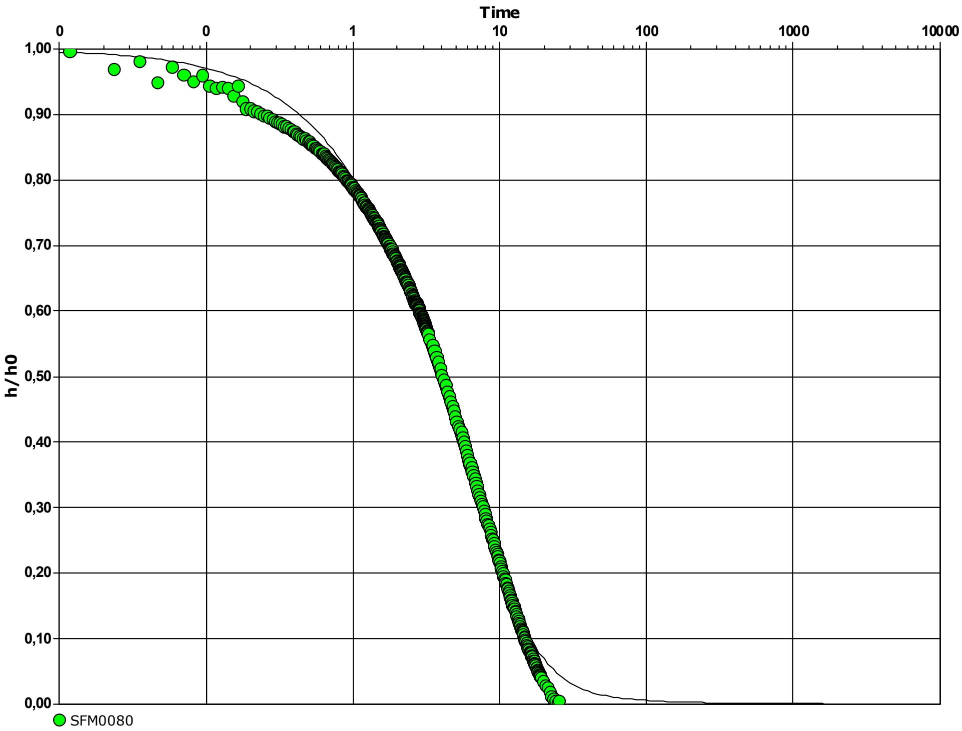

***Figure A1-5.** Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0080** (Cooper et al. method).*

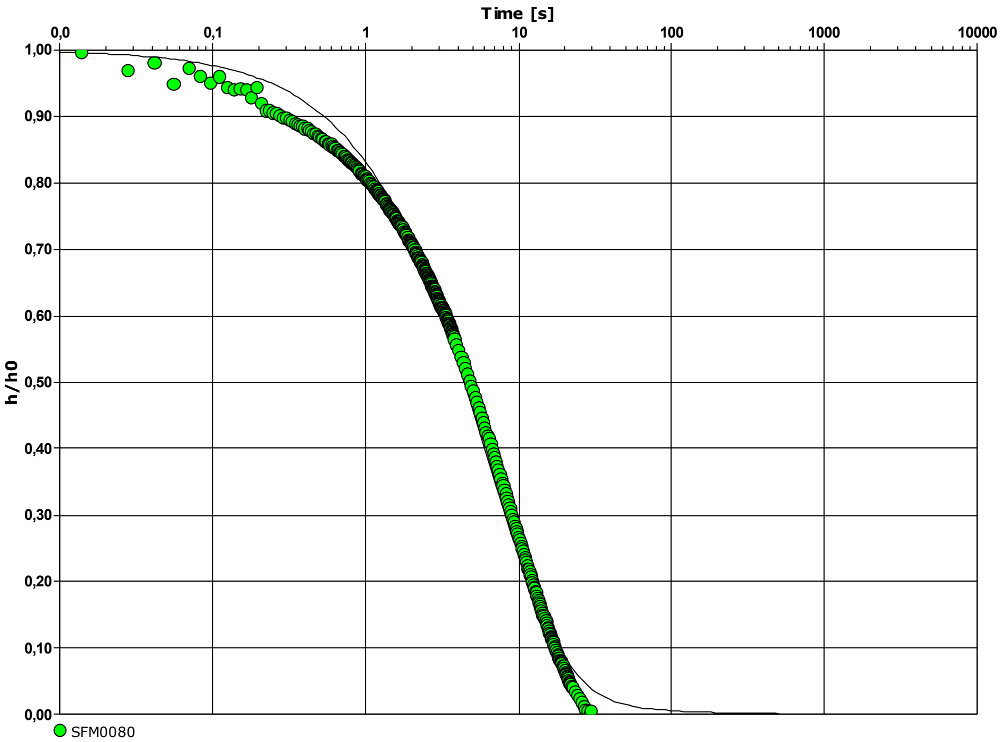

***Figure A1-6.** Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0080** (Cooper et al. method, $S = 10^{-5}$).*

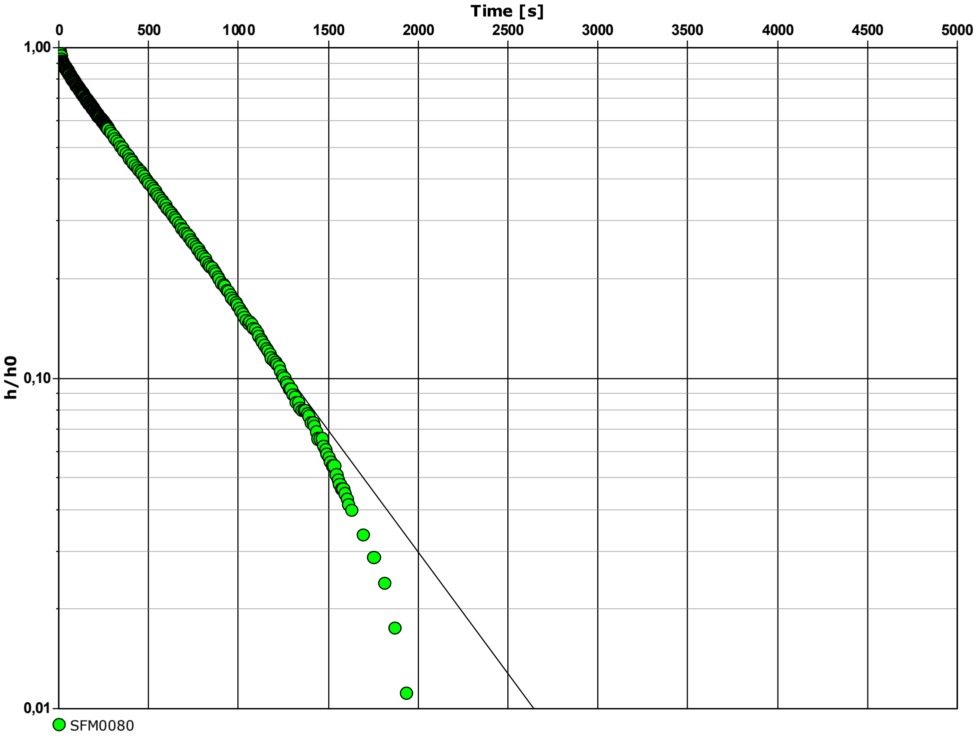

Figure A1-7. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0080*** *(Hvorslev method).*

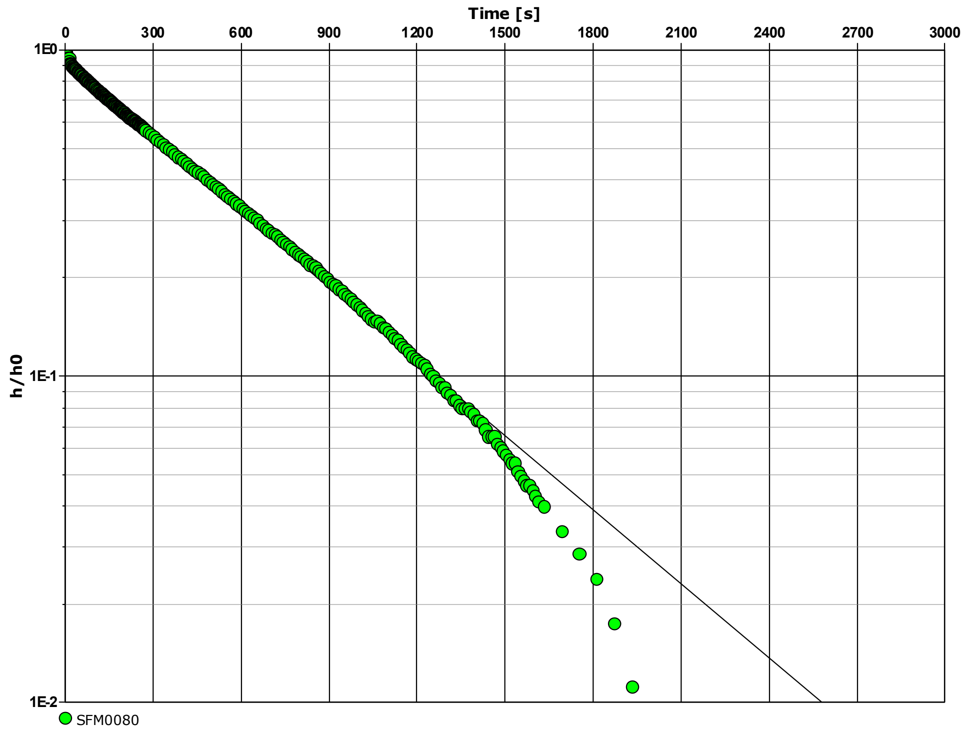

Figure A1-8. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0080*** *(Bouwer & Rice method).*

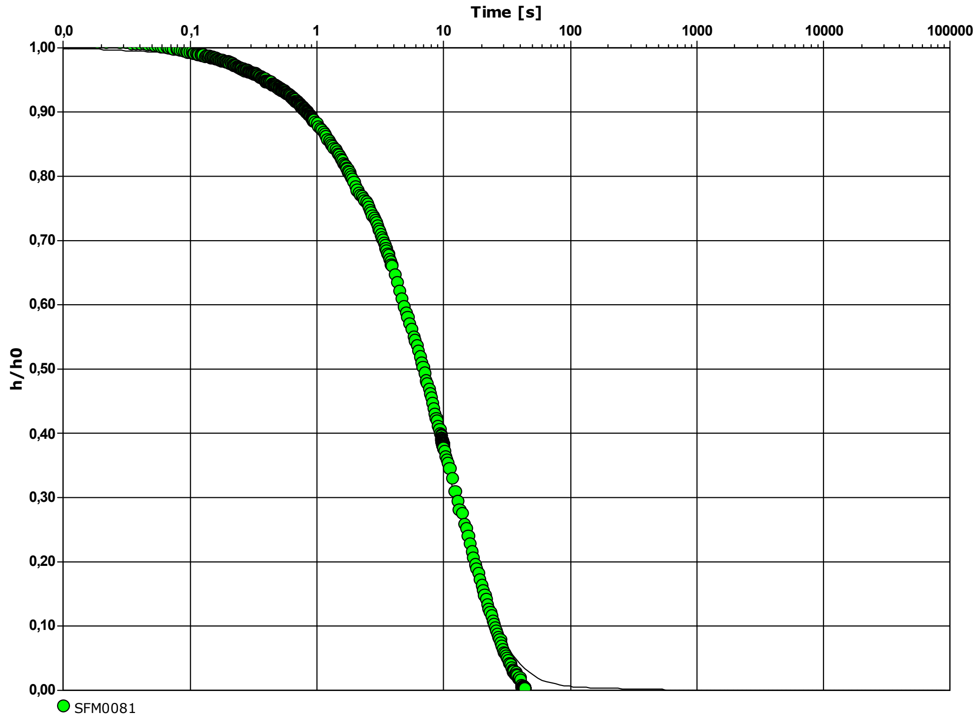

Figure A1-9. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0081** (Cooper et al. method).*

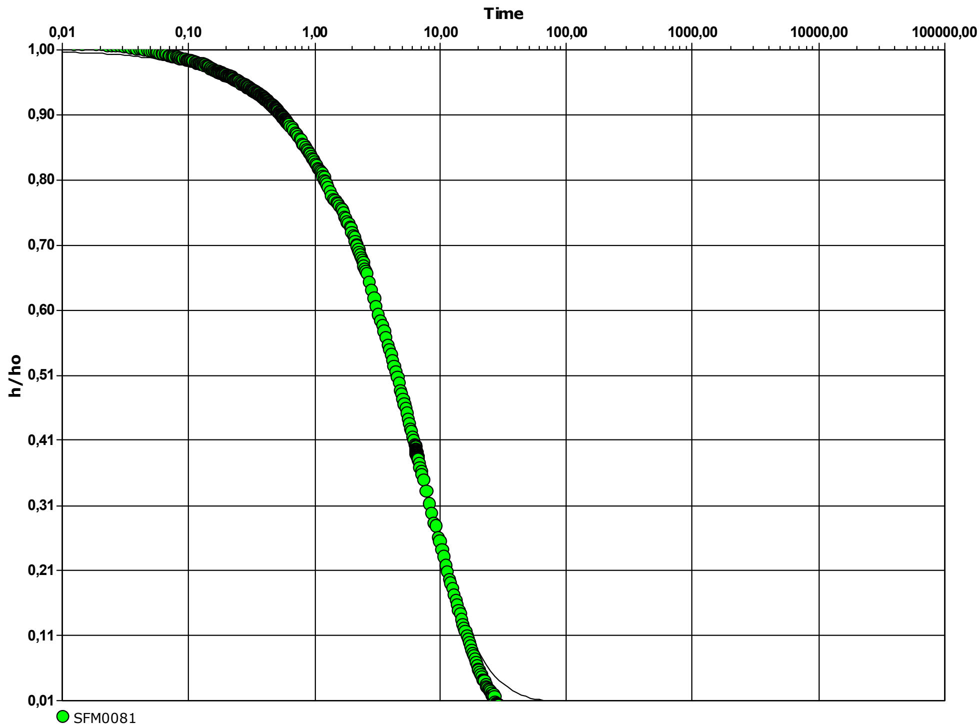

Figure A1-10. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0081** (Cooper et al. method, $S = 10^{-5}$).*

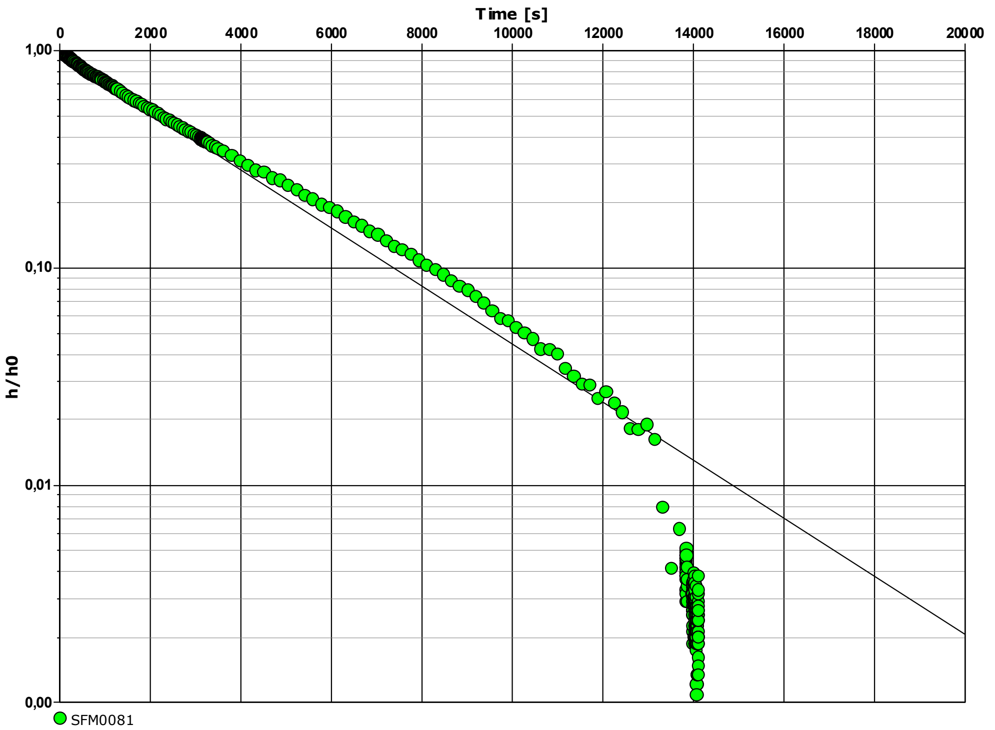

Figure A1-11. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the falling-head test in* ***SFM0081*** *(Hvorslev method).*

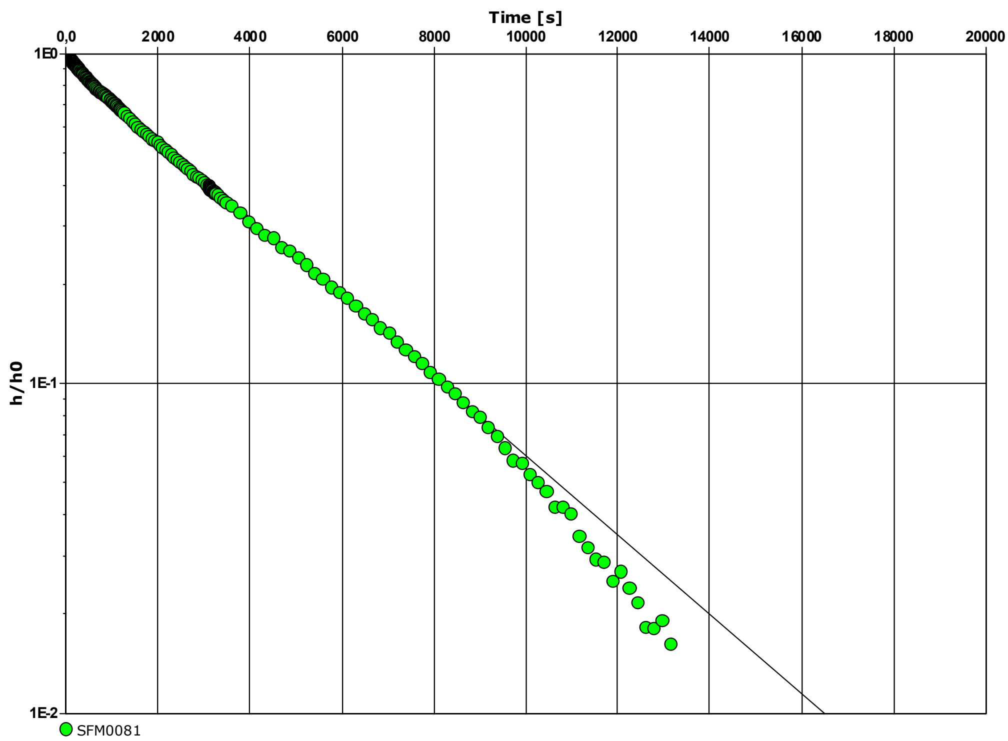

Figure A1-12. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the falling-head test in* ***SFM0081*** *(Bouwer & Rice method).*

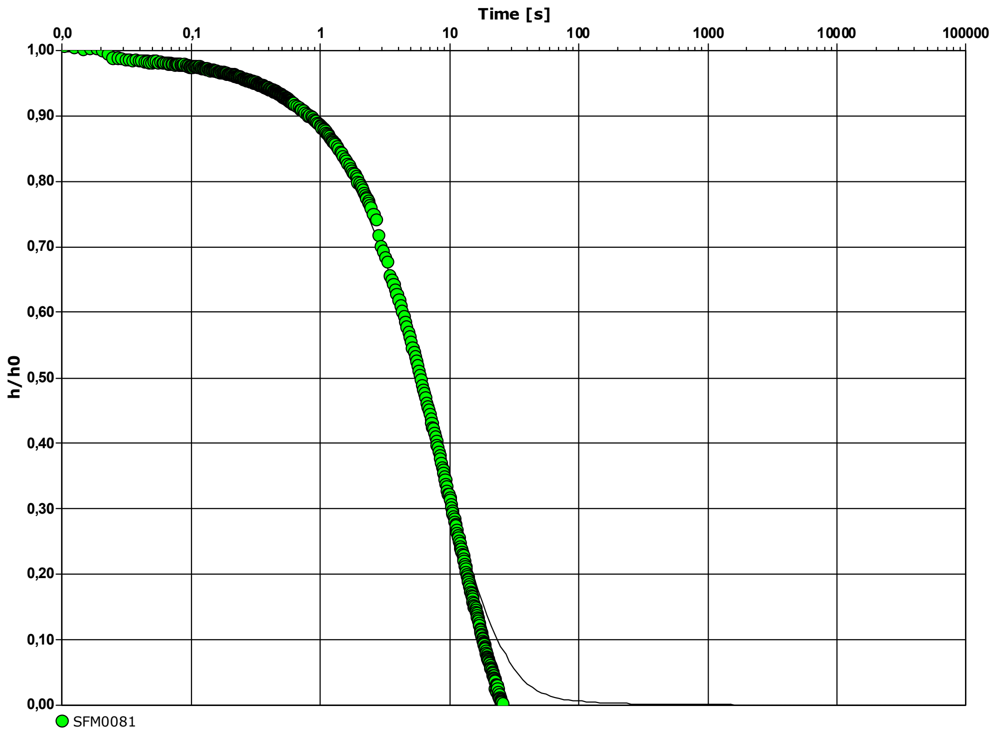

Figure A1-13. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0081*** *(Cooper et al. method).*

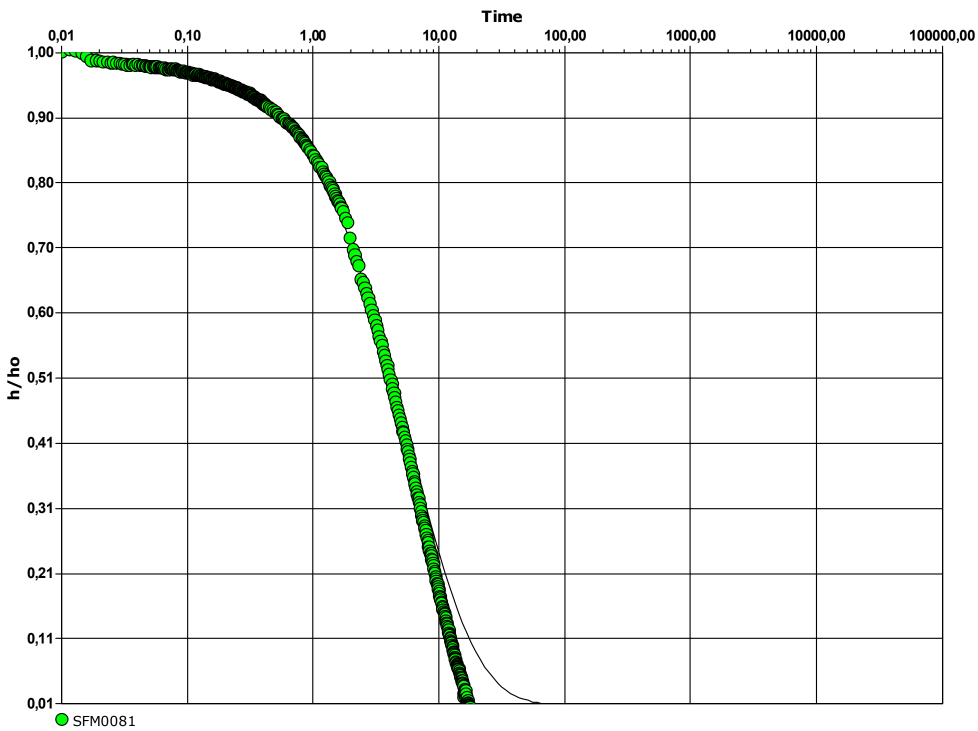

Figure A1-14. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0081*** *(Cooper et al. method, $S = 10^{-5}$).*

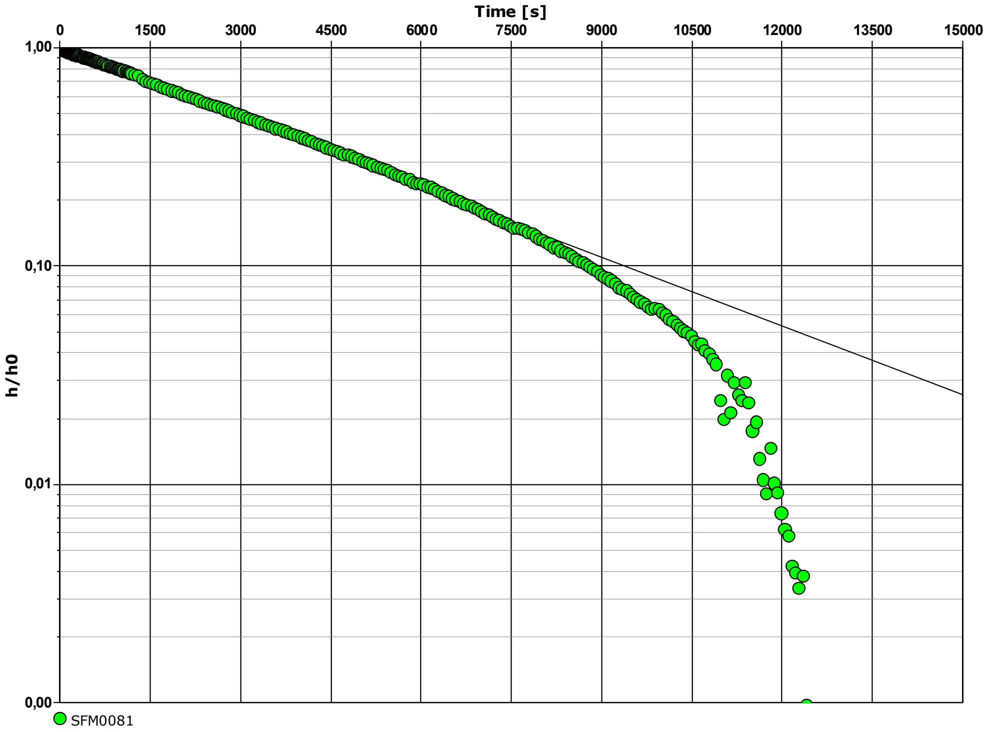

Figure A1-15. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the rising-head test in* ***SFM0081*** *(Hvorslev method).*

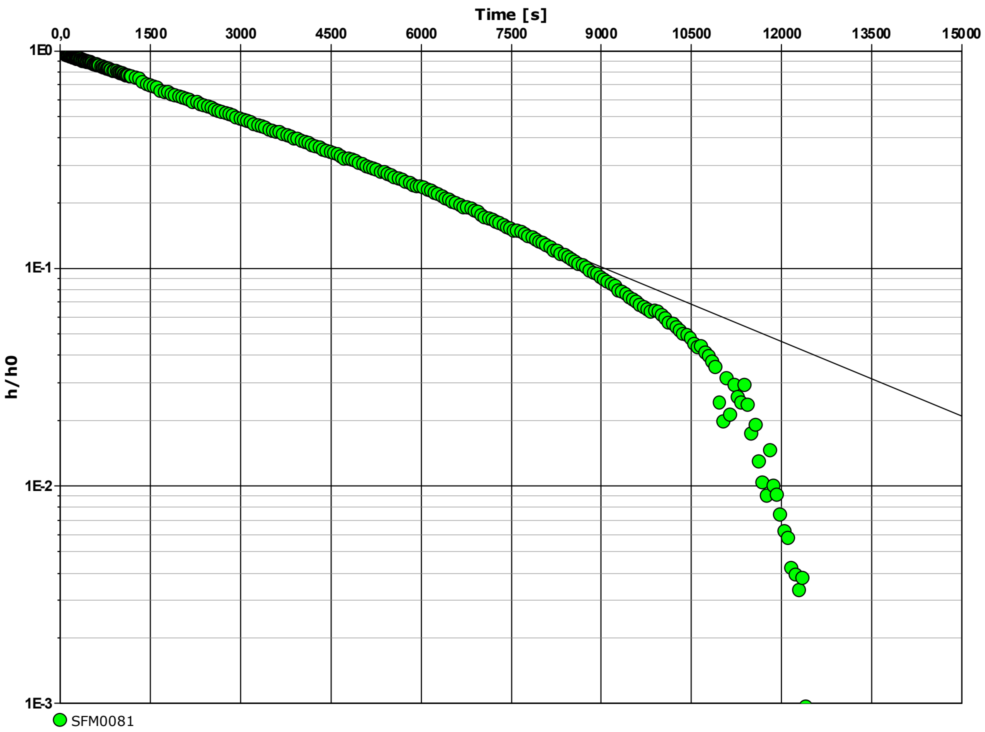

Figure A1-16. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the rising-head test in* ***SFM0081*** *(Bouwer & Rice method).*

