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Forsmark site investigation

Supplementary slug tests in groundwater monitoring wells in soil

Kent Werner
SWECO VIAK AB

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Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

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Abstract

This report presents the methodology, execution, results and analysis of slug tests performed in 12 groundwater monitoring wells in soil (SFM0022, SFM0062-0063, SFM0065, SFM0067-0073, and SFM0075) in the Forsmark area during spring 2004. The present slug tests supplement corresponding tests performed in 36 groundwater monitoring wells in Forsmark during spring 2003. Many of the previously tested wells are screened in the soil-rock contact zone, whereas the majority of the present wells are screened in more near-surface soil layers. The objective of the performed slug tests is to obtain data for estimation of the transmissivity (T) and the storativity (S) of the soil layers at the investigated locations. Data from the tests were evaluated using three separate methods: Cooper et al., Hvorslev, and Bouwer & Rice. The Cooper et al. method allows for the estimation of both T and S, whereas the other two methods provide T-values only.

For most of the wells a good to acceptable fit was