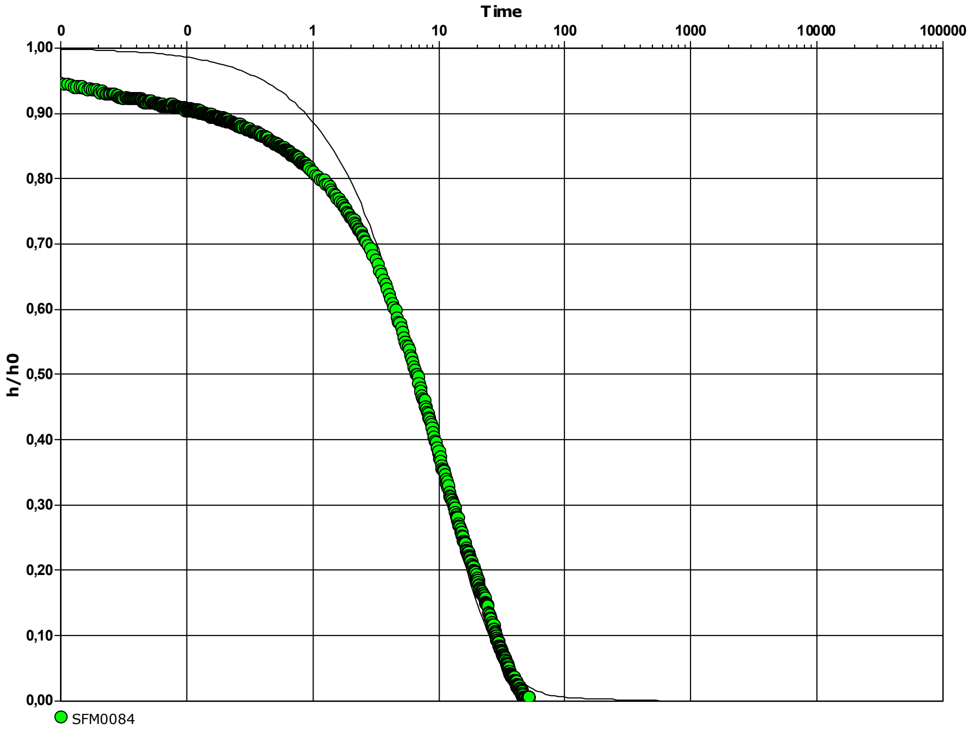

Figure A1-17. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0084** (Cooper et al. method).*

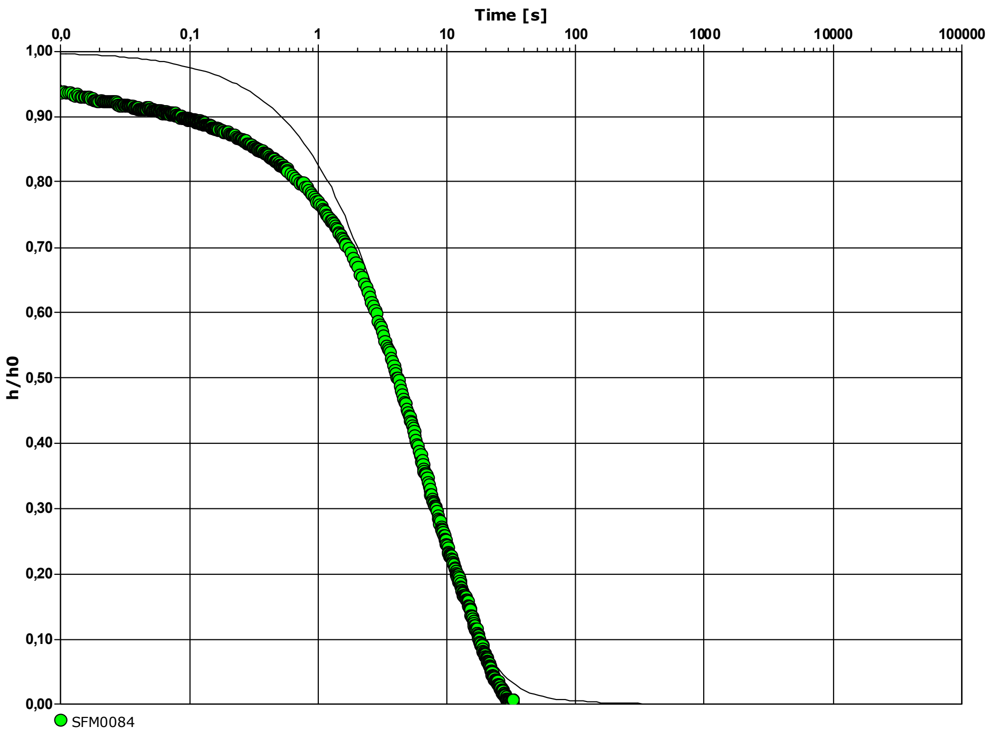

Figure A1-18. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0084** (Cooper et al. method, $S = 10^{-5}$).*

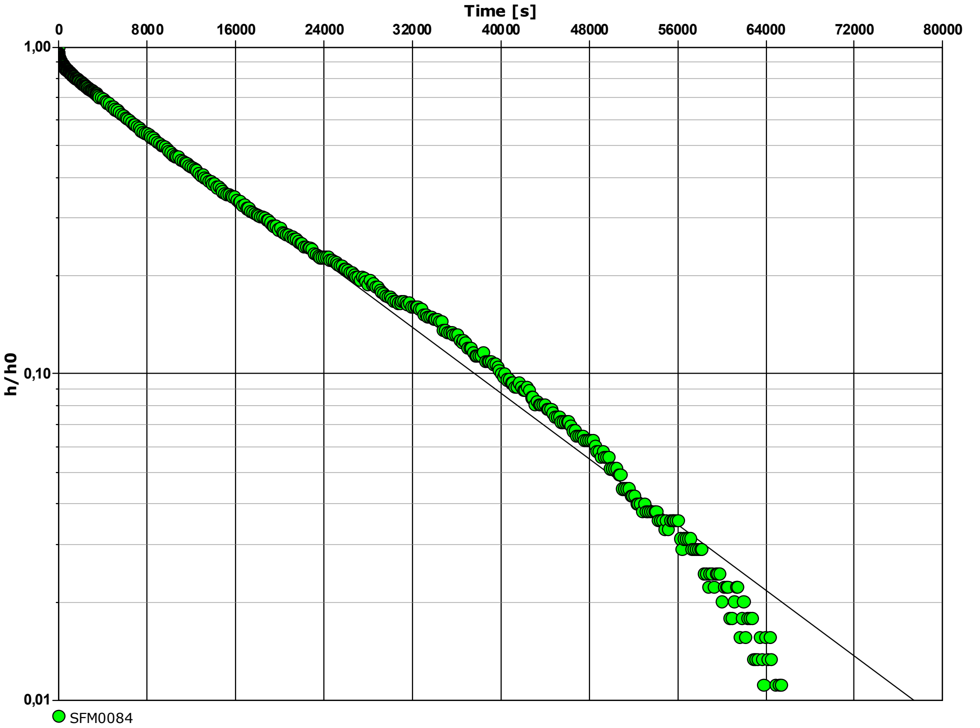

***Figure A1-19.** Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0084** (Hvorslev method).*

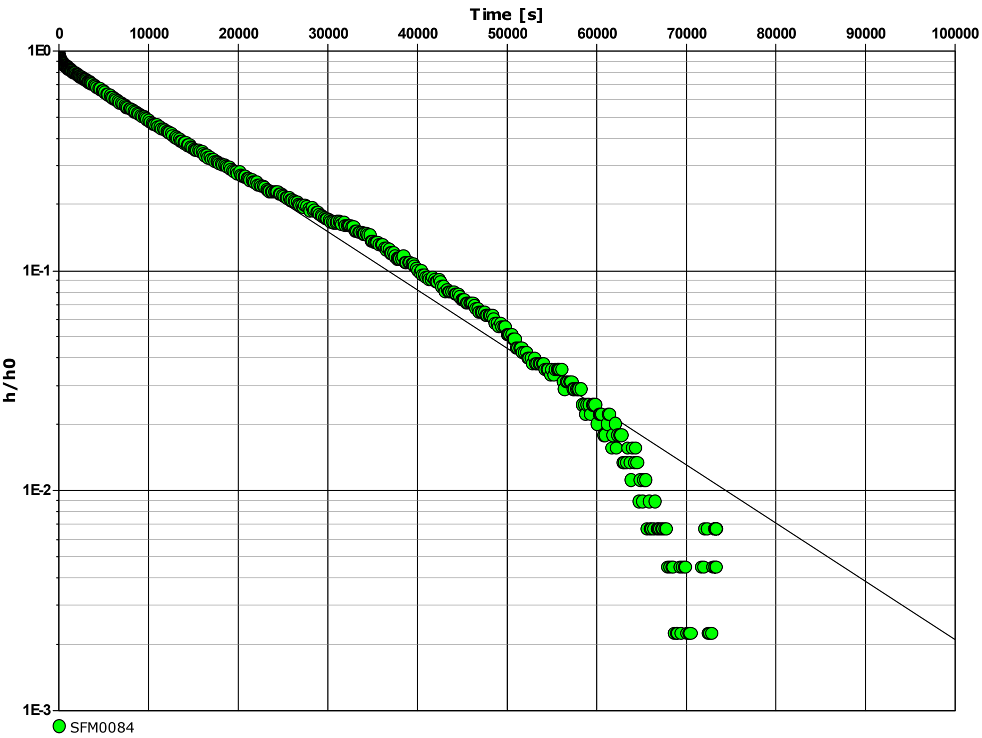

***Figure A1-20.** Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0084** (Bouwer & Rice method).*

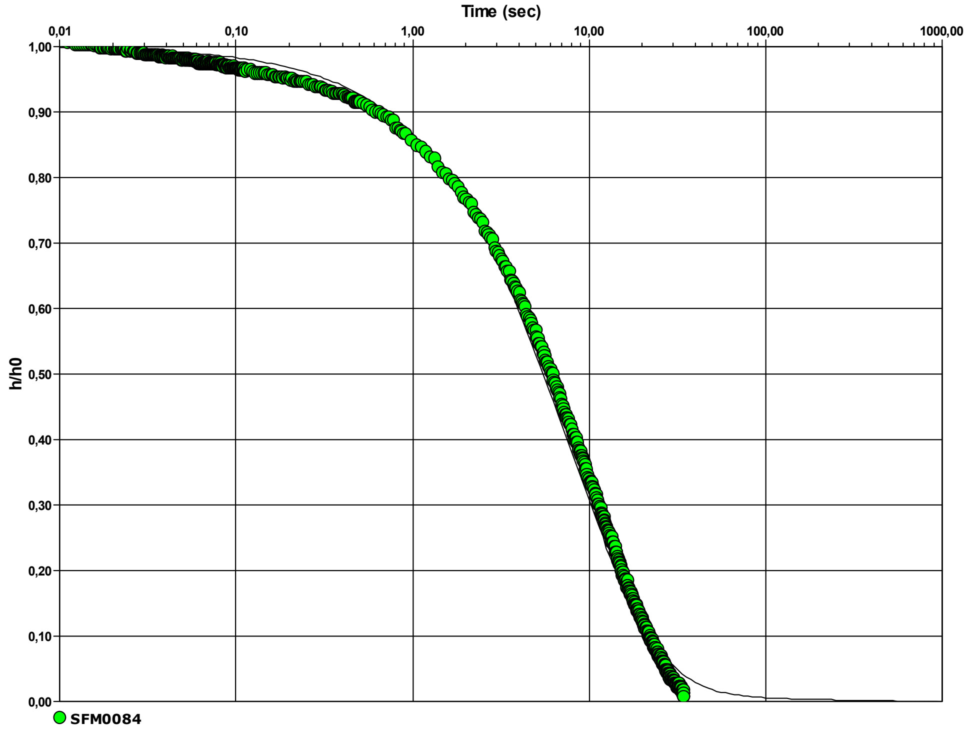

Figure A1-21. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0084*** *(Cooper et al. method).*

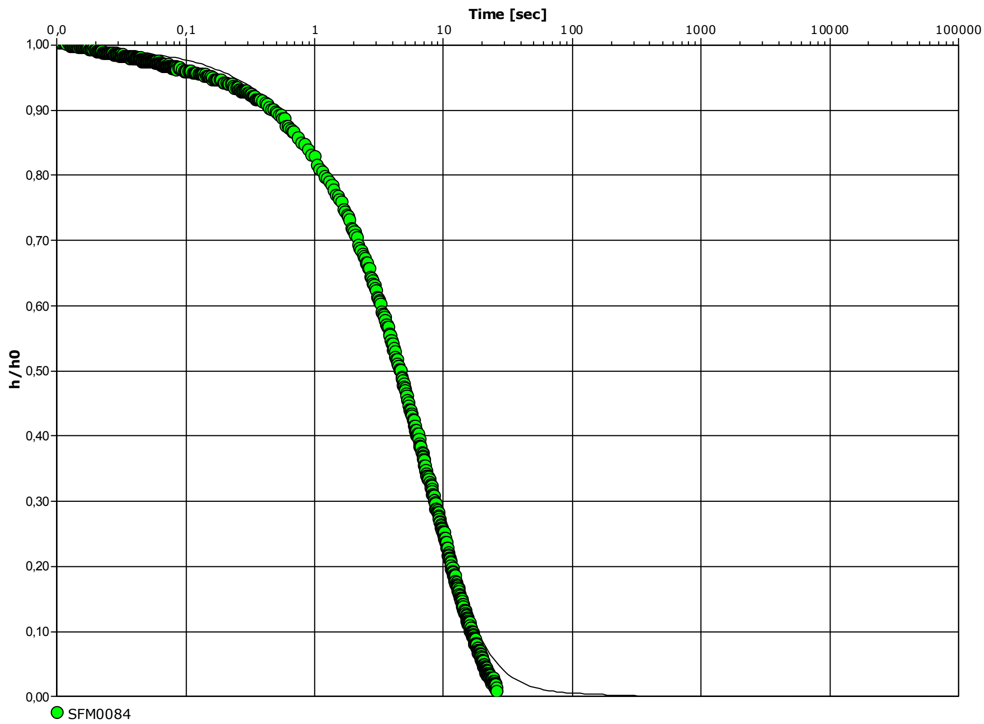

Figure A1-22. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0084*** *(Cooper et al. method, $S = 10^{-5}$).*

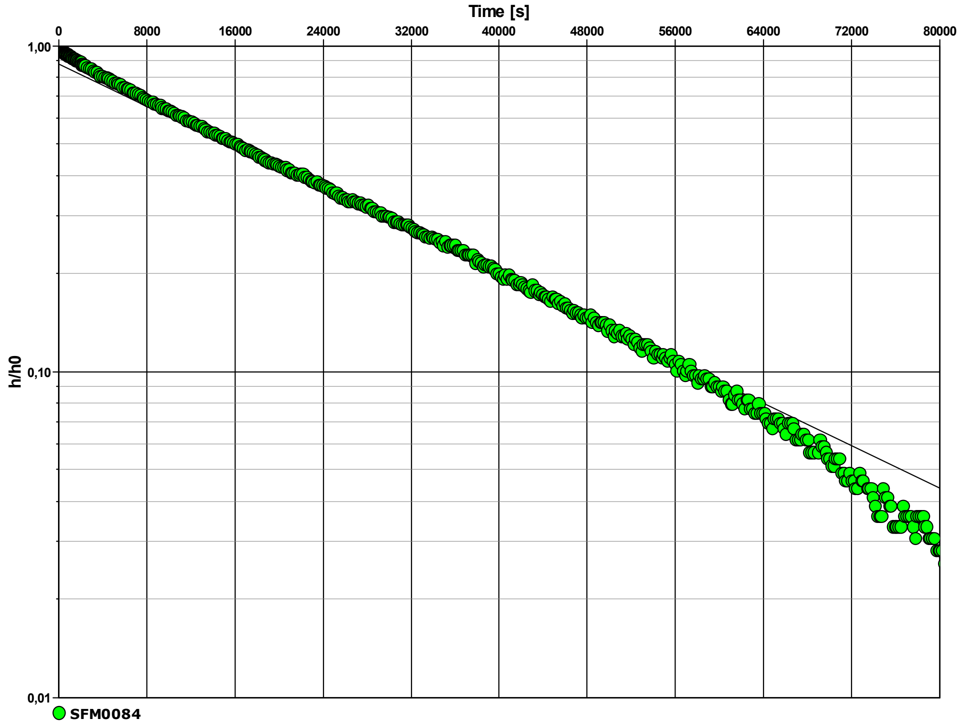

Figure A1-23. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0084*** *(Hvorslev method).*

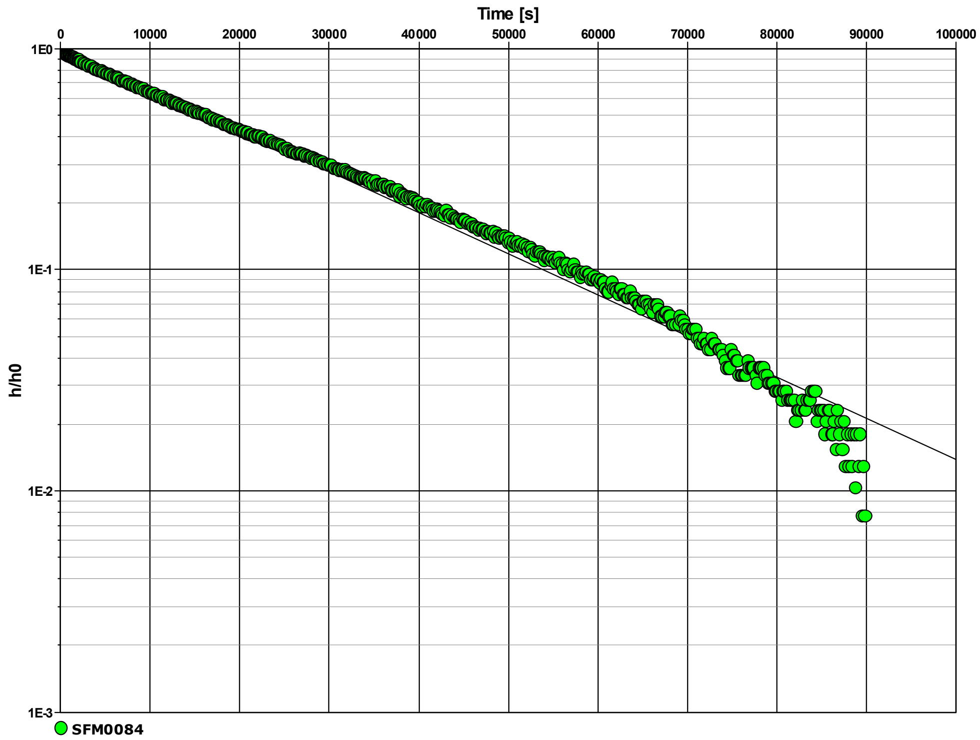

Figure A1-24. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0084*** *(Bouwer & Rice method).*

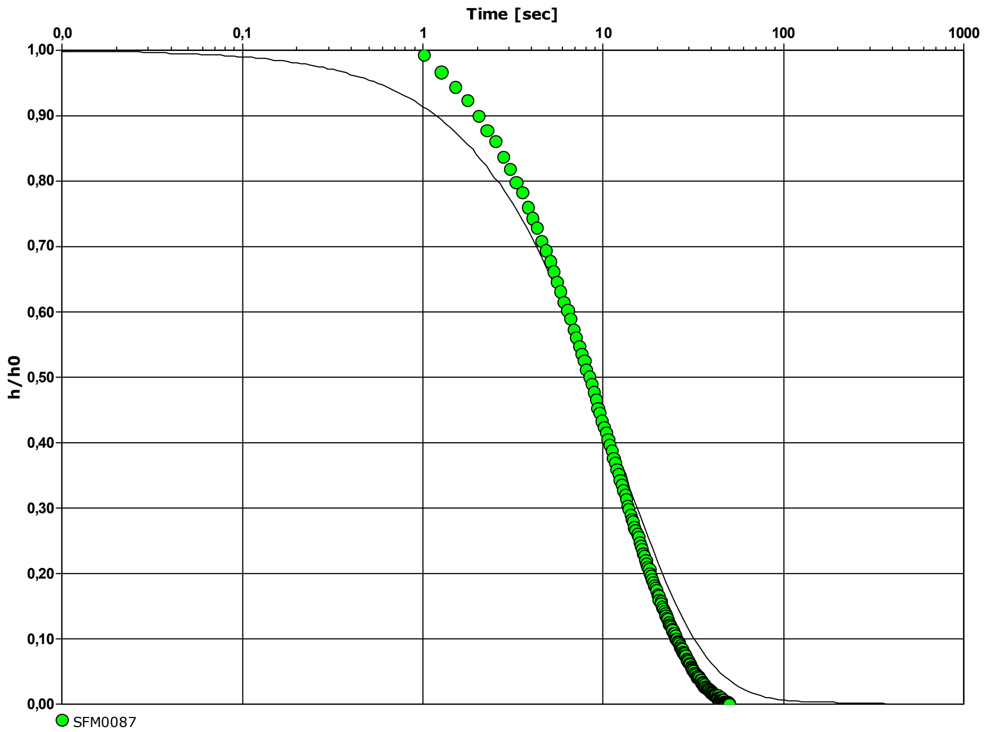

Figure A1-25. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0087*** *(Cooper et al. method).*

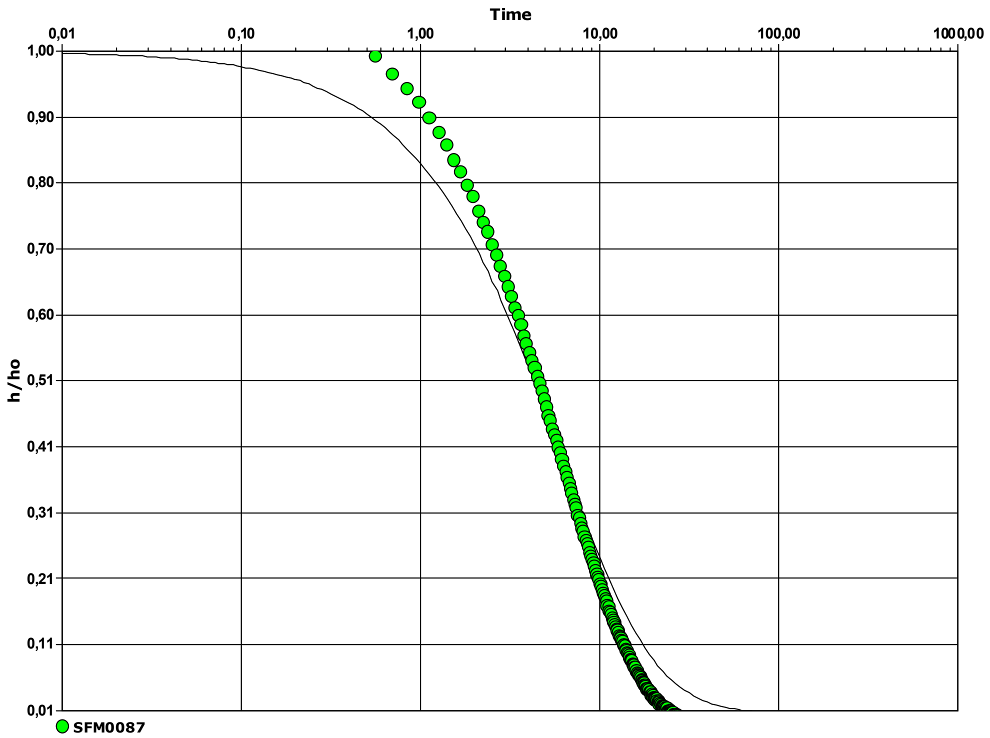

Figure A1-26. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0087*** *(Cooper et al. method, $S = 10^{-5}$).*

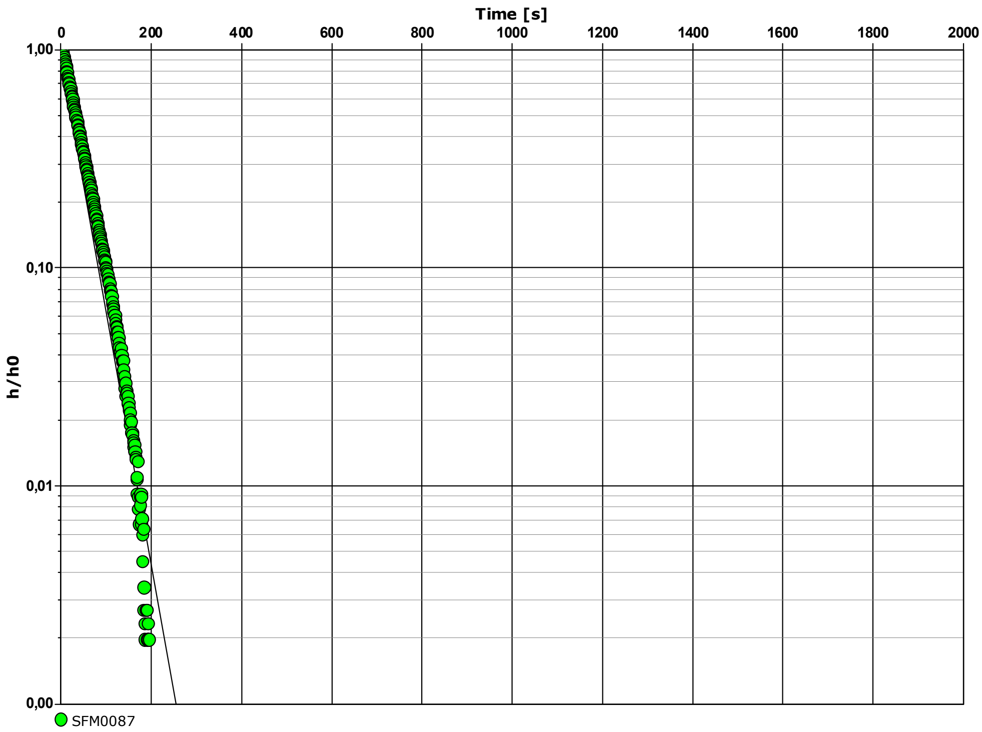

Figure A1-27. Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in ***SFM0087*** *(Hvorslev method).*

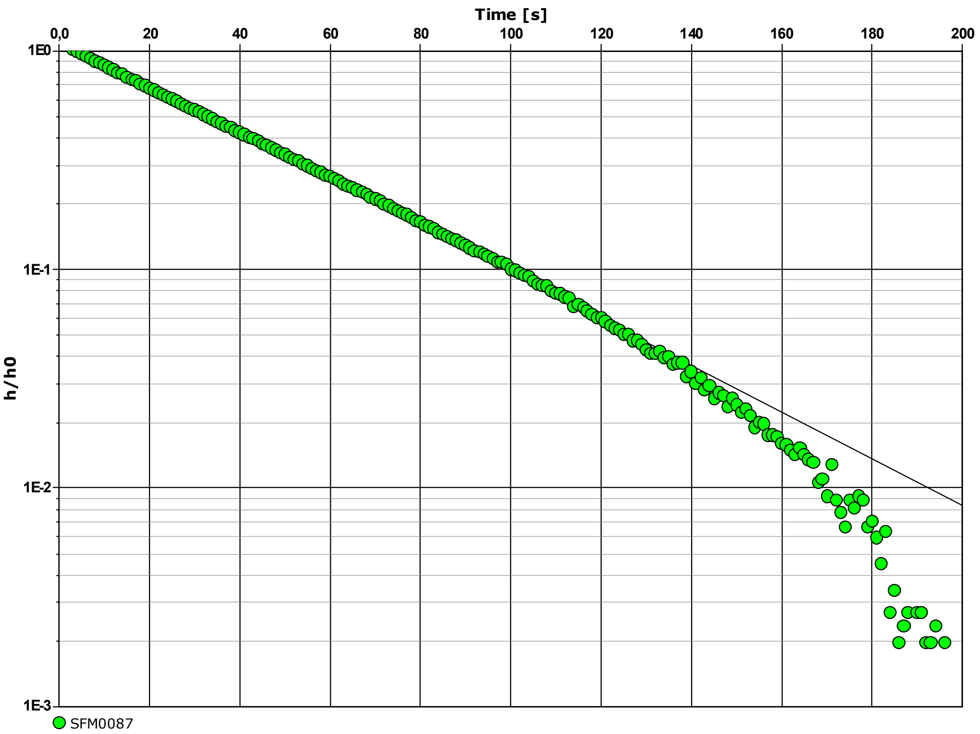

Figure A1-28. Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in ***SFM0087*** *(Bouwer & Rice method).*

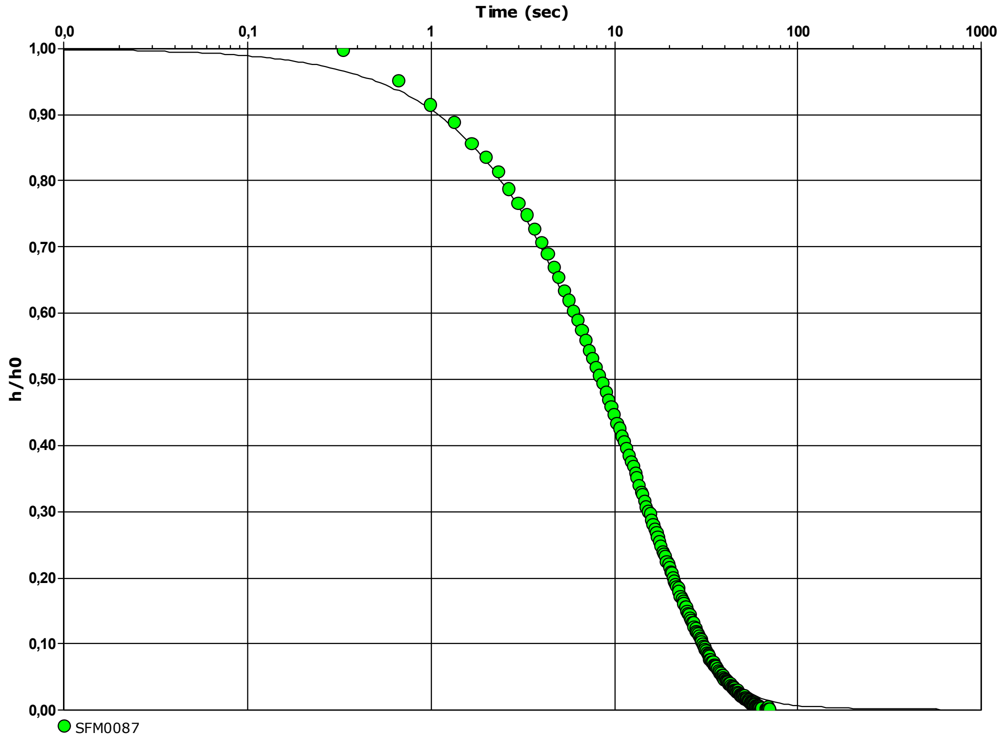

Figure A1-29. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0087** (Cooper et al. method).*

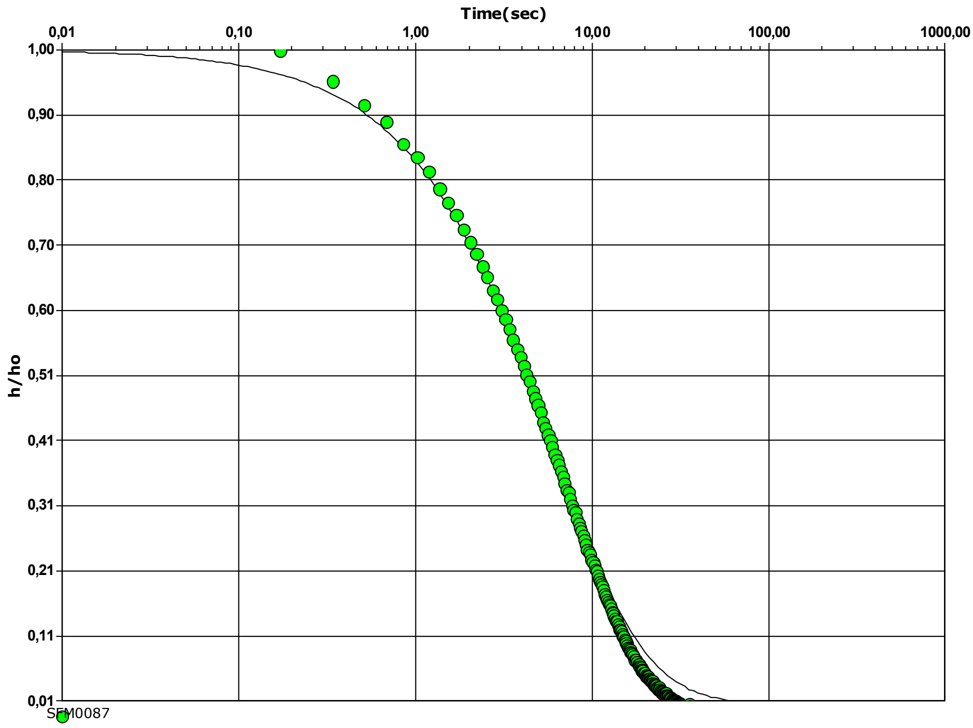

Figure A1-30. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0087** (Cooper et al. method, $S = 10^{-5}$).*

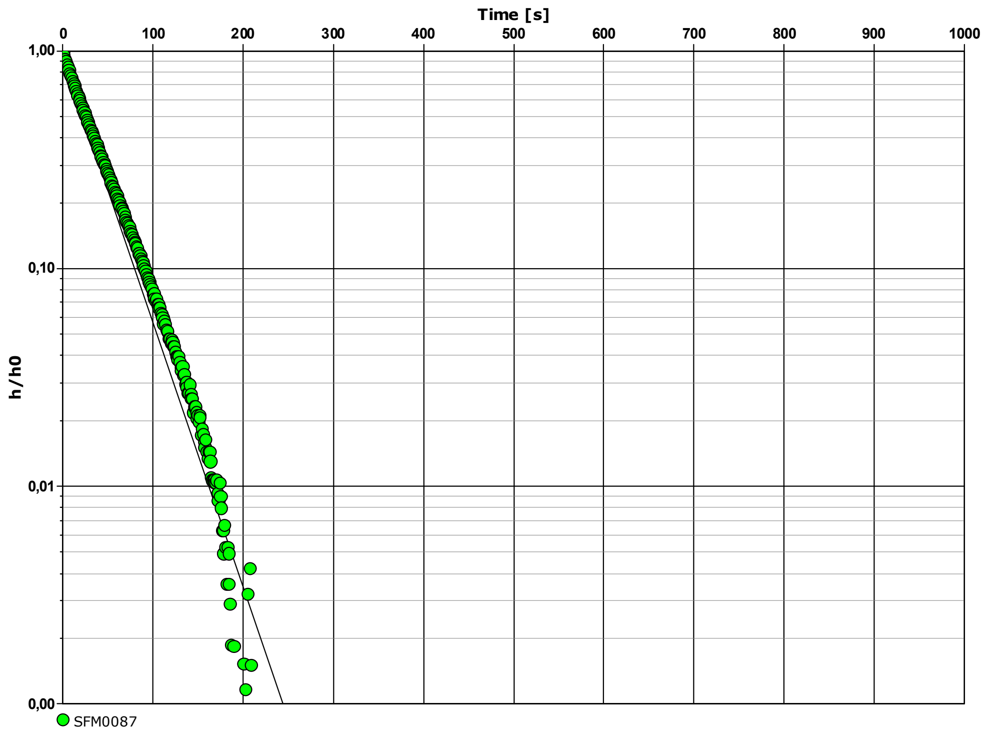

__Figure A1-31.__ Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in __SFM0087__ (Hvorslev method).

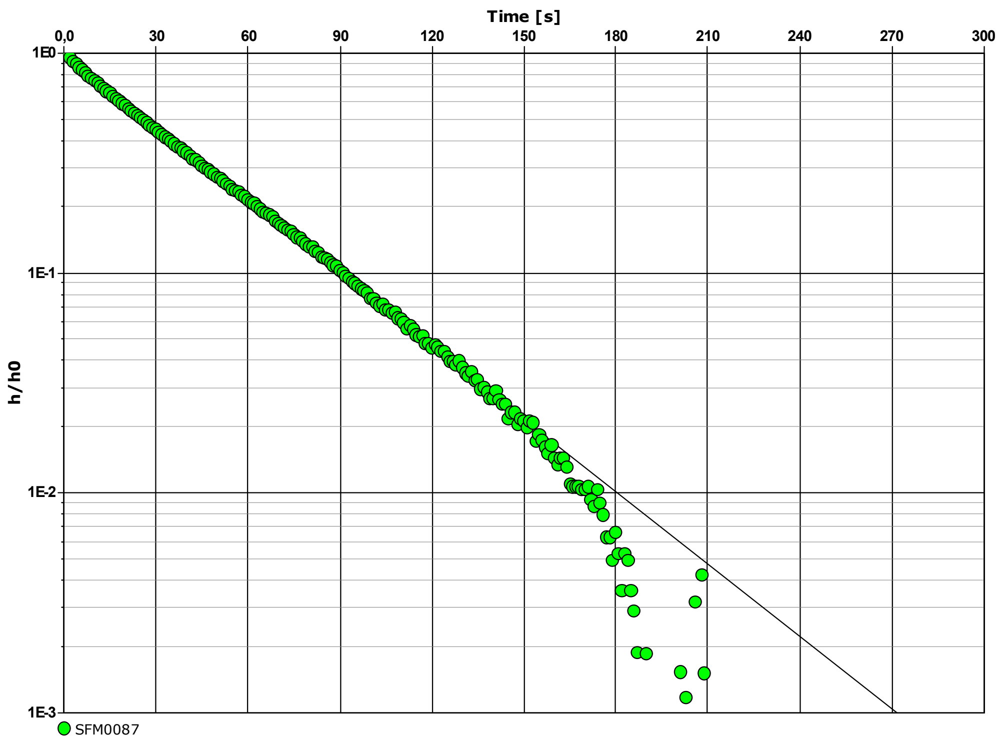

__Figure A1-32.__ Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in __SFM0087__ (Bouwer & Rice method).

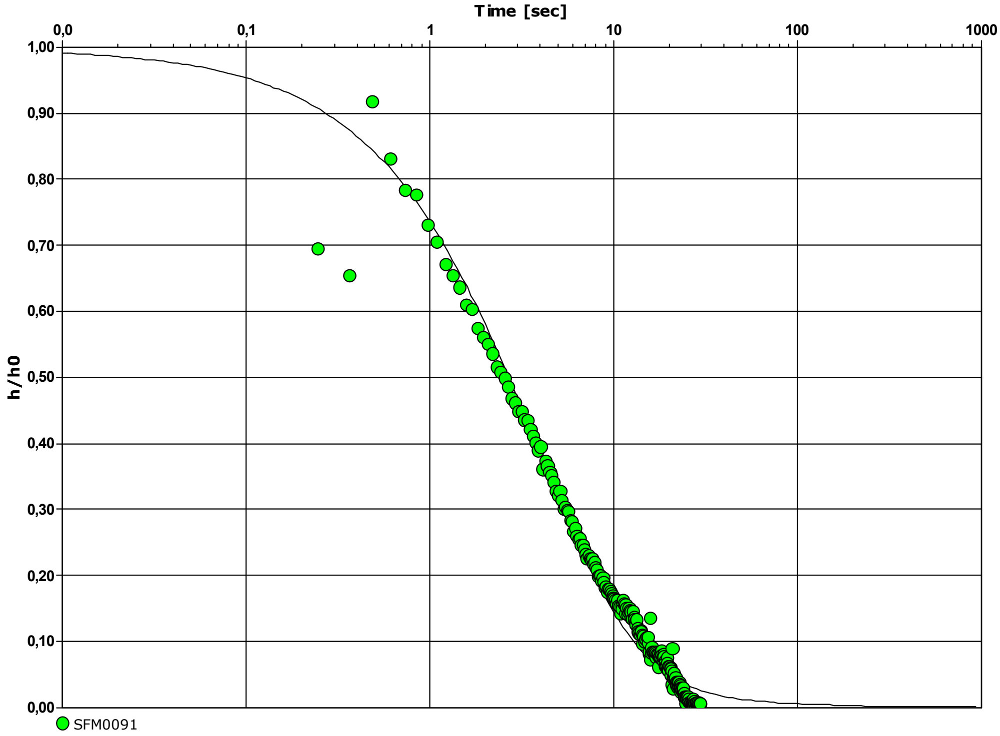

Figure A1-33. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0091*** *(Cooper et al. method).*

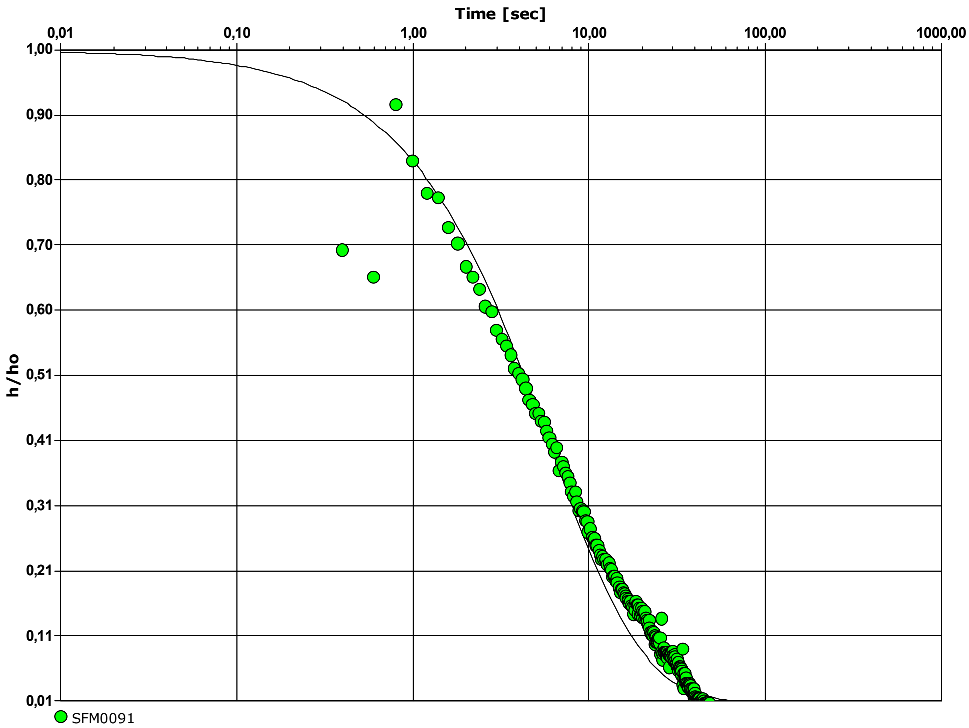

Figure A1-34. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0091*** *(Cooper et al. method, $S = 10^{-5}$).*

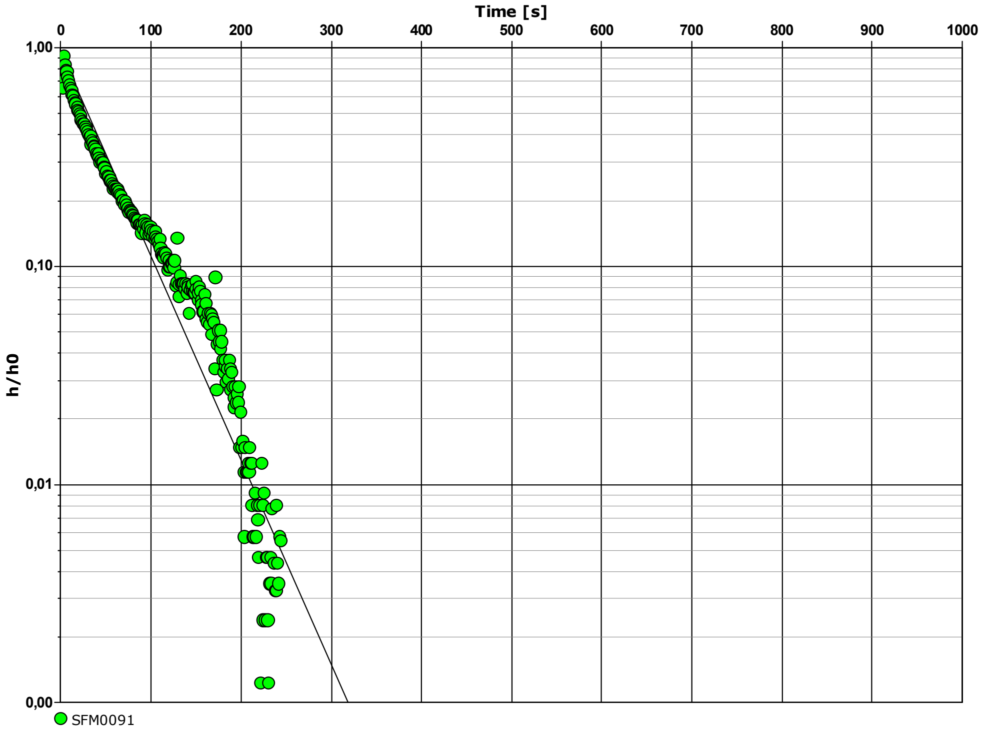

Figure A1-35. *Linear-log plot of the normalized displacement h/h$_0$ versus time for the falling-head test in* ***SFM0091*** *(Hvorslev method).*

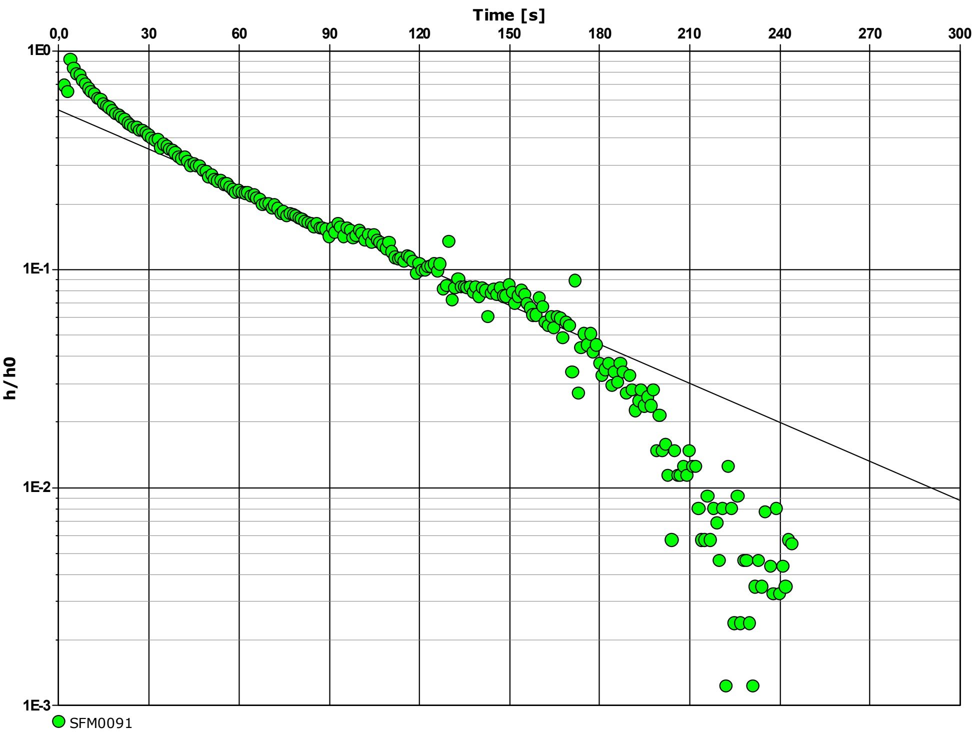

Figure A1-36. *Linear-log plot of the normalized displacement h/h$_0$ versus time for the falling-head test in* ***SFM0091*** *(Bouwer & Rice method).*

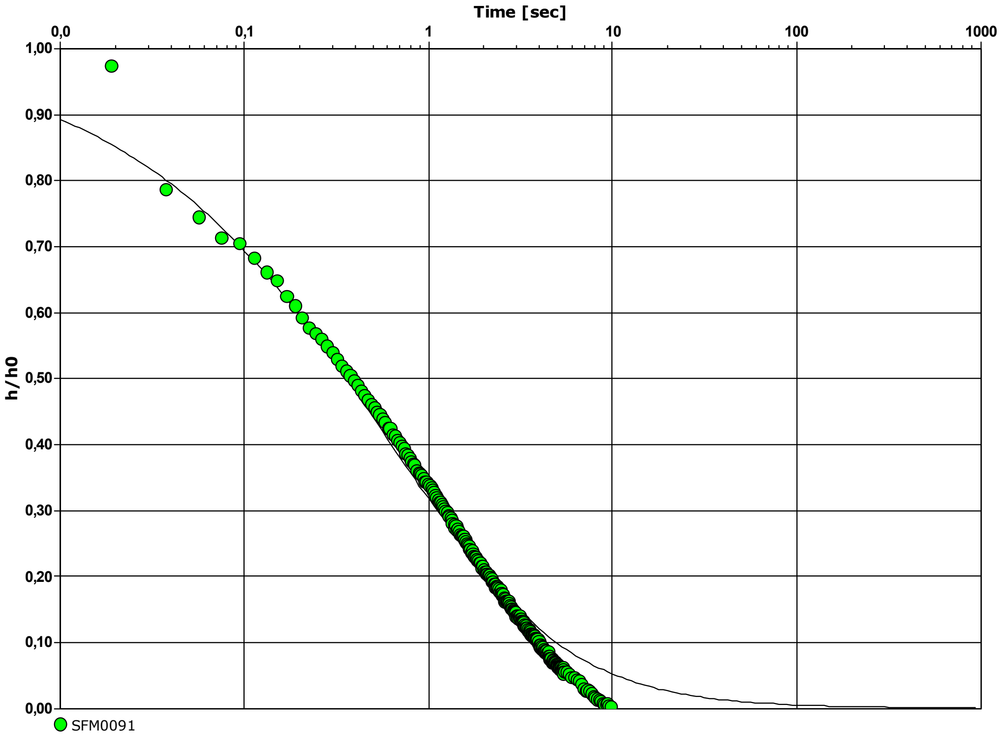

Figure A1-37. *Log-linear plot of the normalized displacement h/h$_0$ versus time for the rising-head test in* ***SFM0091*** *(Cooper et al. method).*

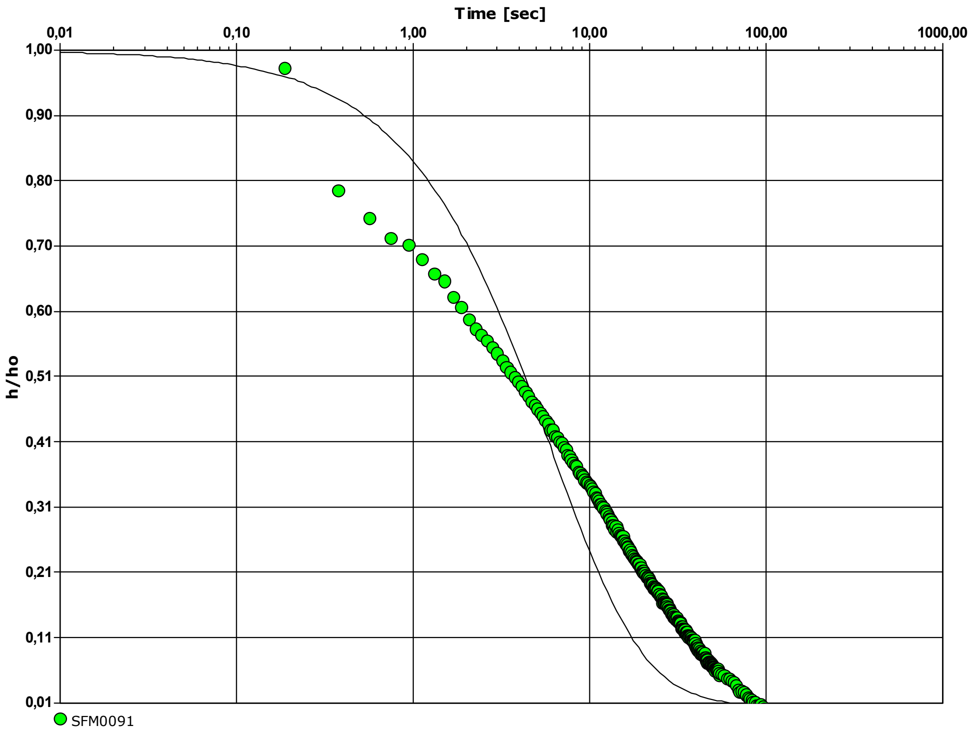

Figure A1-38. *Log-linear plot of the normalized displacement h/h$_0$ versus time for the rising-head test in* ***SFM0091*** *(Cooper et al. method, S = 10^{-5}).*

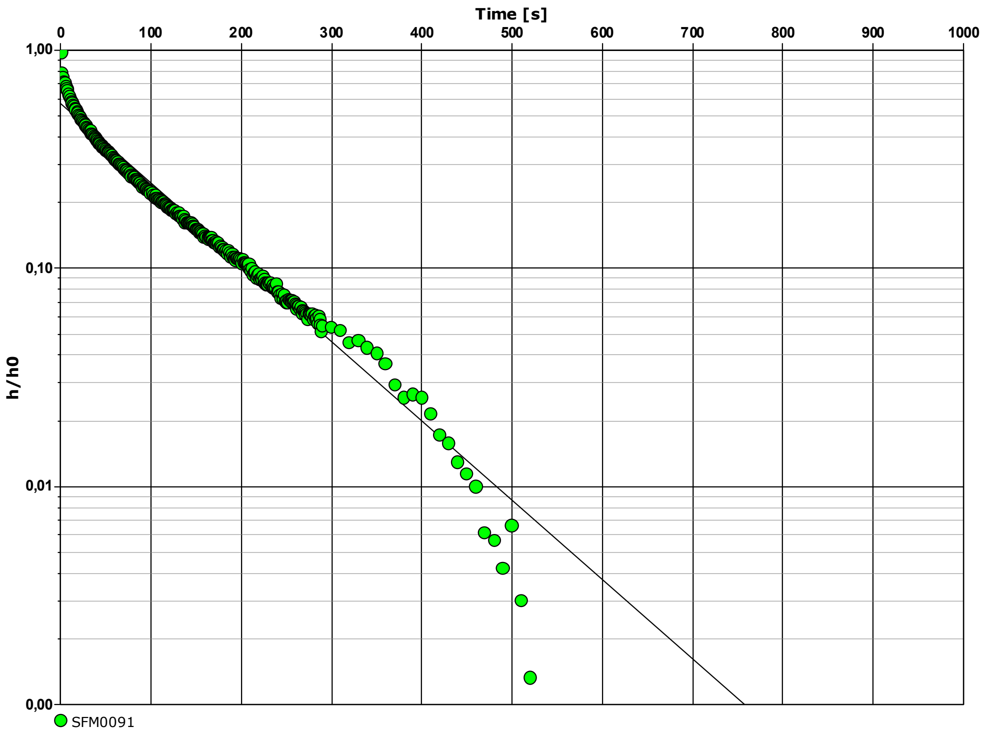

__Figure A1-39.__ Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in __SFM0091__ (Hvorslev method).

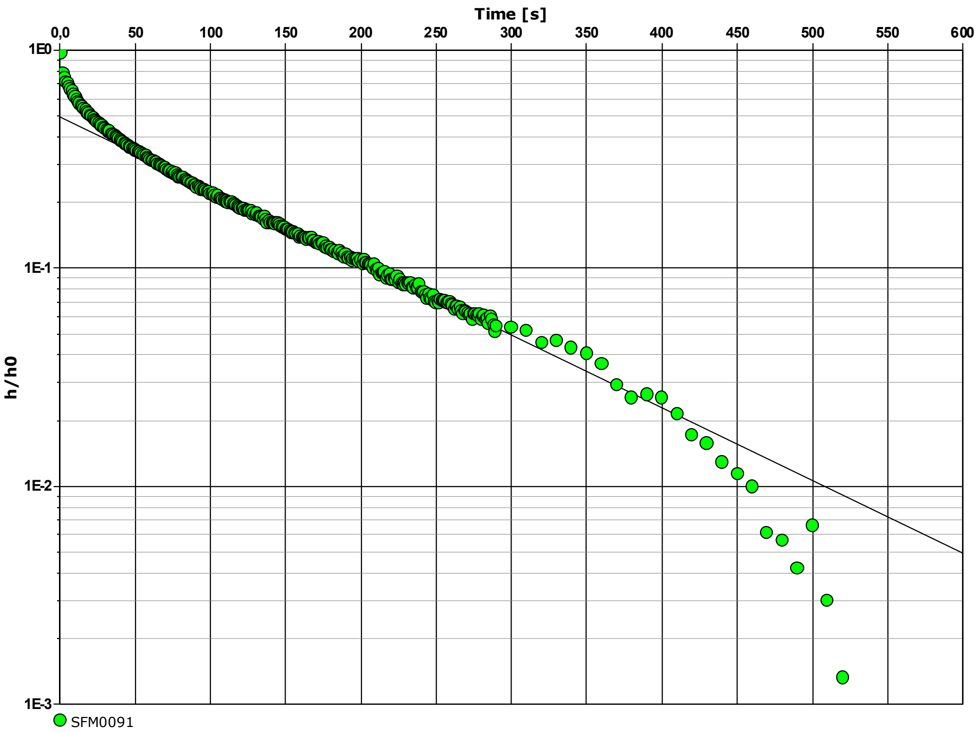

__Figure A1-40.__ Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in __SFM0091__ (Bouwer & Rice method).

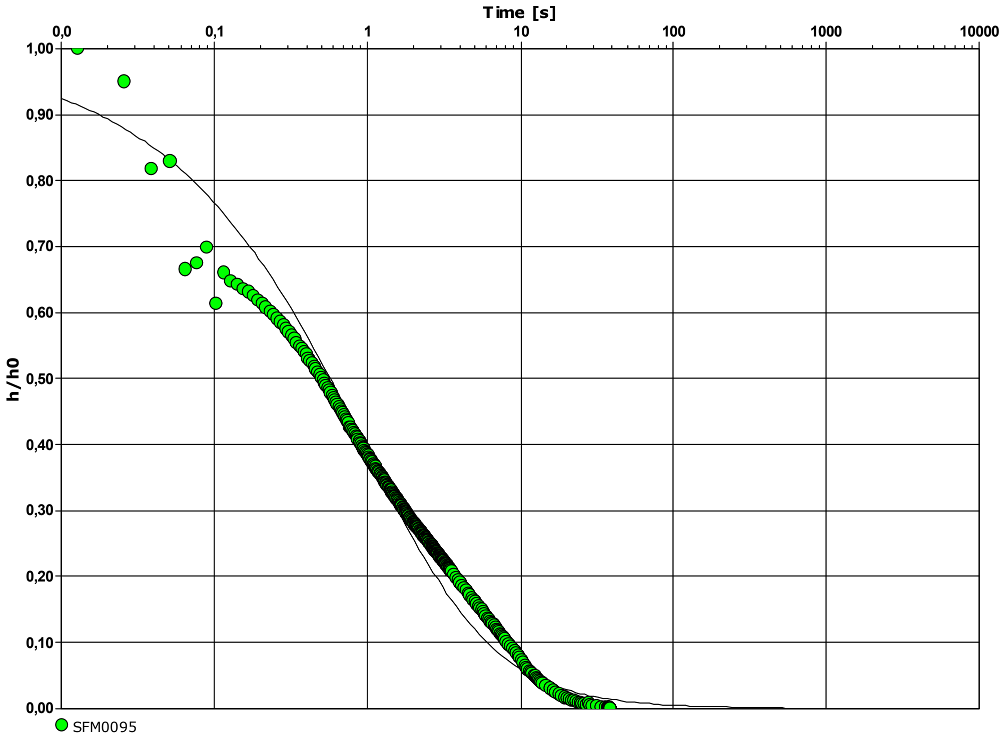

Figure A1-41. *Log-linear plot of the normalized displacement h/h$_0$ versus time for the falling-head test in* ***SFM0095*** *(Cooper et al. method).*

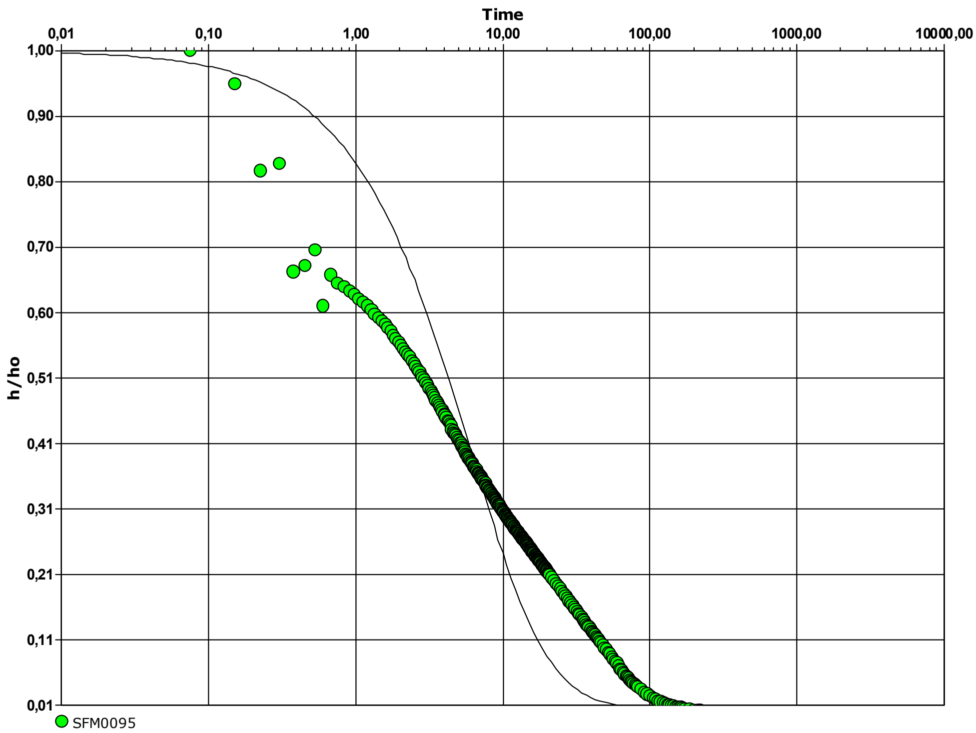

Figure A1-42. *Log-linear plot of the normalized displacement h/h$_0$ versus time for the falling-head test in* ***SFM0095*** *(Cooper et al. method, S = 10^{-5}).*

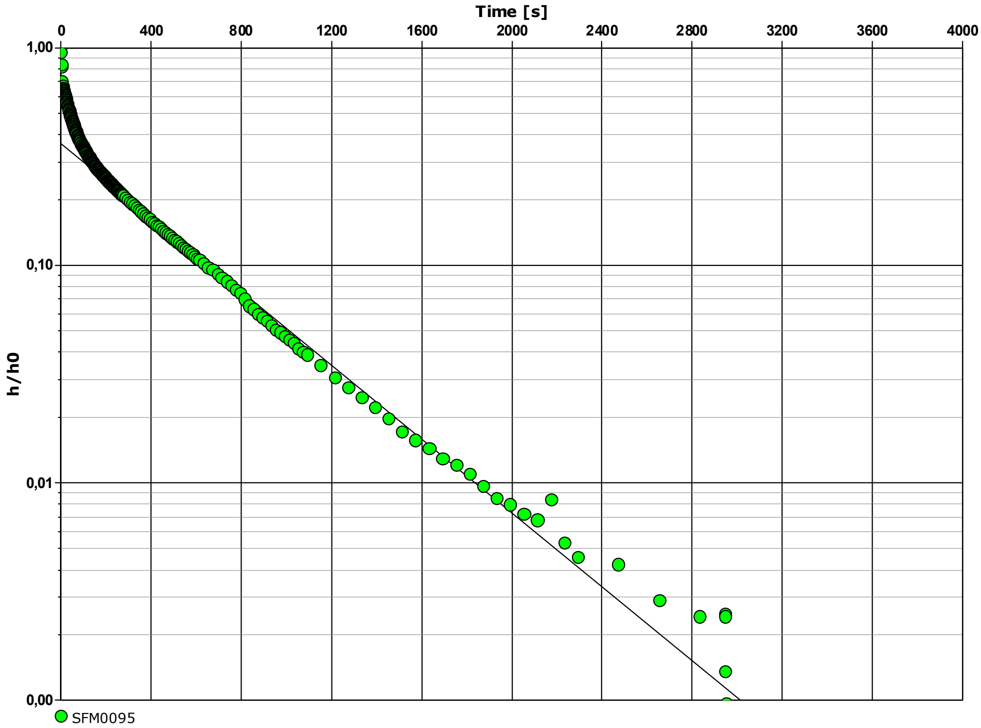

__Figure A1-43.__ Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in __SFM0095__ (Hvorslev method).

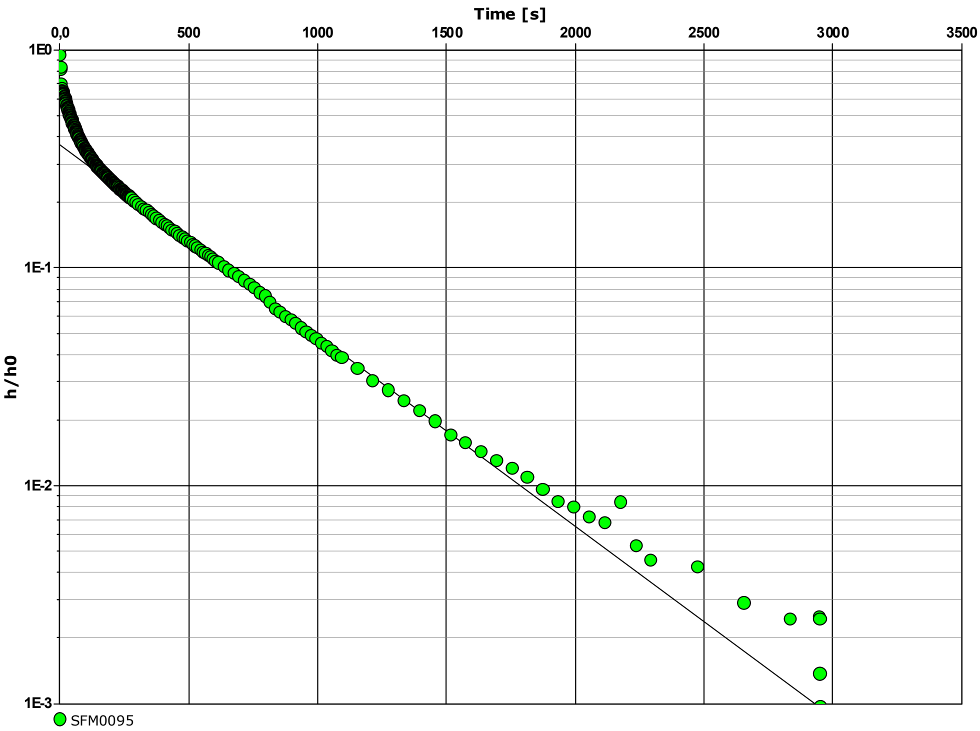

__Figure A1-44.__ Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in __SFM0095__ (Bouwer & Rice method).

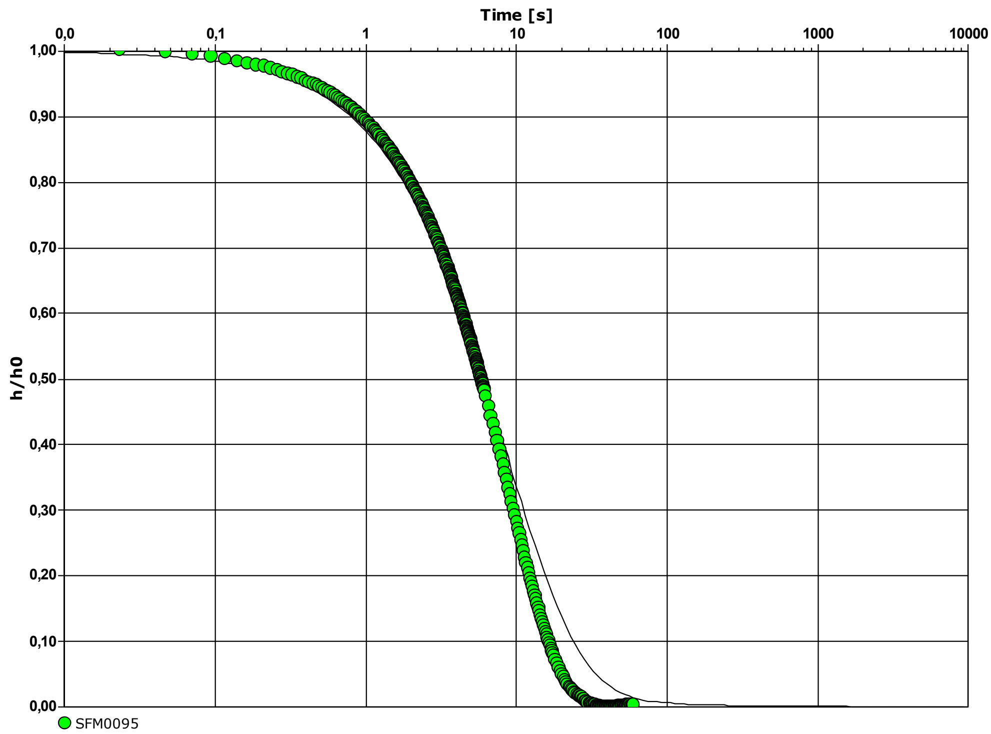

Figure A1-45. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0095** (Cooper et al. method).*

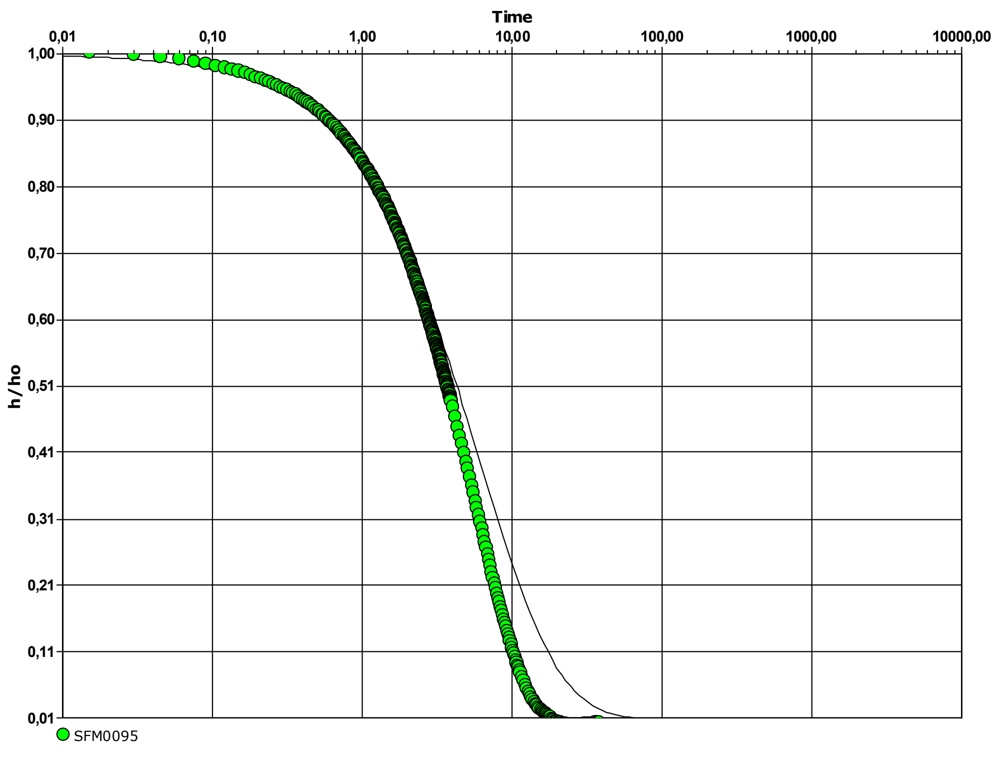

Figure A1-46. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0095** (Cooper et al. method, S = 10^{-5}).*

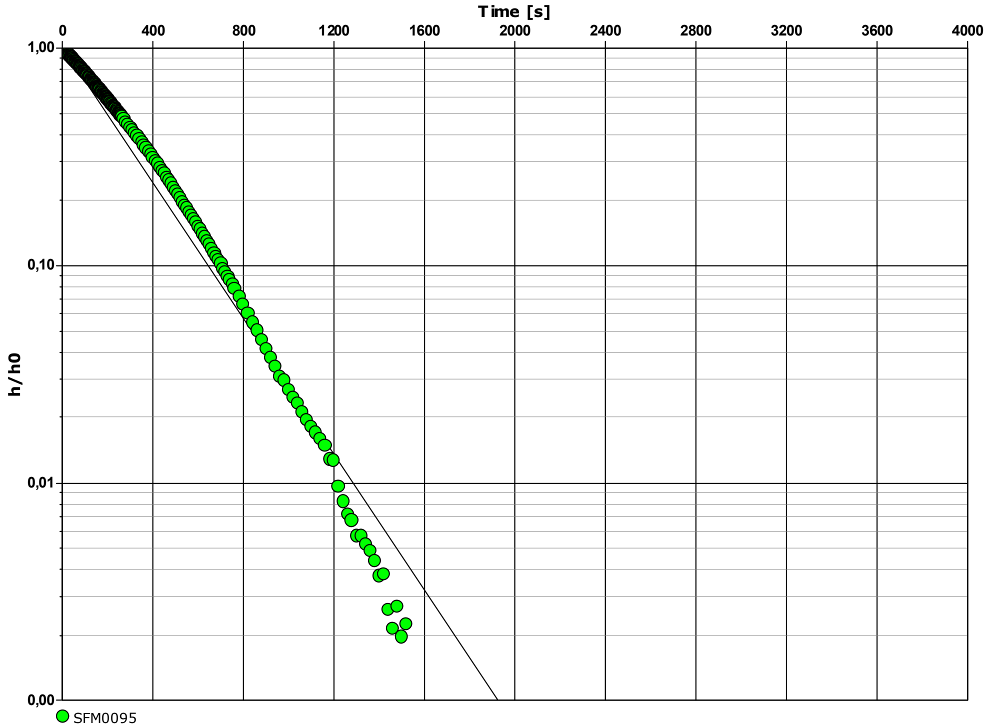

*Figure A1-47. Linear-log plot of the normalized displacement h/h₀ versus time for the rising-head test in **SFM0095** (Hvorslev method).*

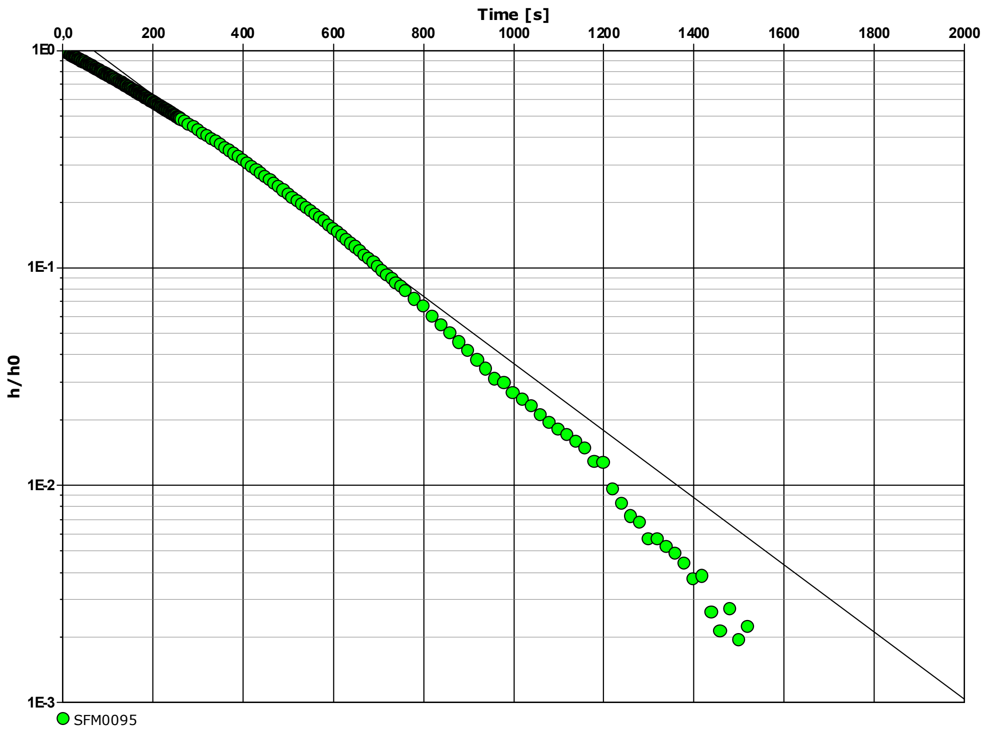

*Figure A1-48. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0095** (Bouwer & Rice method).*

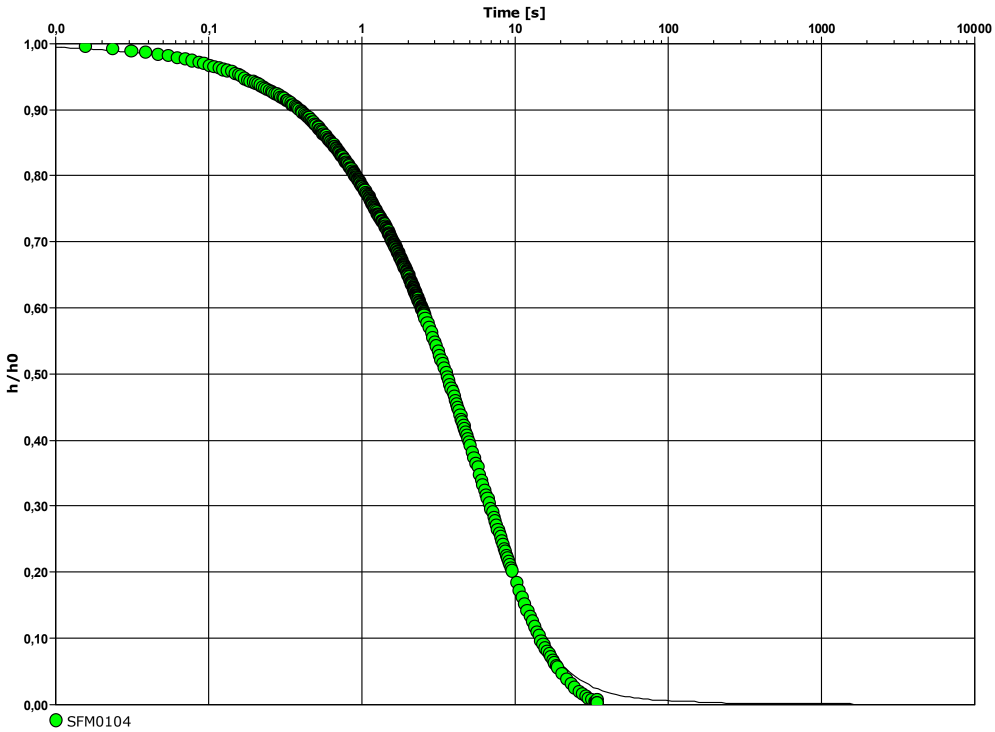

Figure A1-49. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0104** (Cooper et al. method).*

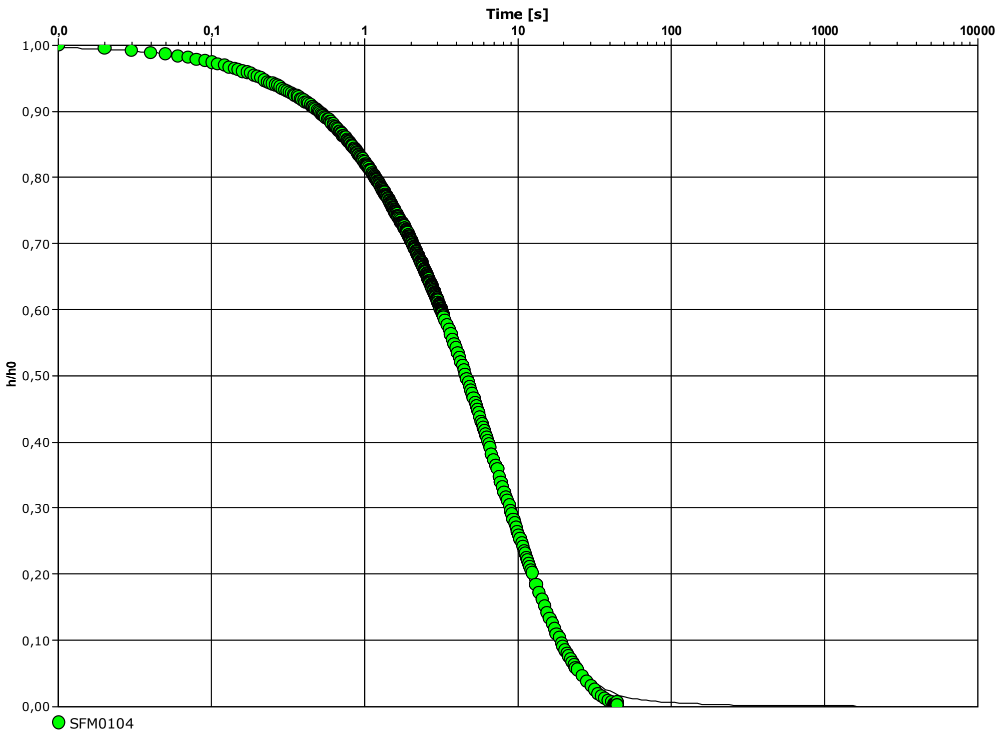

Figure A1-50. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0104** (Cooper et al. method, $S = 10^{-5}$).*

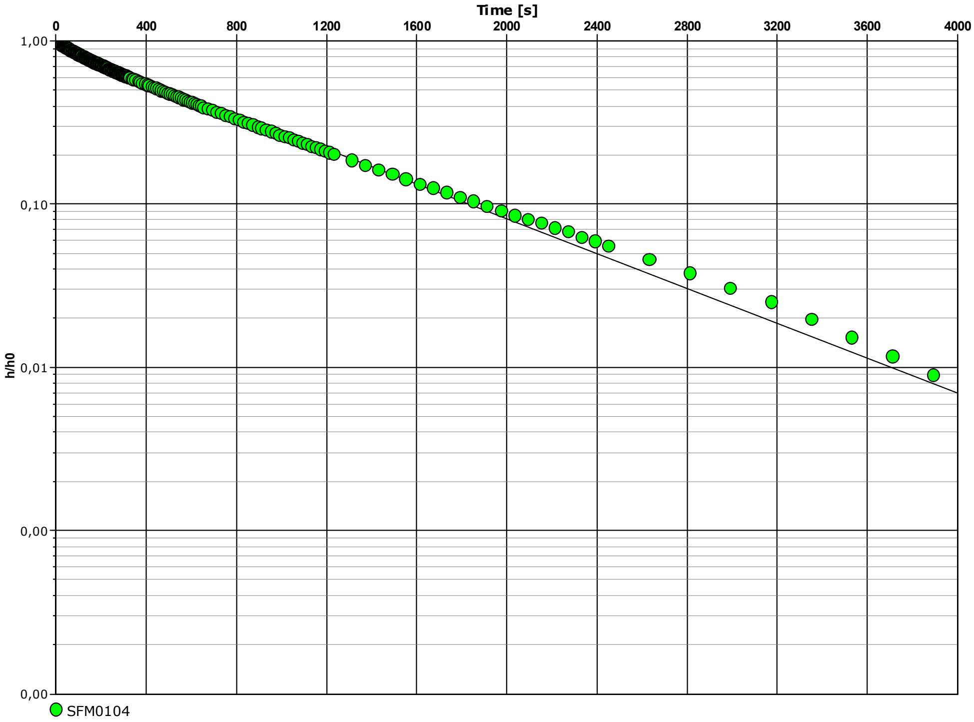

Figure A1-51. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0104** (Hvorslev method).*

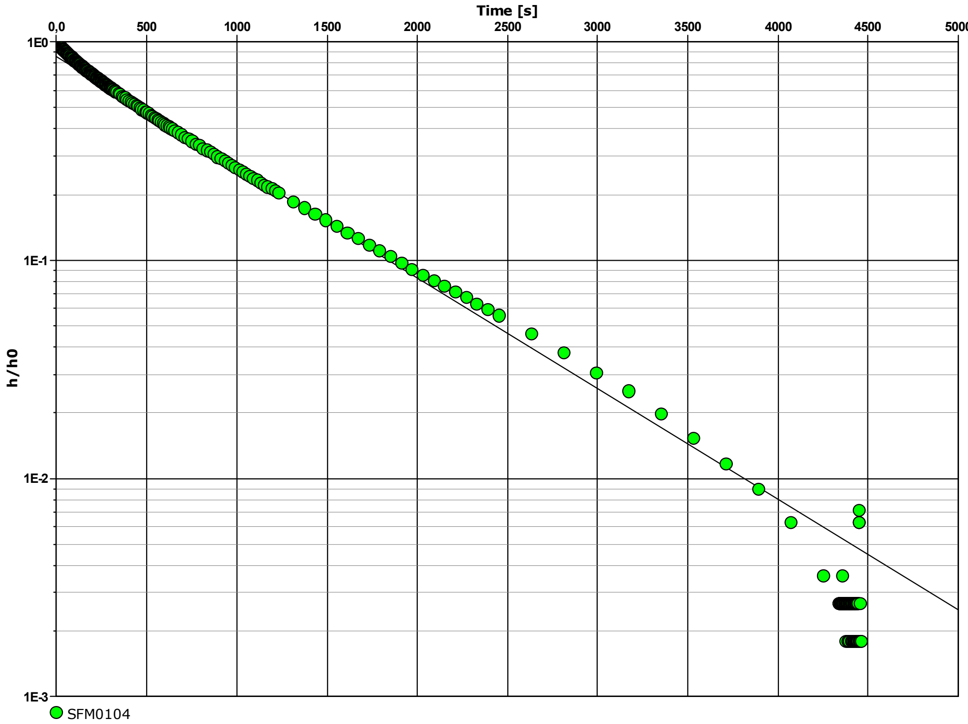

Figure A1-52. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0104** (Bouwer & Rice method).*

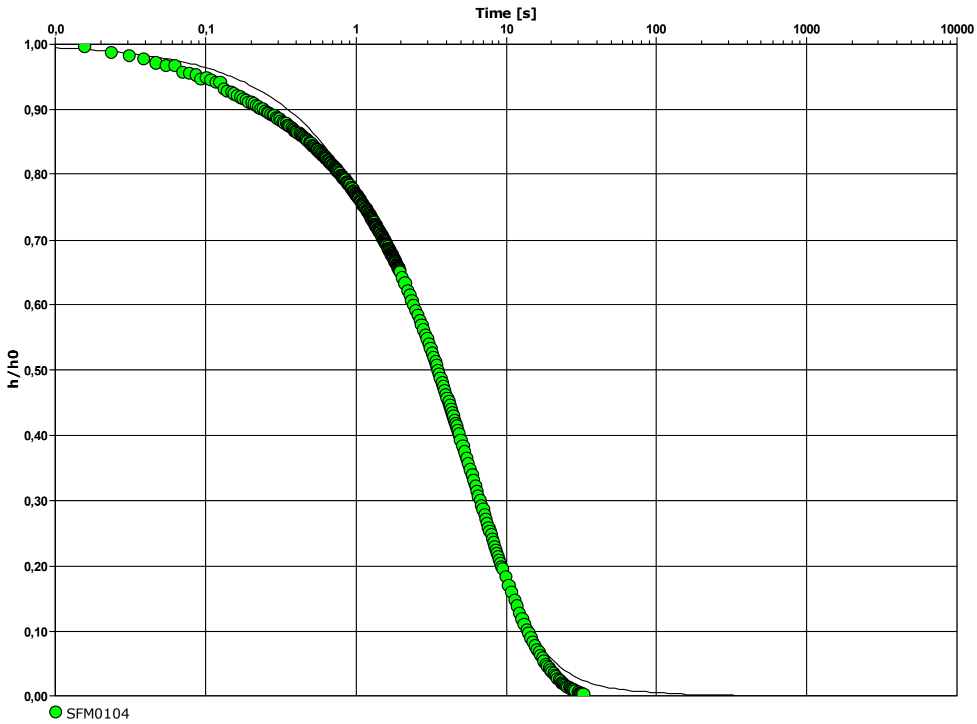

Figure A1-53. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0104*** *(Cooper et al. method).*

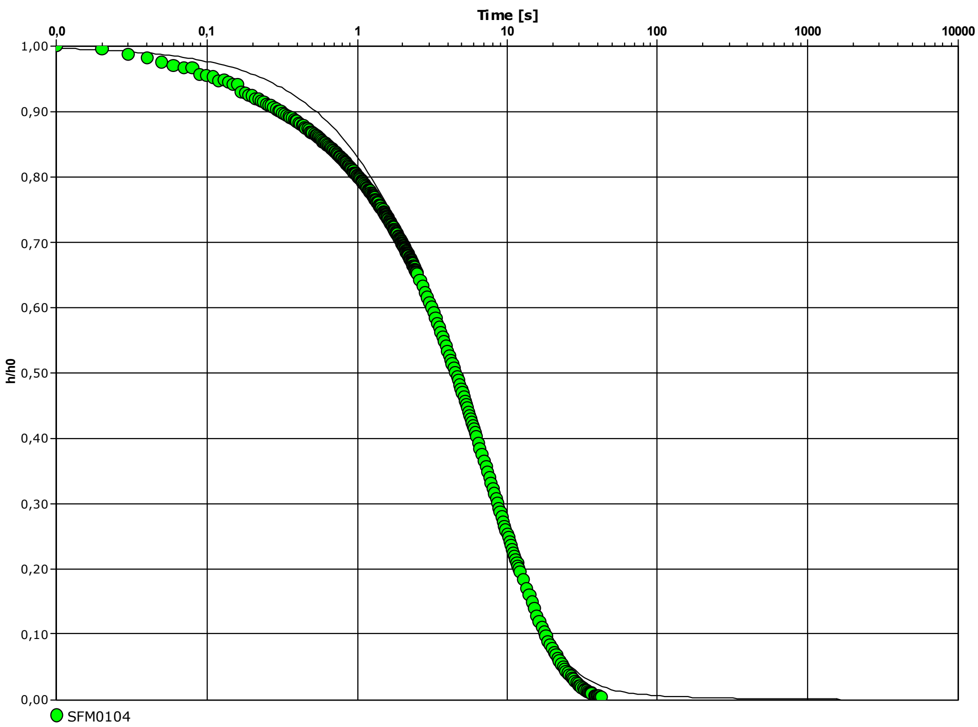

Figure A1-54. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0104*** *(Cooper et al. method, $S = 10^{-5}$).*

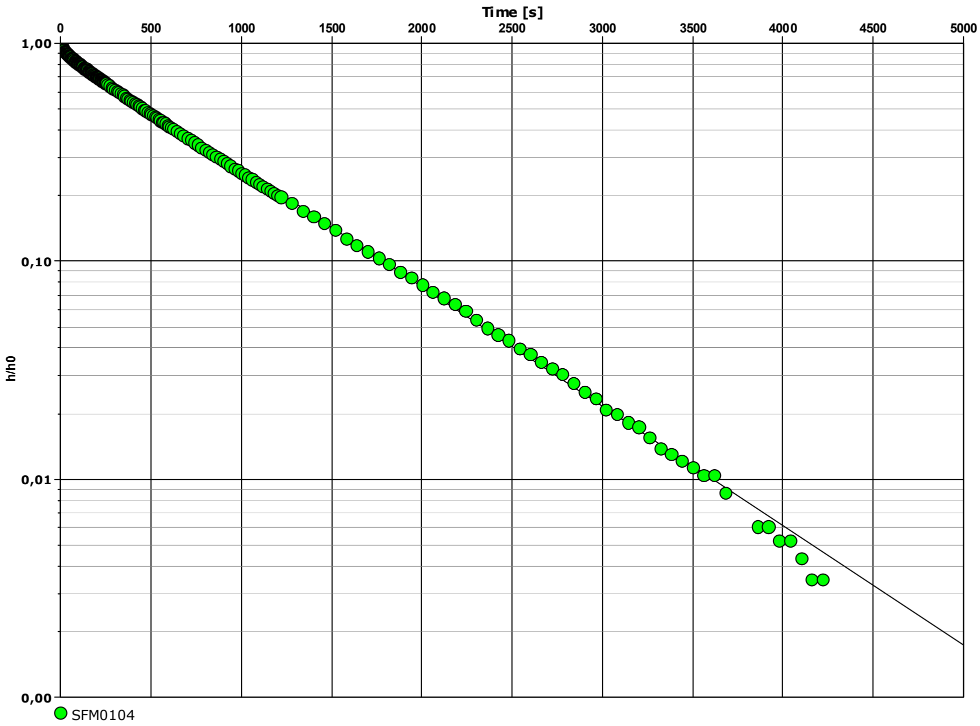

Figure A1-55. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in ***SFM0104***(Hvorslev method).

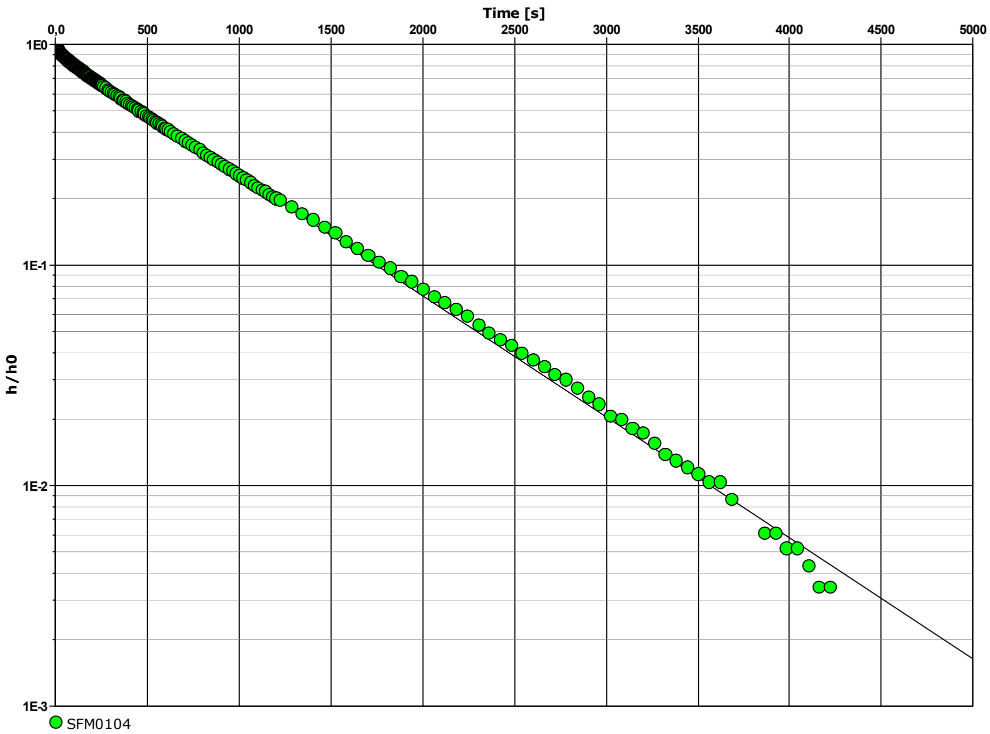

Figure A1-56. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in ***SFM0104*** (Bouwer & Rice method).

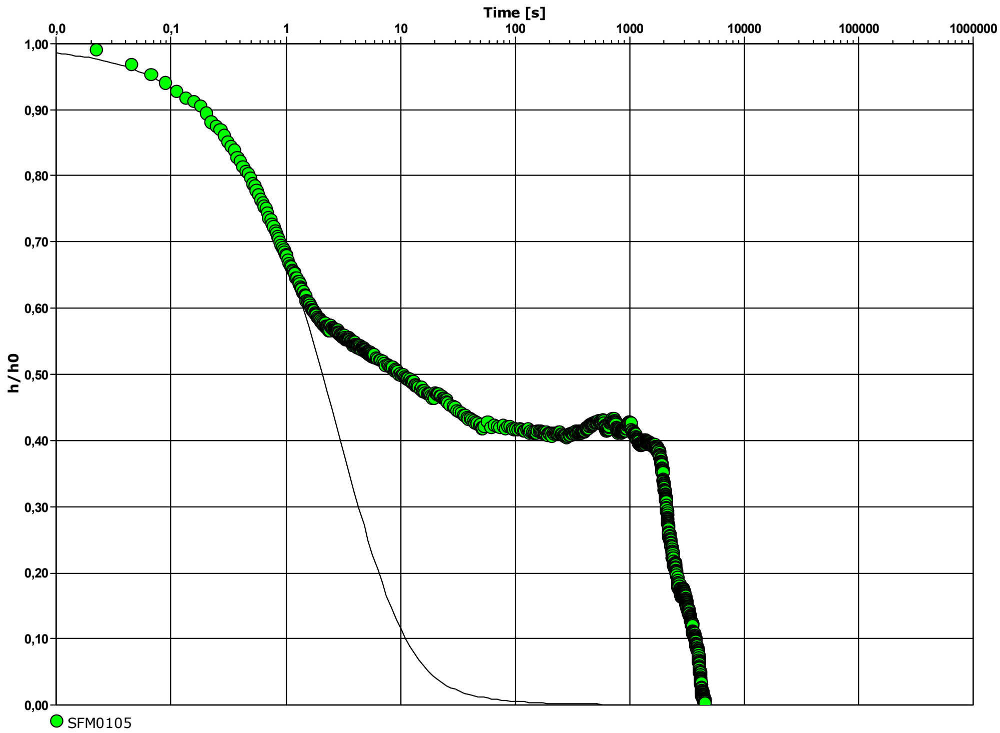

Figure A1-57. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0105*** *(Cooper et al. method).*

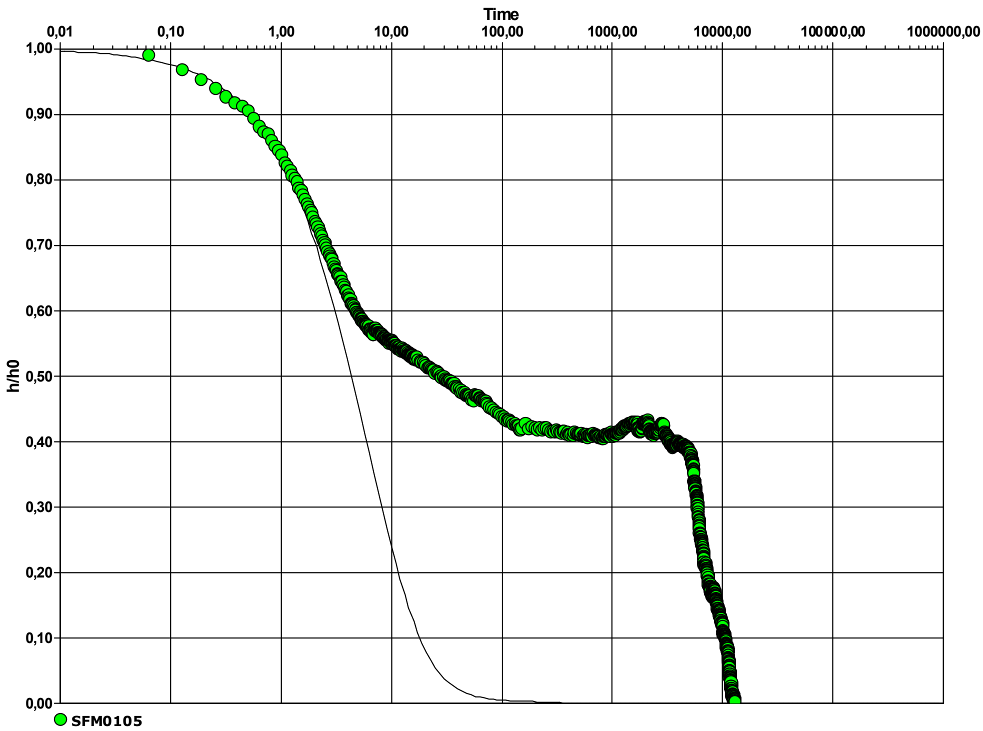

Figure A1-58. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0105*** *(Cooper et al. method, $S = 10^{-5}$).*

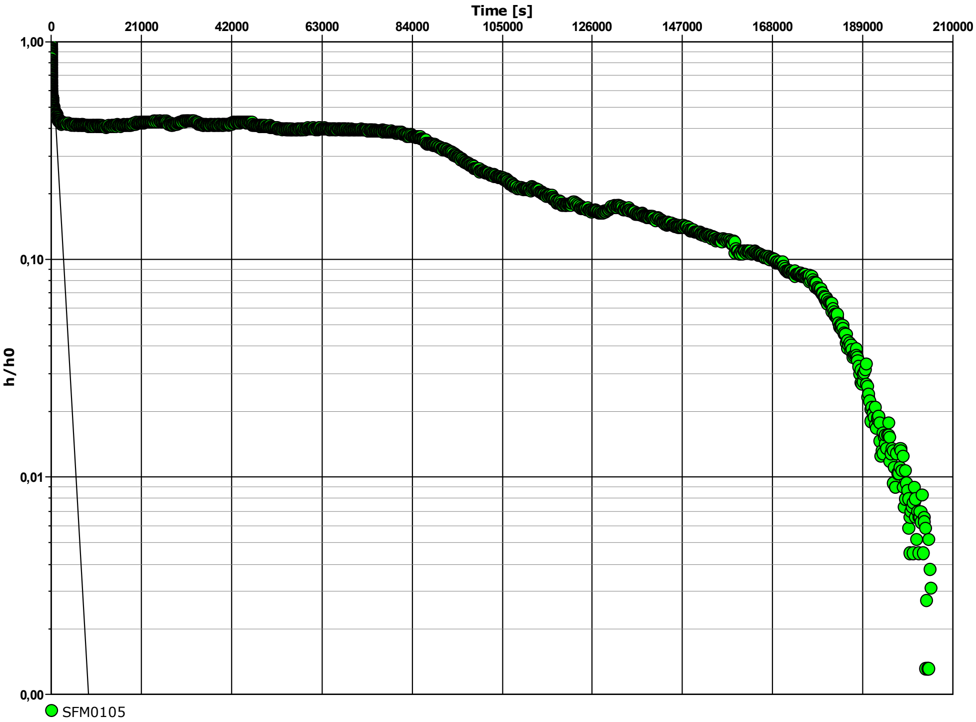

Figure A1-59. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in ***SFM0105***(Hvorslev method).

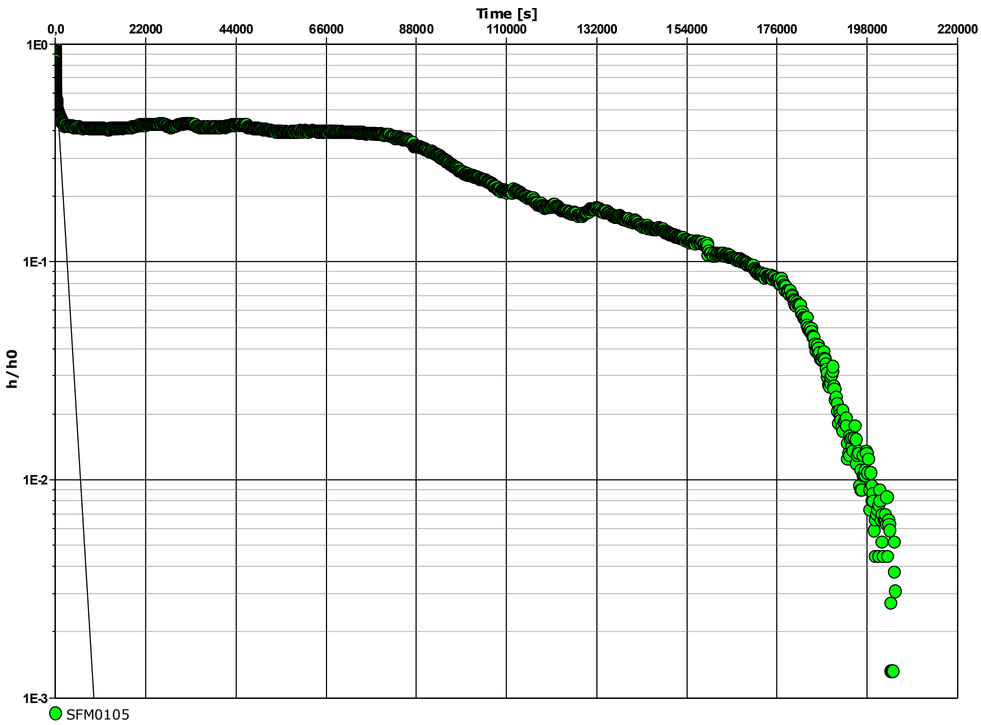

Figure A1-60. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in ***SFM0105*** (Bouwer & Rice method).

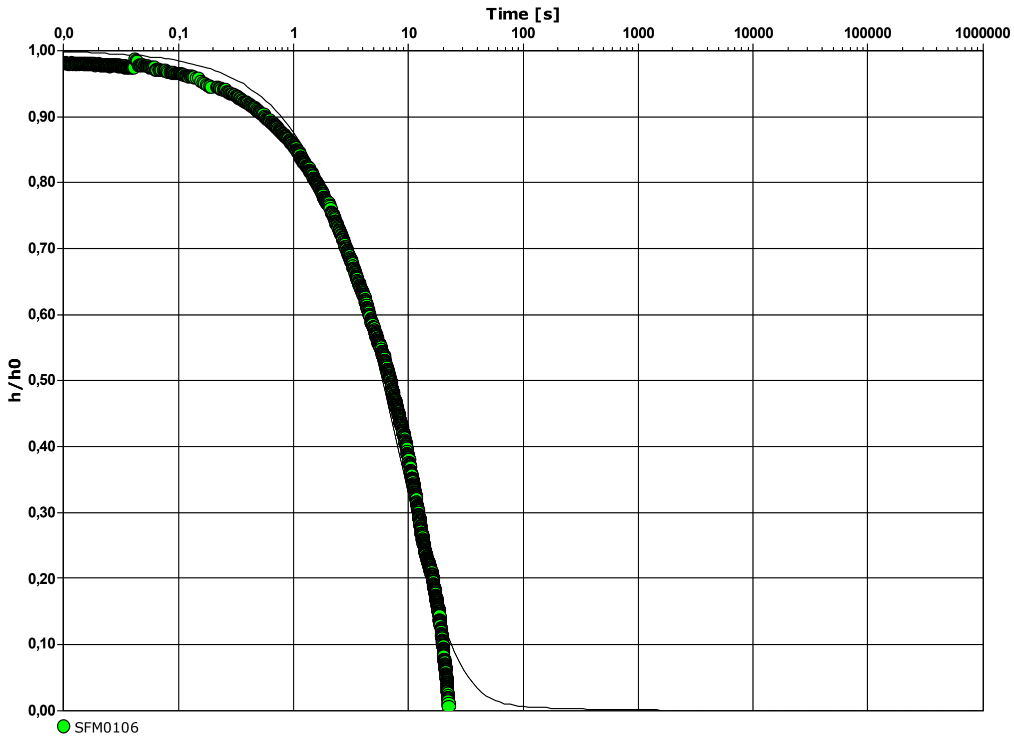

Figure A1-61. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0106*** *(Cooper et al. method)****.***

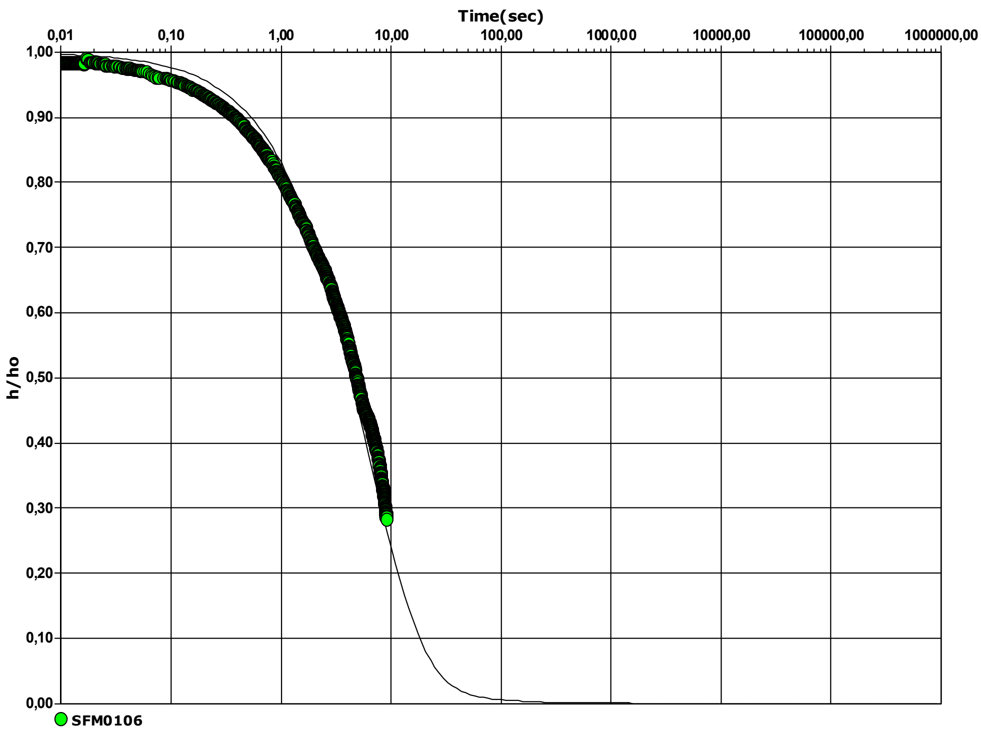

Figure A1-62. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0106*** *(Cooper et al. method, S = 10^{-5}).*

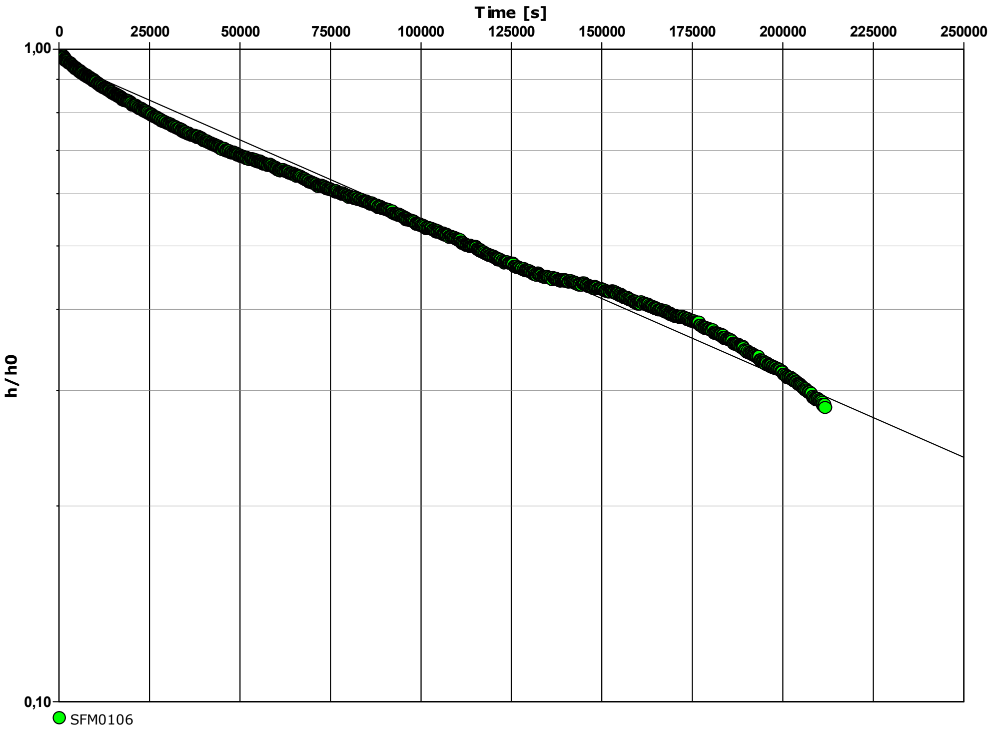

Figure A1-63. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the falling-head test in* ***SFM0106*** *(Hvorslev method).*

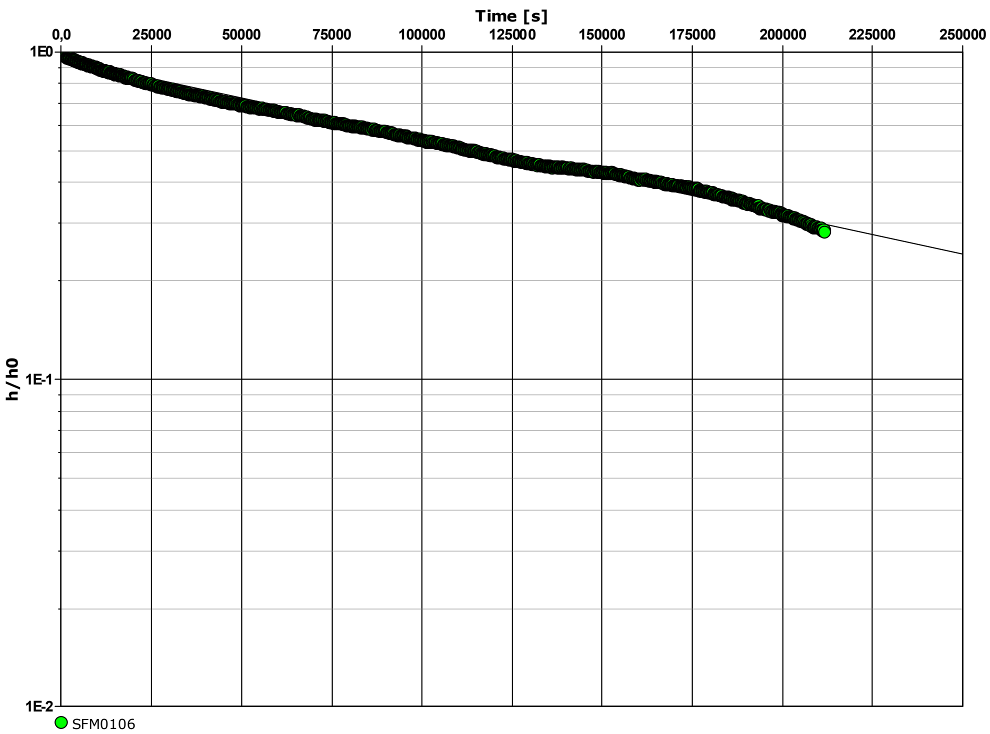

Figure A1-64. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the falling-head test in* ***SFM0106*** *(Bouwer & Rice method).*

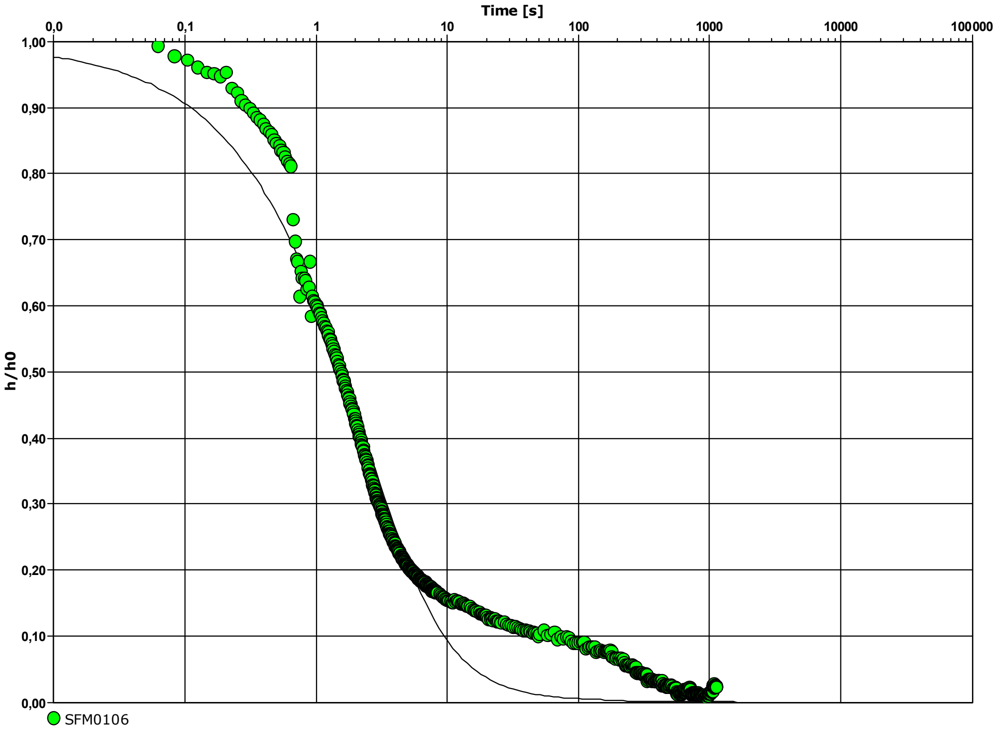

Figure A1-65. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0106** (Cooper et al. method).*

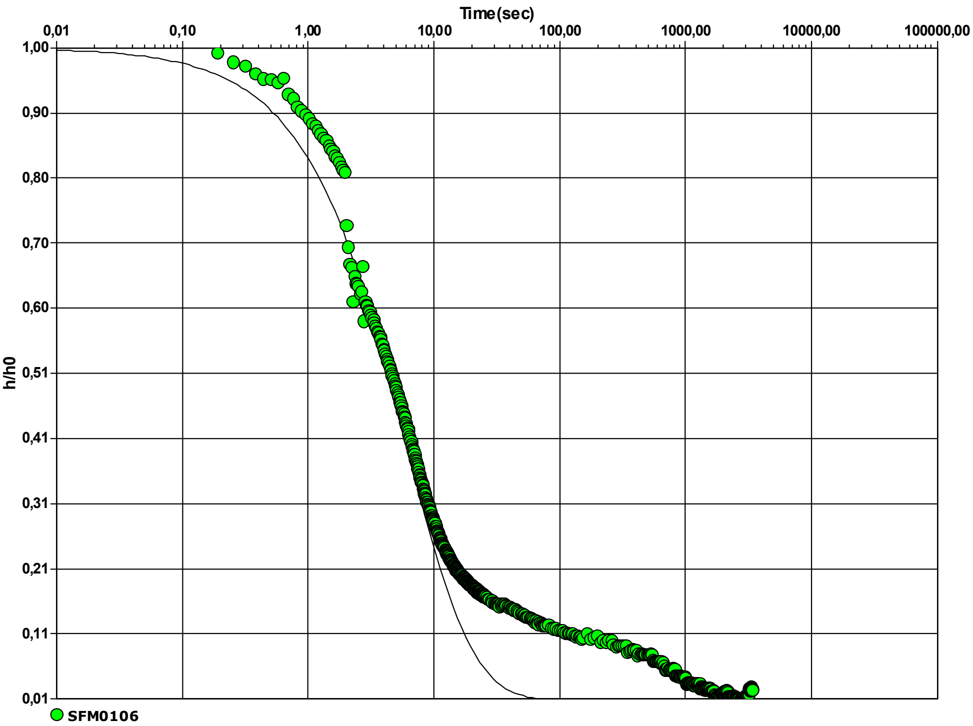

Figure A1-66. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0106** (Cooper et al. method, $S = 10^{-5}$).*

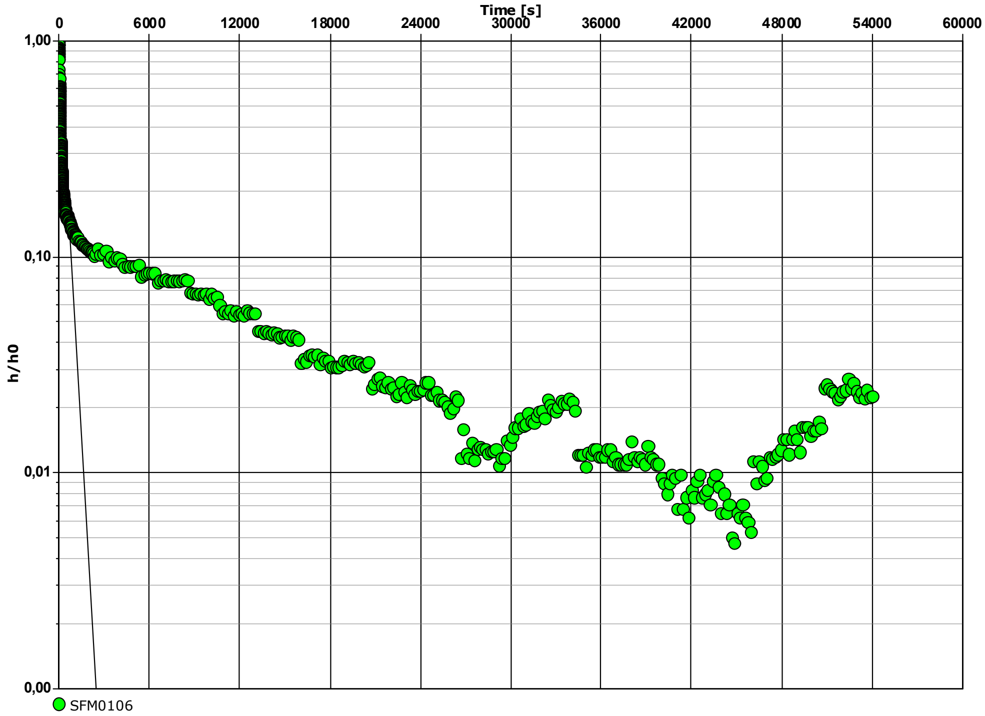

Figure A1-67. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the rising-head test in* ***SFM0106*** *(Hvorslev method).*

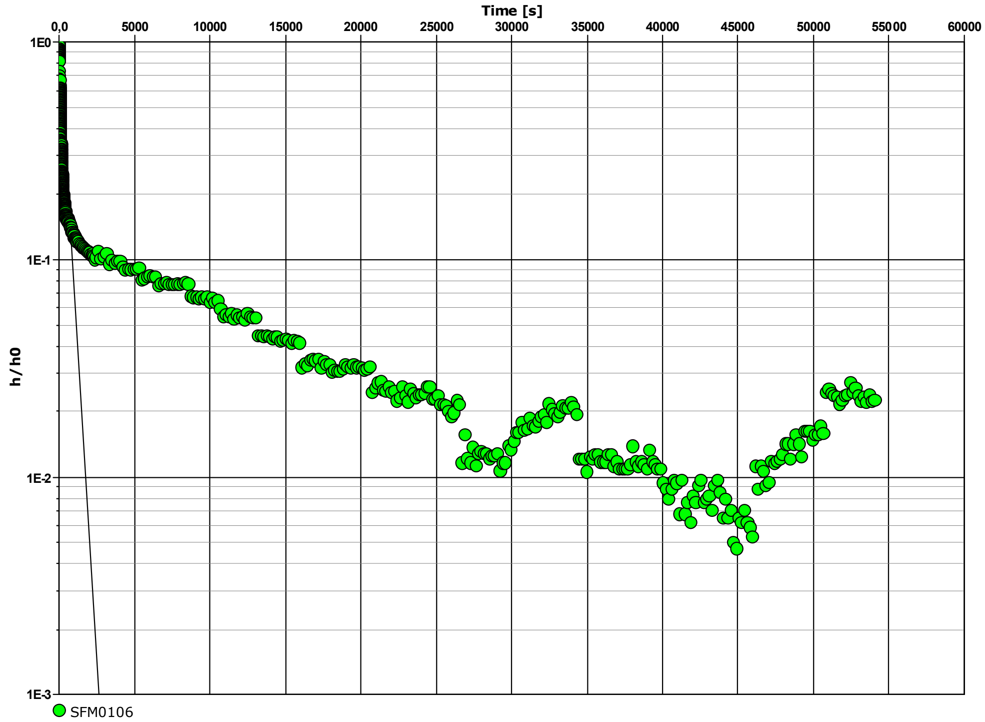

Figure A1-68. *Linear-log plot of the normalized displacement* h/h_0 *versus time for the rising-head test in* ***SFM0106*** *(Bouwer & Rice method).*

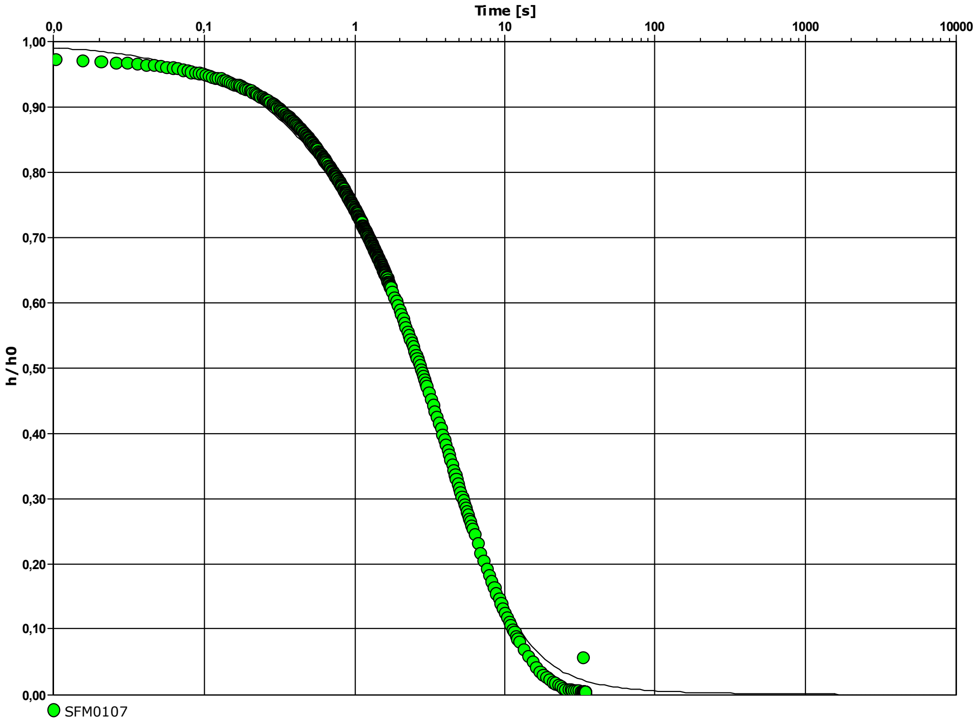

Figure A1-69.** Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM00107** (Cooper et al. method).**

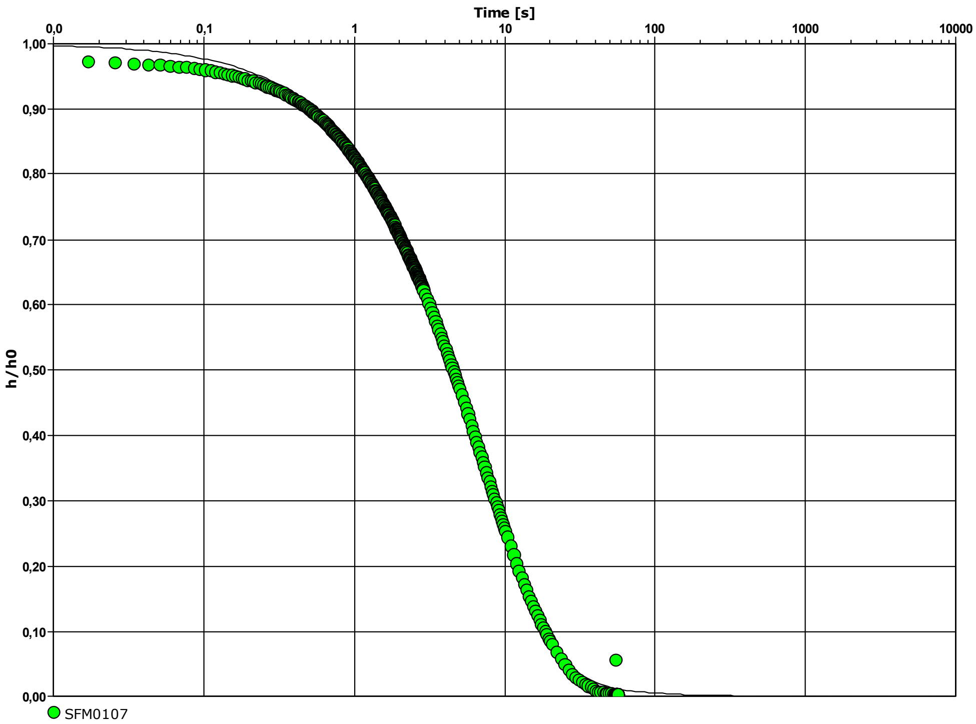

***Figure A1-70.** Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0107** (Cooper et al. method, $S = 10^{-5}$).*

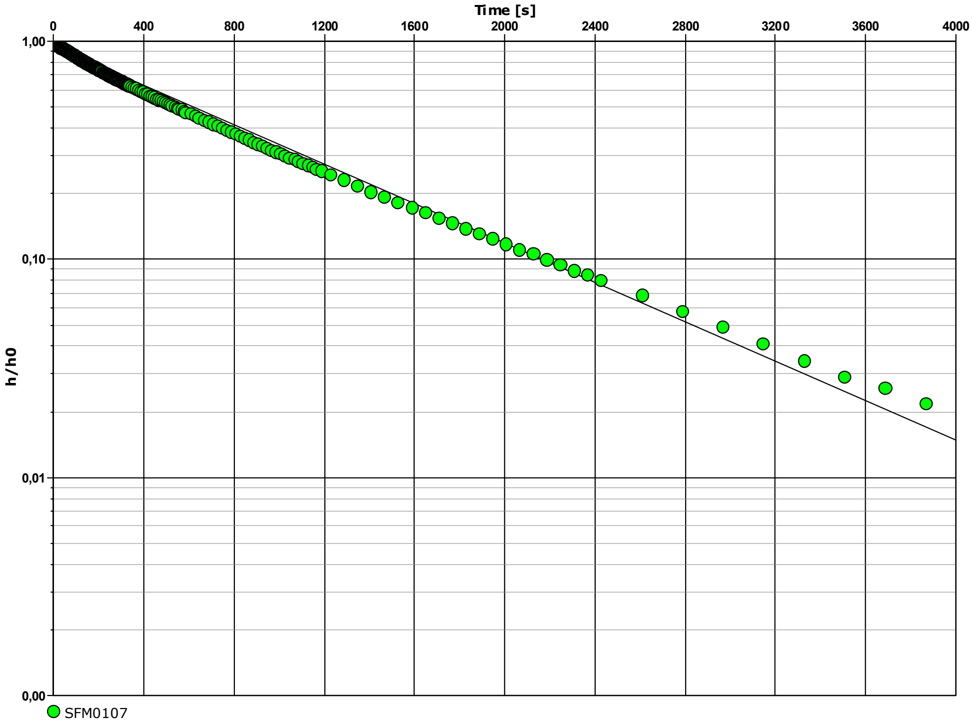

Figure A1-71. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0107*** *(Hvorslev method).*

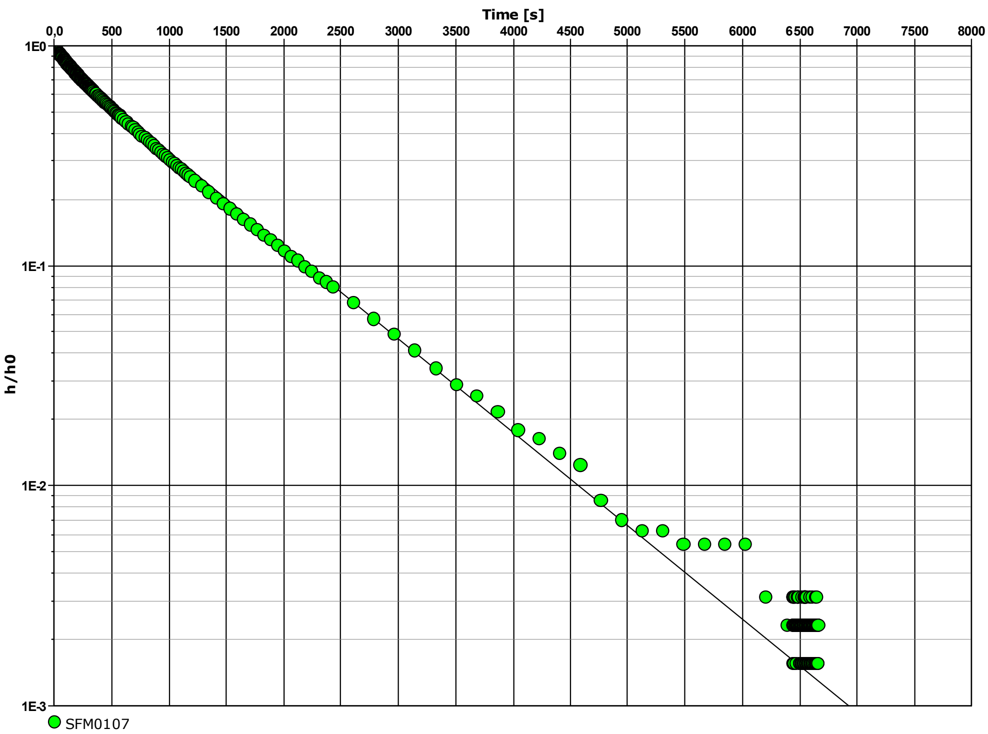

Figure A1-72. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0107*** *(Bouwer & Rice method).*

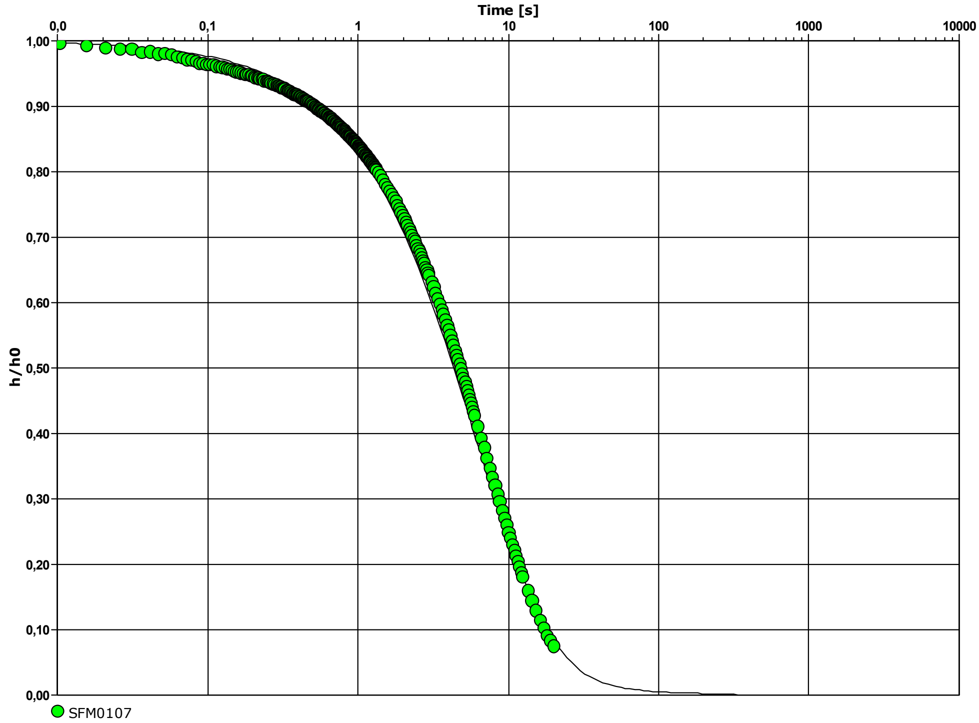

Figure A1-73. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0107** (Cooper et al. method).*

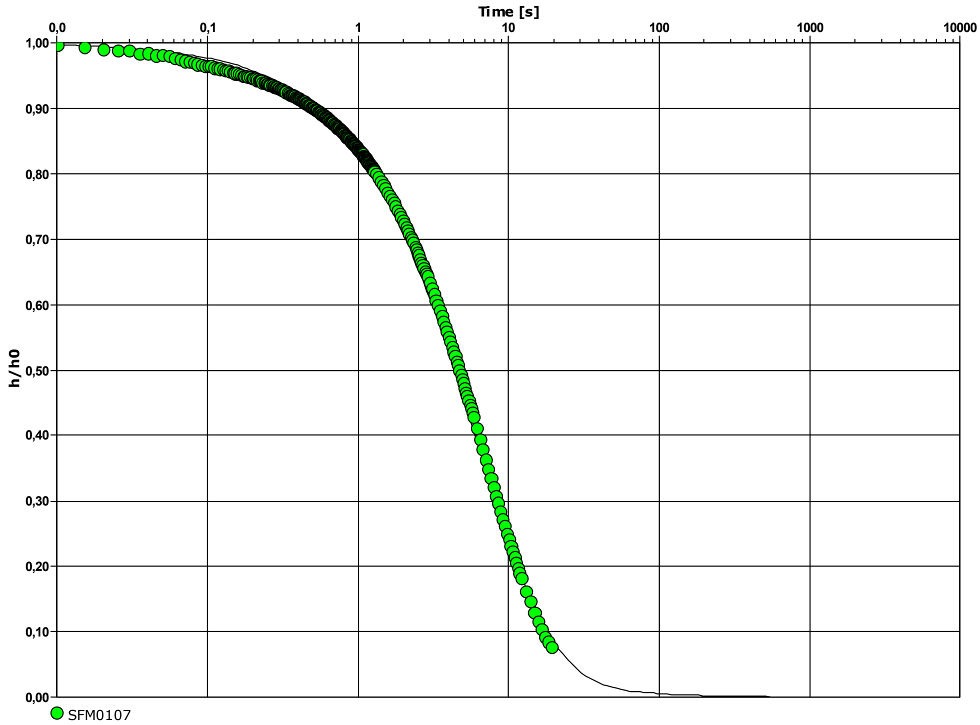

Figure A1-74. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0107** (Cooper et al. method, $S = 10^{-5}$)*

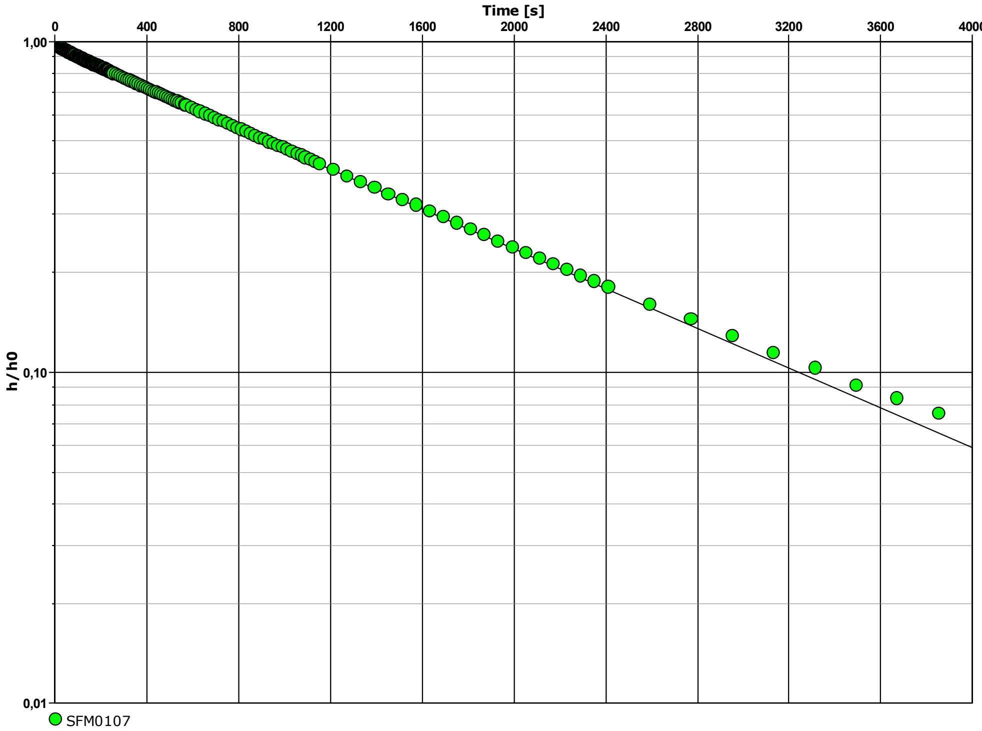

Figure A1-75. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0107*** *(Hvorslev method).*

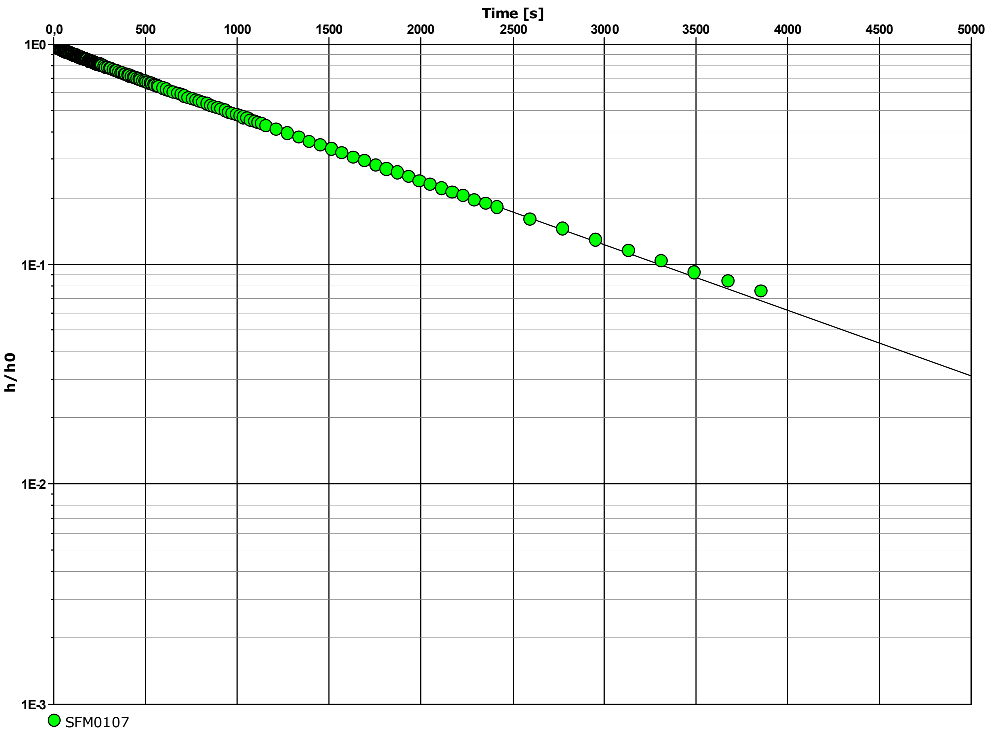

Figure A1-76. *Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0107*** *(Bouwer & Rice method).*

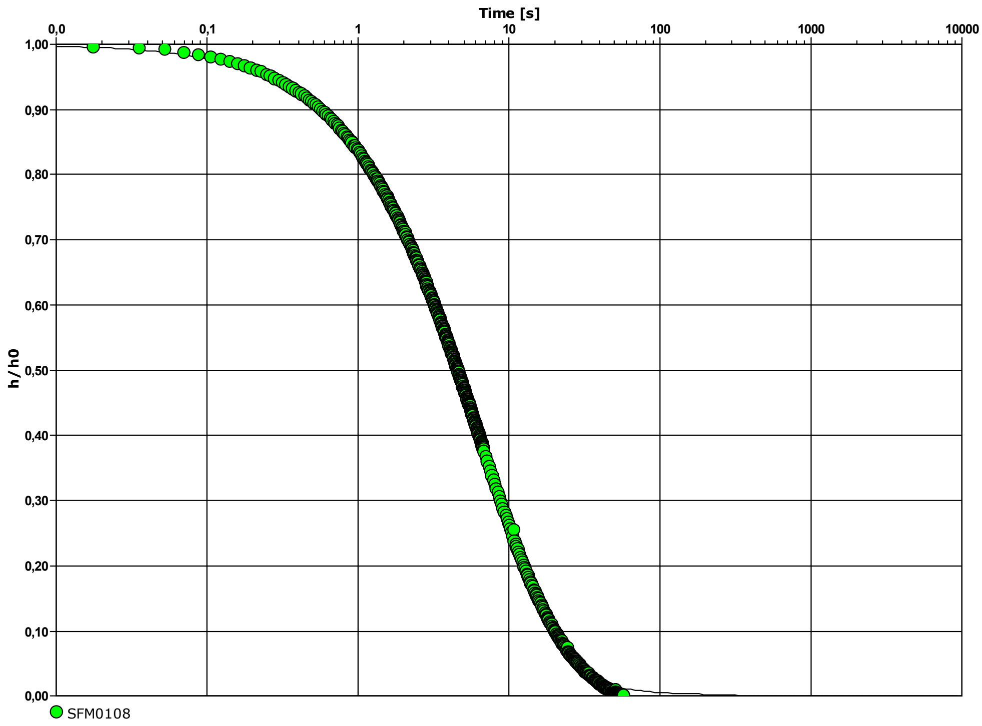

Figure A1-77. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0108*** *(Cooper et al. method).*

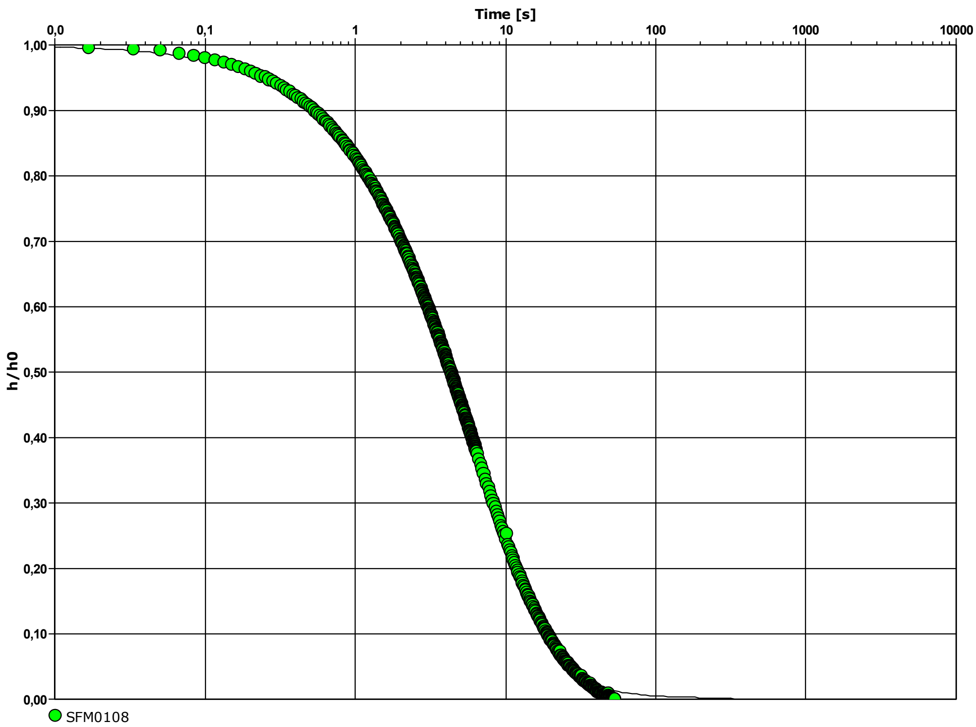

Figure A1-78. *Log-linear plot of the normalized displacement h/h_0 versus time for the falling-head test in* ***SFM0108*** *(Cooper et al. method, $S = 10^{-5}$).*

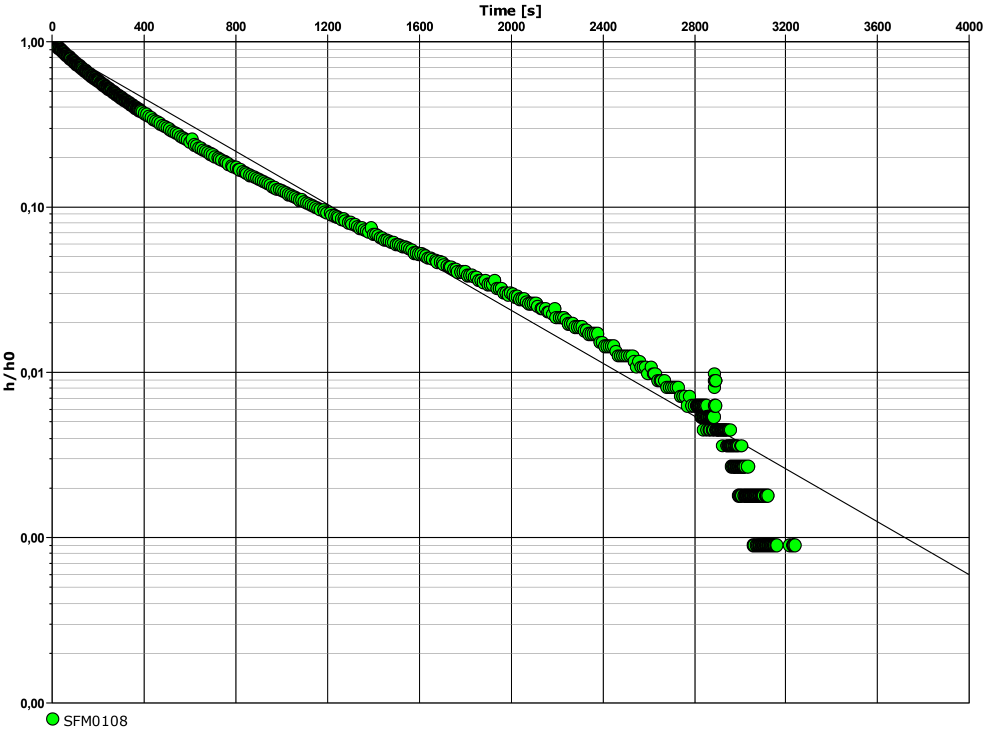

Figure A1-79. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0108** (Hvorslev method).*

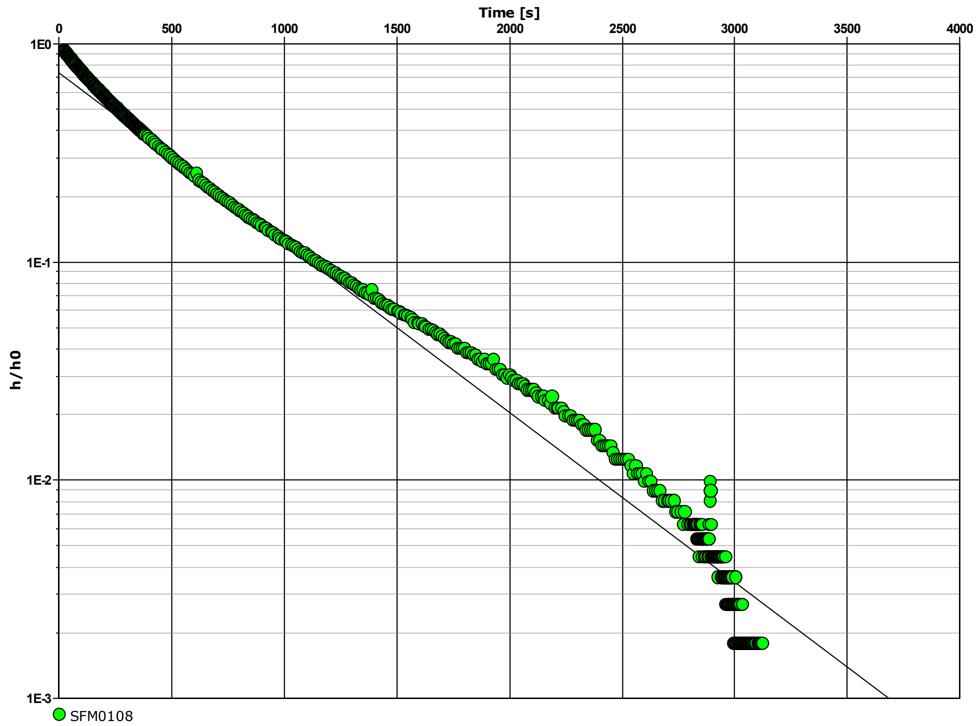

Figure A1-80. *Linear-log plot of the normalized displacement h/h_0 versus time for the falling-head test in **SFM0108** (Bouwer & Rice method).*

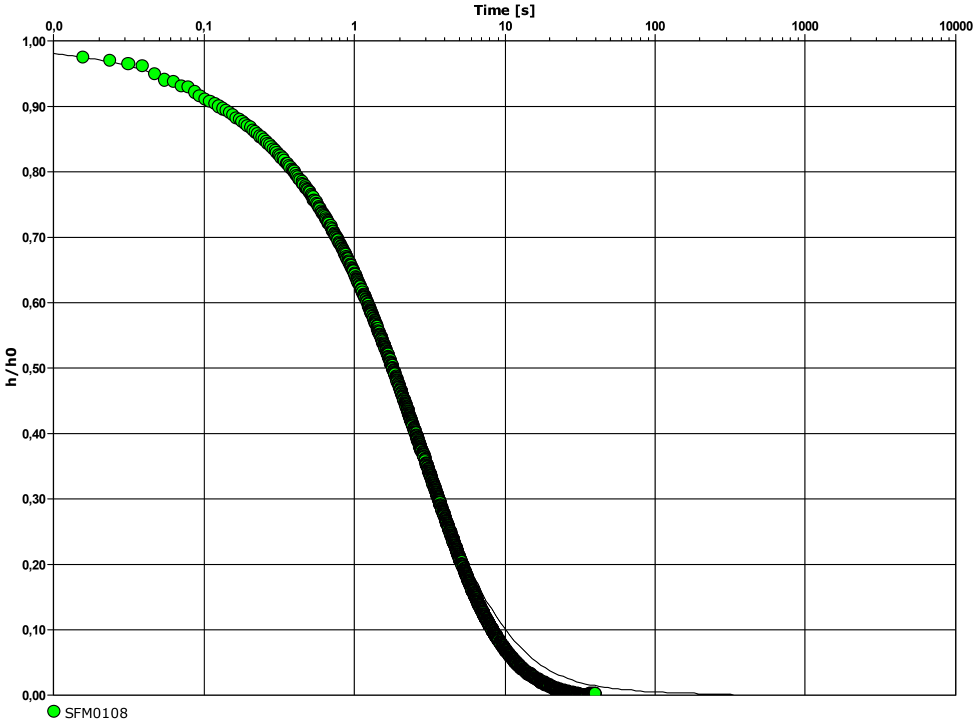

Figure A1-81. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0108*** *(Cooper et al. method).*

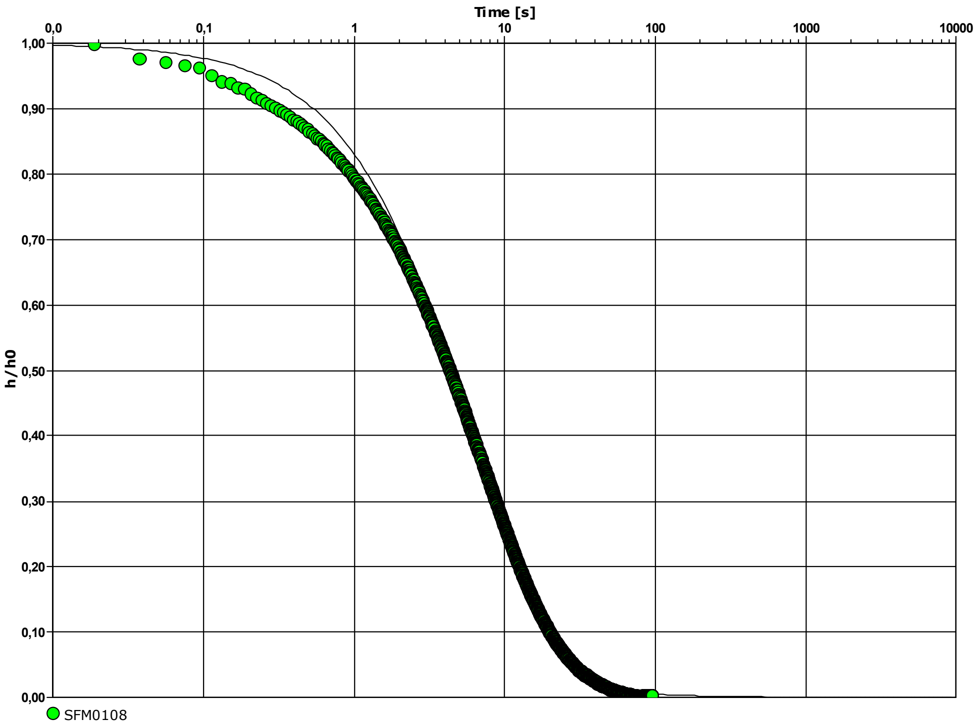

Figure A1-82. *Log-linear plot of the normalized displacement h/h_0 versus time for the rising-head test in* ***SFM0108*** *(Cooper et al. method, $S = 10^{-5}$)*

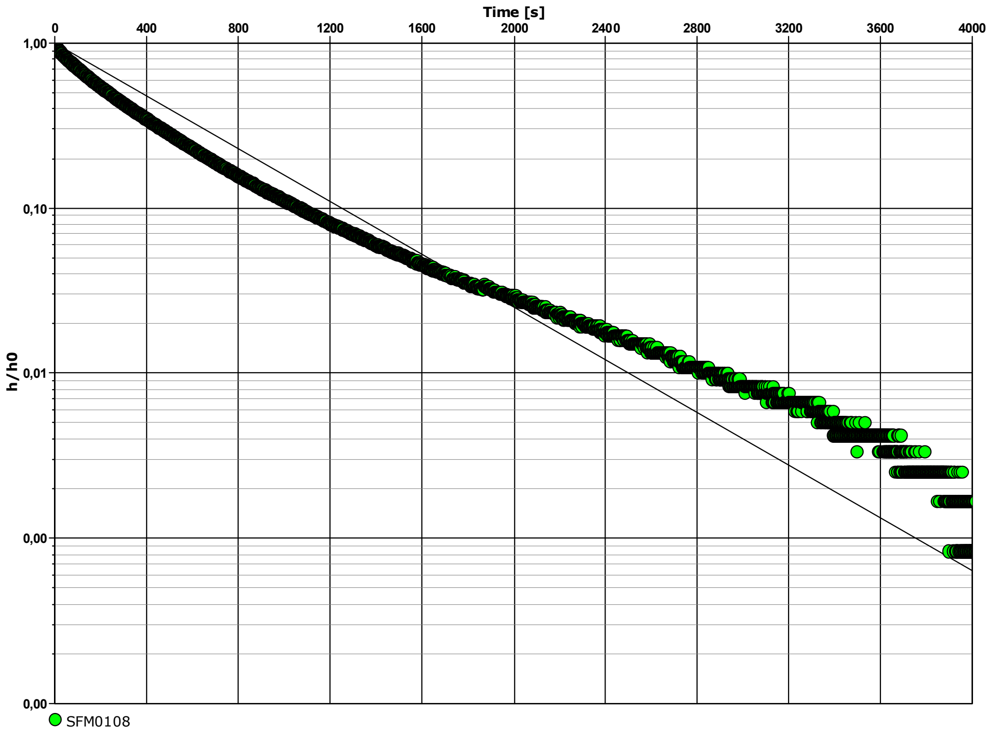

*Figure A1-83. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0108** (Hvorslev method).*

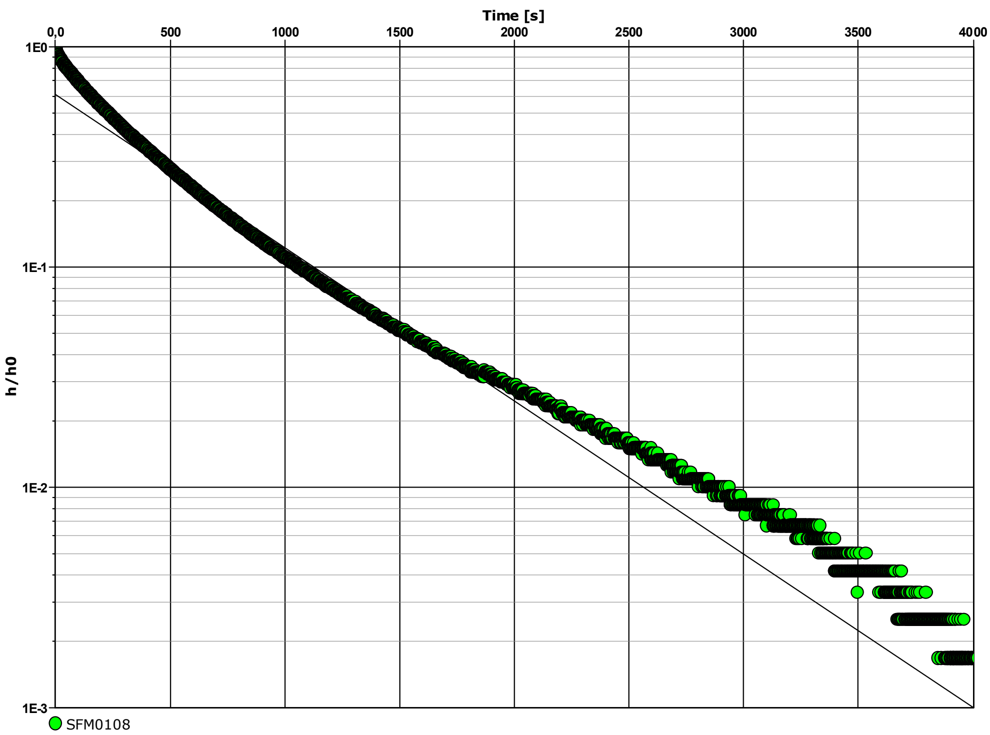

*Figure A1-84. Linear-log plot of the normalized displacement h/h_0 versus time for the rising-head test in **SFM0108** (Bouwer & Rice method).*

Appendix 2

Diagrams Pumping tests

Appendix 2 contains diagrams of the analysis of the pumping tests performed in Aquifer Test. Note that the values on time and drawdown axes are connected to the curve fitting process, i.e. time/drawdown values should not be compared between the figures. To see the actual test, the diagnostic plots (Chapter 7) are recommended.

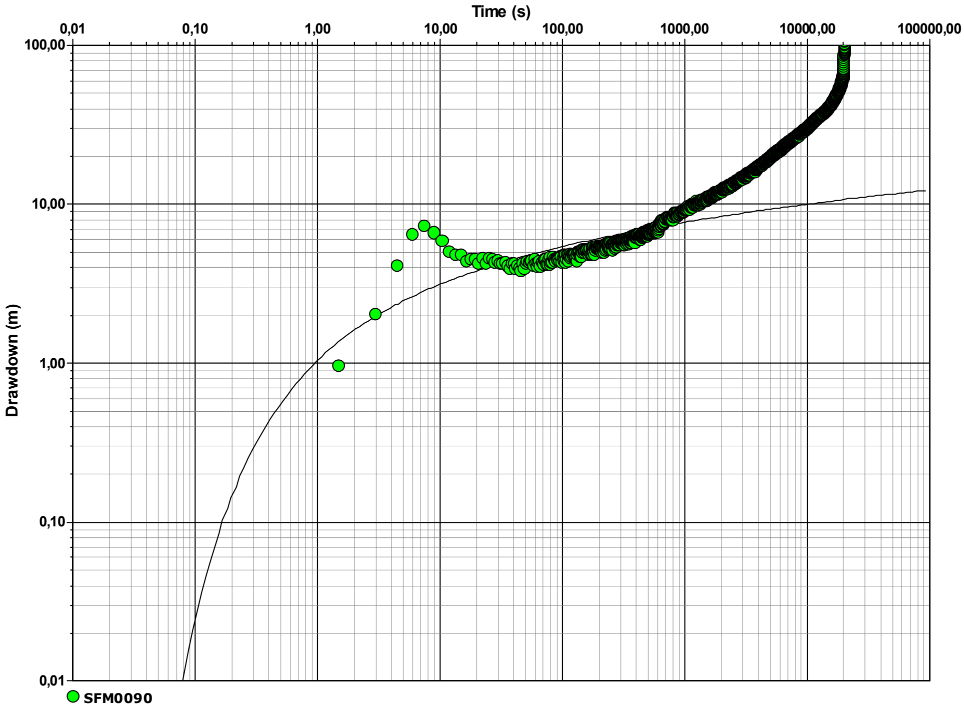

Figure A2-1. *Evaluation of the drawdown data from monitoring well **SFM0090** using the Theis method.*

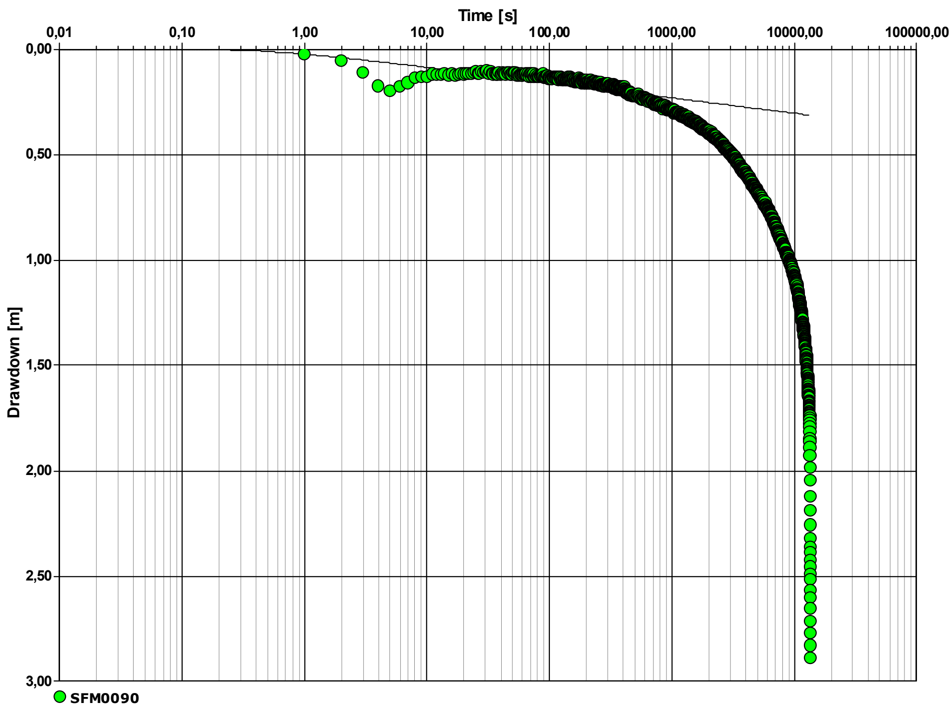

Figure A2-2. *Evaluation of the drawdown data from monitoring well **SFM0090** using the Jacob method.*

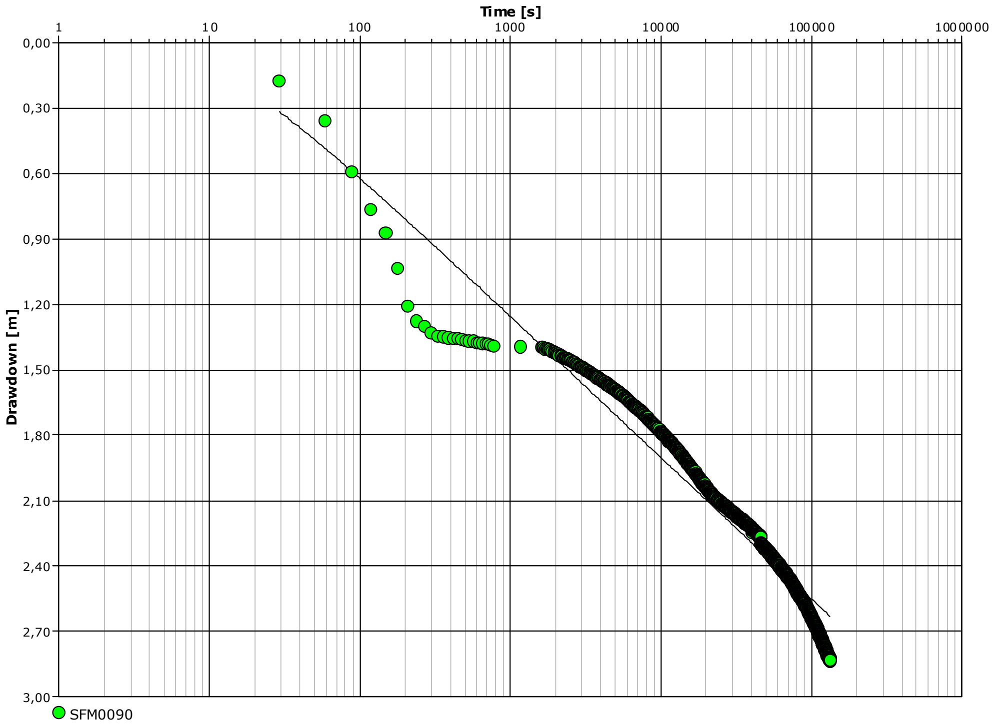

Figure A2-3. *Evaluation of the recovery data from monitoring well* ***SFM0090*** *using the Theis recovery method.*

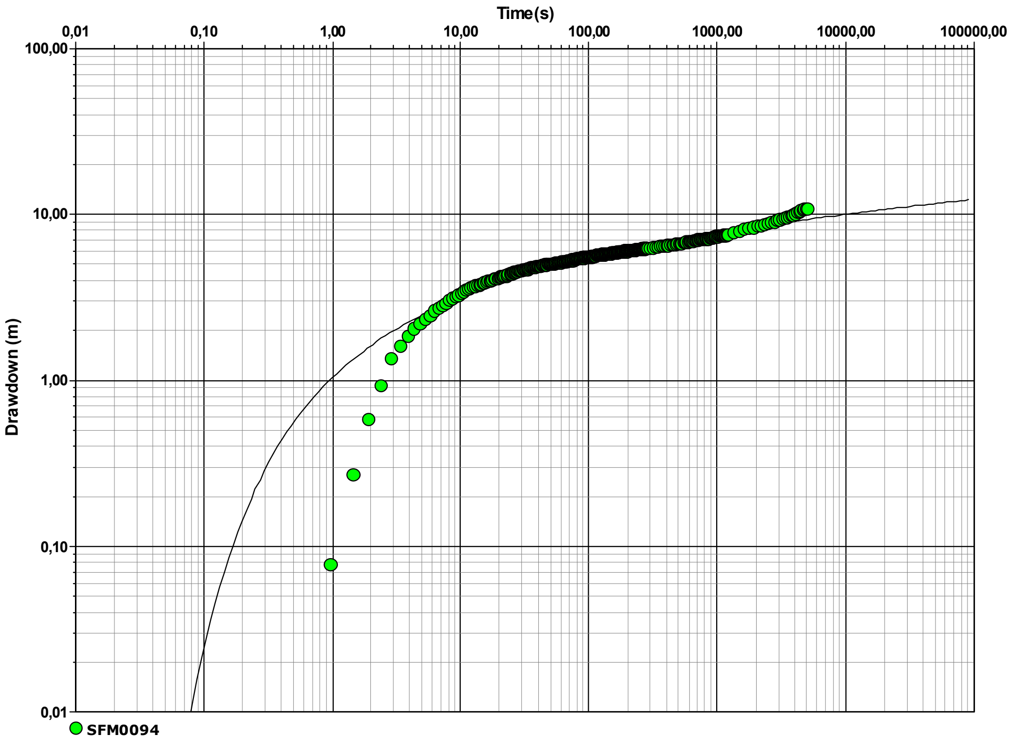

Figure A2-4. *Evaluation of the drawdown data from monitoring well* ***SFM0094*** *using the Theis method.*

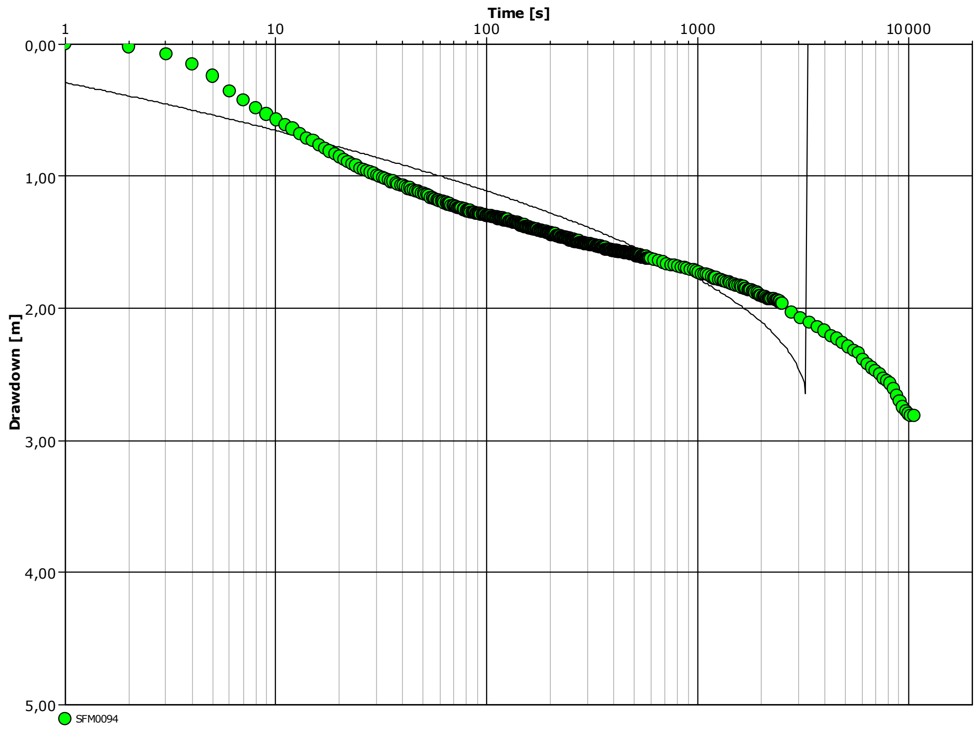

Figure A2-5. *Evaluation of the drawdown data from monitoring well **SFM0094** using the Jacob method.*

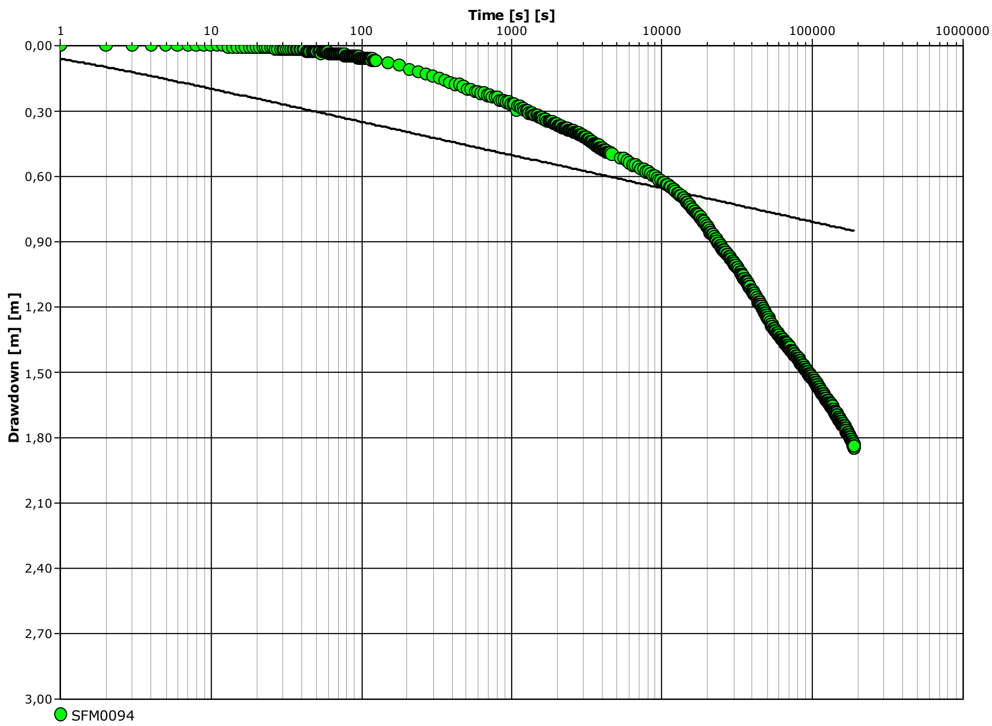

Figure A2-6. *Evaluation of the recovery data from monitoring well **SFM0094** using the Theis recovery method.*

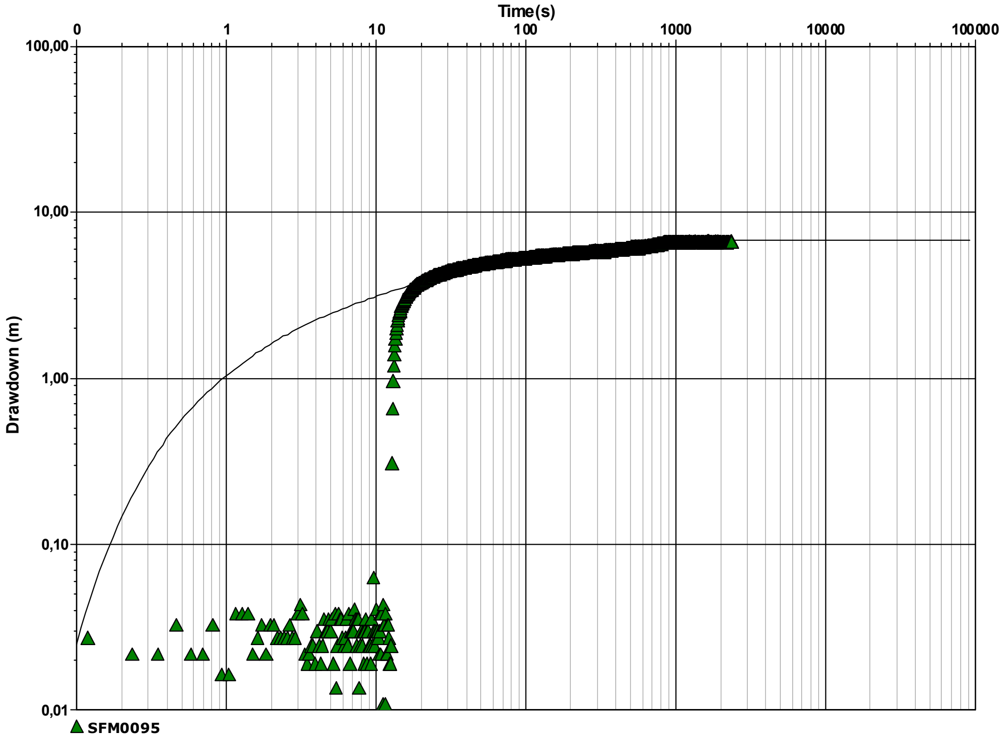

Figure A2-7. *Evaluation of the drawdown data from monitoring well* ***SFM0095*** *using the Hantush method.*

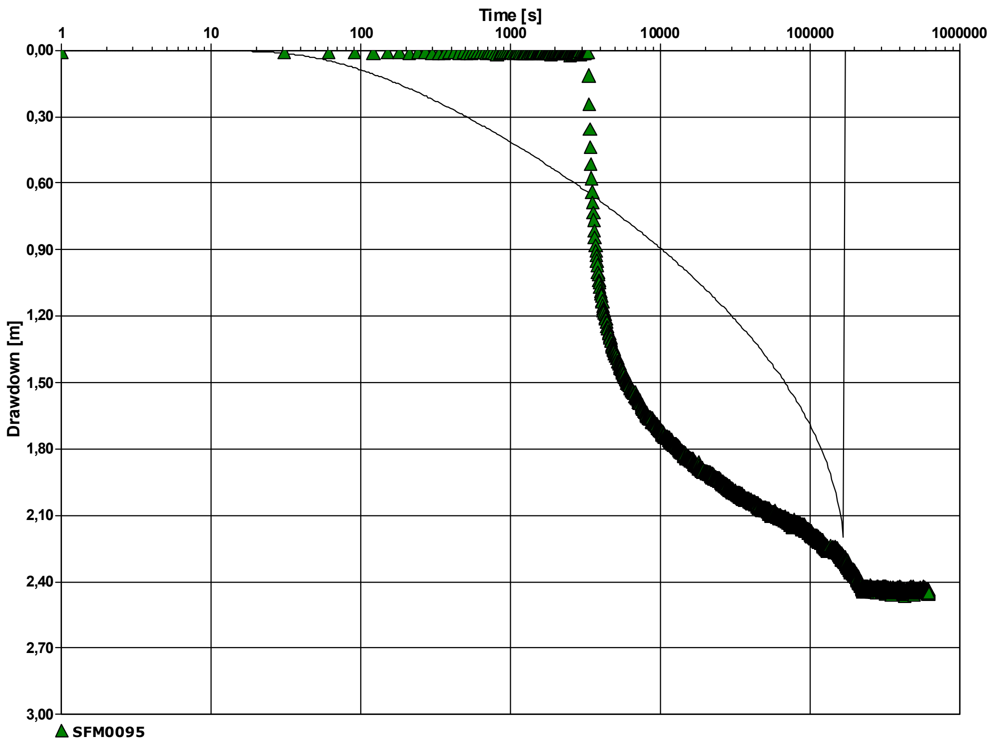

Figure A2-8. *Evaluation of the drawdown data from monitoring well* ***SFM0095*** *using the Jacob method.*

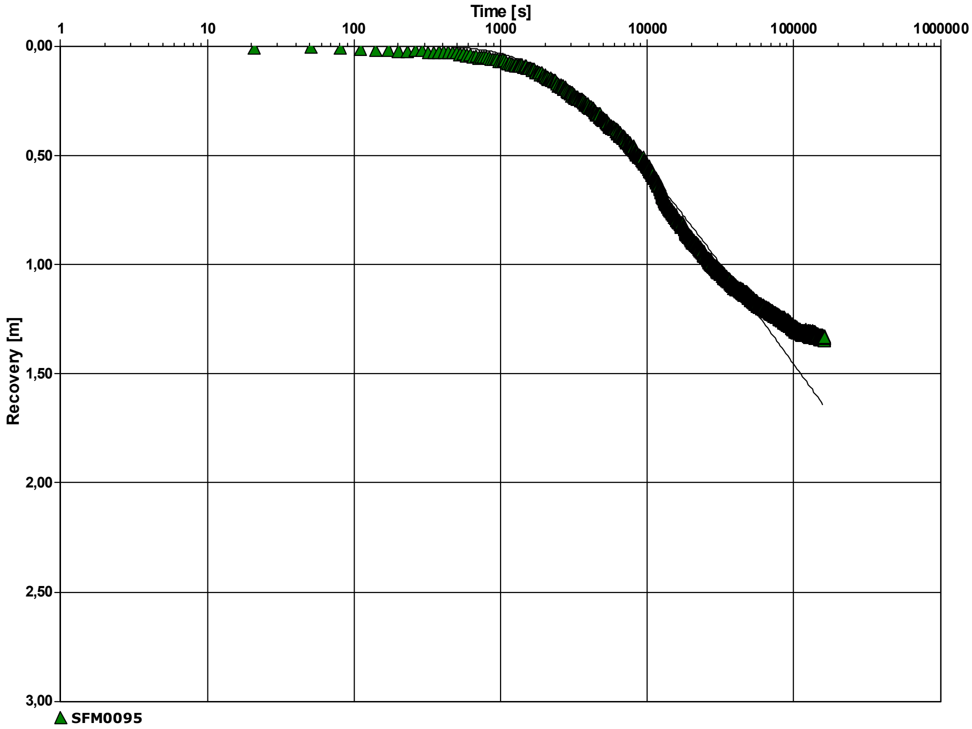

__Figure A2-9.__ Evaluation of the recovery data from monitoring well __SFM0095__ using the Theis recovery method.

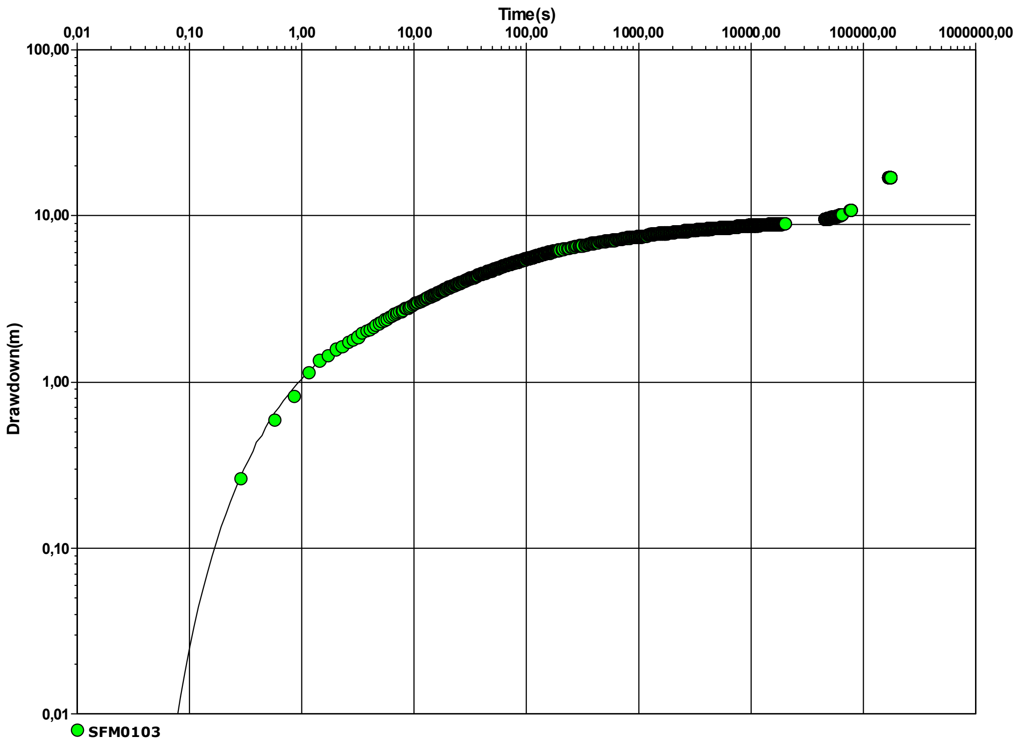

__Figure A2-10.__ Evaluation of the drawdown data from pumping well __SFM0103__ using the Hantush method.

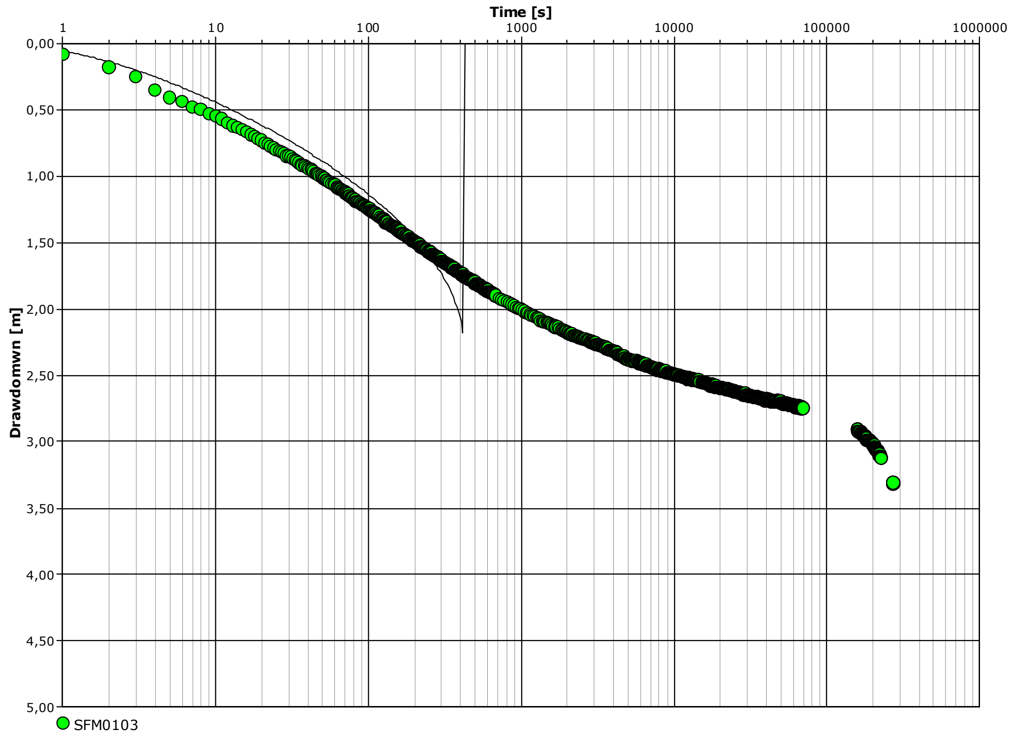

__Figure A2-11.__ Evaluation of the drawdown data from the pumping well __SFM0103__ using the Jacob method.

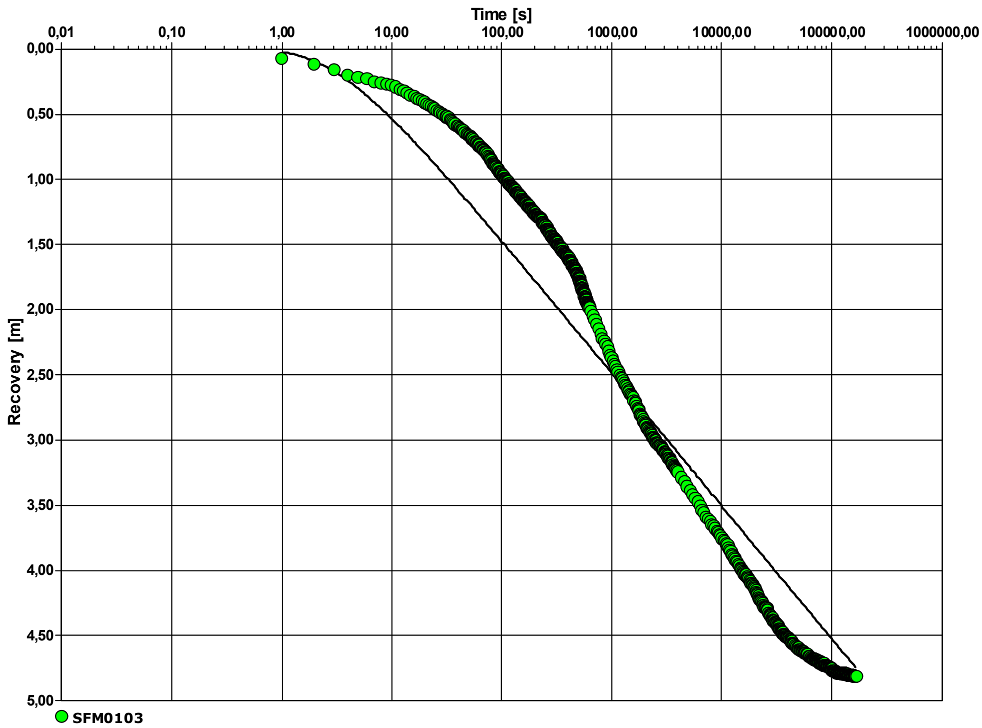

__Figure A2-12.__ Evaluation of the recovery data from the pumping well __SFM0103__ using the Theis recovery method.

Appendix 3

Permeameter tests in situ by GeoNordic AB

Golder Associates AB
Patrik Alm
Anders Personsgatan 12
416 64 Göteborg

PM angående mätning av permeabilitet vid Forsmark Kraftstation, 2006-05-18

GeoNordic AB, civing Ove Hallberg, har på uppdrag av Golder Associates AB, Patrik Alm, utfört mätning av jordens permeabilitet i sju punkter invid Forsmark Kraftstation. Mätningarna har utförts med GeoN Permeameter. För information om utrustningens funktion hänvisas till www.geonordic.se.

De sju undersökningspunkterna har benämning (i den ordning de undersöktes) SFM0092, SFM0082, SFM0085, SFM0088, SFM0096, SFM0099 och SFM0101. GeoN filterspetsar har tidigare installerats i undersökningspunkterna genom SWECO VIAK AB's försorg (Leif Lundholm). Under försöken har vatten under kontrollerade former infiltrerats i jorden genom filterspetsarna (utströmningsförsök/outflow test). Detta tillgår i princip så att en glasbehållare fylls med en noggrant uppmätt volym vatten och trycksätts varefter behållaren ansluts hydrauliskt till filterspetsen via en kanyl. Härvid pressas vatten ut ur behållaren, genom kanylen och filtret och vidare ut i jorden. Tryckförändringens hastighet i behållaren mäts kontinuerligt under försökets gång med instrument typ GeoN Pi301. Uppgifter om initialtrycket i behållaren, vattenvolymen i behållaren innan försöket igångsattes, det statiska portrycket i jorden och filtrets area, matas in i instrumentet varefter permeabiliteten beräknas automatiskt.

Vid permeabilitetsberäkningen erhålls upp till 24 k-värden för varje försök. Den avslutande manuella utvärderingen syftar till att bedöma inom vilken del av försöket som den bästa uppskattningen av verklig permeabilitet kan göras. Vid utvärderingen söker man en del av försöket där k-värdena är stabila och förändras så lite som möjligt. För utströmningsförsök finner man oftast detta stabila läge i försökets mitt. I början och slutet av ett försök kan randeffekter påverka värdena.

I bilaga 1-7 visas primärdata och beräknade k-värden för de utförda försöken. Nedan ges undertecknads utvärdering av presenterade k-värdena.

Utvärdering

GeoN Permeameter används för mätning av finkornig jords permeabilitet. Utrustningen kan användas i jord med en högsta permeabilitet av ca 10^{-4} cm/s. Som framgår av bilagorna 1-7 ligger samtliga k-värden i intervallet 8.2 x 10^{-5} till 1.3 x 10^{-5} cm/s. Dessa värden ligger sålunda nära utrustningens begränsning. Vidare utvecklas samtliga försök enligt samma mönster. I startläget anges k-värden på ca 1,3 x 10^{-5} till 2.0 x 10^{-5} cm/s och mot slutet av testet anges värden upp mot ca 7-8 x 10^{-5} cm/s. Något påtagligt stabilt läge kan inte noteras. Detta bedöms bero på att resultaten ligger så nära utrustningens begränsning. Mot bakgrund av att randeffekterna är minst runt mitten av försöken bedöms den verkliga permeabiliteten dock ligga i intervallet 2 x 10^{-5} till 4 x 10^{-5} cm/s, motsvarande 2 x 10^{-7} till 4x 10^{-7} m/s. Det är knappast meningsfullt att göra en mer exakt bedömning än så.

Värt att notera är att även försöken i de ”djupare” installerade filterspetsarna som enligt uppgift sitter i lera (SFM0085 och SFM0096) anger förhållandevis höga permeabilitetsvärden. Att permeabilitetsvärdena är höga överensstämmer väl med hur de inledande portrycksmätningarna utvecklades. I tätare material tar det alltid viss tid för det registrerade trycket att stabilisera sig, vanligen minst 3-5 minuter och i t ex de täta Göteborgslerorna ofta upp mot 15-20 minuter. I samtliga de 7 aktuella mätpunkterna, alltså även i de punkter där filterspetsarna enligt uppgift sitter i lera, stabiliserades portrycket dock omedelbart och utan någon som helst fördröjning, efter att tryckgivaren anslutits till filterspetsen.

Stockholm som ovan
GeoNordic AB

Ove B Hallberg
Vd, civing SVR

Bilagor 1-7: primärdata och beräknade k-värden från mätning av permeabilitet

Punkt	SFM0092
Datum	2006-05-18
Tidpunkt	11:09
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	1.11 mvp
Initialtryck	5.38 mvp

Tid från start [tt:mm:ss]	**Tryck [mvp]**	**Permeabilitet [cm/s]**
00:00:00	5.38	-
00:00:14	5.24	1.39E-05
00:00:15	5.10	1.46E-05
00:00:16	4.96	1.54E-05
00:00:17	4.82	1.62E-05
00:00:18	4.68	1.72E-05
00:00:19	4.54	1.81E-05
00:00:20	4.39	1.92E-05
00:00:21	4.25	2.04E-05
00:00:22	4.11	2.16E-05
00:00:23	3.97	2.30E-05
00:00:24	3.83	2.51E-05
00:00:25	3.69	2.71E-05
00:00:26	3.55	2.89E-05
00:00:27	3.41	3.05E-05
00:00:28	3.27	3.29E-05
00:00:29	3.13	3.56E-05
00:00.30	2.99	3.87E-05
00:00:31	2.85	4.22E-05
00:00:32	2.70	4.63E-05
00:00:33	2.56	5.11E-05
00:00:34	2.42	5.68E-05
00:00:35	2.28	6.35E-05
00:00:36	2.14	7.17E-05
00:00:37	2.00	8.20E-05

Punkt	SFM0082
Datum	2006-05-18
Tidpunkt	12:00
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	1.84 mvp
Initialtryck	7.85 mvp

Tid från start [tt:mm:ss]	Tryck [mvp]	Permeabilitet [cm/s]
00:00:00	7.85	-
00:00:48	7.65	2.00E-07
00:01:51	7.46	4.17E-07
00:01:52	7.26	1.38E-05
00:01:53	7.06	1.47E-05
00:01:54	6.87	1.55E-05
00:01:55	6.67	1.65E-05
00:01:56	6.48	1.76E-05
00:01:57	6.28	1.87E-05
00:01:58	6.08	2.01E-05
00:01:59	5.89	2.15E-05
00:02:00	5.69	2.30E-05
00:02:01	5.49	2.45E-05
00:02:02	5.30	2.67E-05
00:02:03	5.10	2.90E-05
00:02:04	4.90	3.16E-05
00:02:05	4.71	3.43E-05
00:02:06	4.51	3.77E-05
00:02:07	4.31	4.16E-05
00:02:08	4.12	4.57E-05
00:02:09	3.92	5.12E-05
00:02:10	3.73	5.75E-05
00:02:11	3.53	6.47E-05
00:02:12	3.33	7.32E-05
00:02:13	3.14	8.48E-05

Punkt	SFM0085
Datum	2006-05-18
Tidpunkt	13:06
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	2.12 mvp
Initialtryck	5.97 mvp

Tid från start [tt:mm:ss]	**Tryck [mvp]**	**Permeabilitet [cm/s]**
00:00:00	5.97	-
00:00:23	5.84	1.36E-05
00:00:24	5.72	1.40E-05
00:00:25	5.59	1.46E-05
00:00:26	5.46	1.54E-05
00:00:27	5.34	1.63E-05
00:00:28	5.21	1.70E-05
00:00:29	5.08	1.81E-05
00:00:30	4.96	1.92E-05
00:00:31	4.83	2.01E-05
00:00:32	4.70	2.15E-05
00:00:33	4.58	2.29E-05
00:00:34	4.45	2.42E-05
00:00:35	4.32	2.61E-05
00:00:36	4.19	2.80E-05
00:00:37	4.07	2.98E-05
00:00:38	3.94	3.24E-05
00:00:39	3.81	3.51E-05
00:00:40	3.69	3.79E-05
00:00:41	3.56	4.16E-05
00:00:42	3.43	4.58E-05
00:00:43	3.31	5.02E-05
00:00:44	3.18	4.19E-05
00:00:45	3.05	1.87E-05
00:00:47	2.93	2.12E-05

Punkt	SFM0088
Datum	2006-05-18
Tidpunkt	13:13
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	0.84 mvp
Initialtryck	4.24 mvp

Tid från start [tt:mm:ss]	**Tryck [mvp]**	**Permeabilitet [cm/s]**
00:00:00	4.24	-
00:00:15	4.13	1.45E-05
00:00:16	4.02	1.51E-05
00:00:17	3.90	1.63E-05
00:00:18	3.79	1.73E-05
00:00:19	3.68	1.81E-05
00:00:20	3.57	1.85E-05
00:00:21	3.45	2.01E-05
00:00:22	3.34	2.14E-05
00:00:23	3.23	2.25E-05
00:00:24	3.12	2.32E-05
00:00:25	3.00	2.53E-05
00:00:26	2.89	2.73E-05
00:00:27	2.78	2.89E-05
00:00:28	2.67	3.01E-05
00:00:29	2.55	3.31E-05
00:00:30	2.44	3.61E-05
00:00:31	2.33	3.88E-05
00:00:32	2.22	4.09E-05
00:00:33	2.10	4.57E-05
00:00:34	1.99	5.07E-05
00:00:35	1.88	5.56E-05
00:00:36	1.77	6.00E-05
00:00:37	1.65	6.70E-05
00:00:38	1.54	7.56E-05

Punkt	SFM0096
Datum	2006-05-18
Tidpunkt	14:14
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	2.44 mvp
Initialtryck	5.44 mvp

Tid från start [tt:mm:ss]	Tryck [mvp]	Permeabilitet [cm/s]
00:00:00	5.44	-
00:00:24	5.34	1.34E-05
00:00:25	5.24	1.40E-05
00:00:26	5.14	1.47E-05
00:00:27	5.04	1.54E-05
00:00:28	4.94	1.66E-05
00:00:29	4.84	1.72E-05
00:00:30	4.74	1.77E-05
00:00:31	4.64	1.82E-05
00:00:32	4.54	1.98E-05
00:00:33	4.44	2.16E-05
00:00:34	4.34	2.24E-05
00:00:35	4.24	2.34E-05
00:00:36	4.14	2.43E-05
00:00:37	4.04	2.67E-05
00:00:38	3.94	2.85E-05
00:00:39	3.84	3.06E-05
00:00:40	3.74	3.29E-05
00:00:41	3.64	3.55E-05
00:00:42	3.54	3.86E-05
00:00:43	3.44	4.20E-05
00:00:44	3.34	4.61E-05
00:00:45	3.24	5.09E-05
00:00:46	3.14	5.66E-05
00:00:47	3.04	6.36E-05

Punkt	SFM0099
Datum	2006-05-18
Tidpunkt	14:20
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	1.62 mvp
Initialtryck	5.55 mvp

Tid från start [tt:mm:ss]	Tryck [mvp]	Permeabilitet [cm/s]
00:00:00	5.55	-
00:00:25	5.42	1.37E-05
00:00:26	5.29	1.44E-05
00:00:27	5.16	1.51E-05
00:00:28	5.03	1.59E-05
00:00:29	4.90	1.68E-05
00:00:30	4.77	1.77E-05
00:00:31	4.64	1.87E-05
00:00:32	4.51	1.98E-05
00:00:33	4.38	2.10E-05
00:00:34	4.25	2.24E-05
00:00:35	4.12	2.38E-05
00:00:36	3.99	2.54E-05
00:00:37	3.87	2.72E-05
00:00:38	3.74	2.92E-05
00:00:39	3.61	3.14E-05
00:00:40	3.48	3.39E-05
00:00:41	3.35	3.68E-05
00:00:42	3.22	4.01E-05
00:00:43	3.09	4.38E-05
00:00:44	2.96	4.82E-05
00:00:45	2.83	5.34E-05
00:00:46	2.70	5.96E-05
00:00:47	2.57	6.55E-05
00:00:48	2.44	7.42E-05

Punkt	SFM0101
Datum	2006-05-18
Tidpunkt	14:26
Typ av försök	Outflow
Filterstorlek	30/40 mm (dia/l)
Provbehållare	35 ml
Extension-cylinder	0.5 ml
Portryck	1.01 mvp
Initialtryck	3.97 mvp

Tid från start [tt:mm:ss]	**Tryck [mvp]**	**Permeabilitet [cm/s]**
00:00:00	3.97	-
00:00:28	3.87	1.50E-05
00:00:29	3.77	1.57E-05
00:00:30	3.67	1.65E-05
00:00:31	3.57	1.73E-05
00:00:32	3.48	1.82E-05
00:00:33	3.38	1.91E-05
00:00:34	3.28	1.96E-05
00:00:35	3.18	2.04E-05
00:00:36	3.08	2.17E-05
00:00:37	2.98	2.37E-05
00:00:38	2.88	2.51E-05
00:00:39	2.78	2.67E-05
00:00:40	2.69	2.85E-05
00:00:41	2.59	3.05E-05
00:00:42	2.49	3.17E-05
00:00:43	2.39	3.36E-05
00:00:44	2.29	3.65E-05
00:00:45	2.19	4.07E-05
00:00:46	2.09	4.43E-05
00:00:47	1.99	4.84E-05
00:00:48	1.90	5.33E-05
00:00:49	1.80	5.90E-05
00:00:50	1.70	6.39E-05
00:00:51	1.60	7.16E-05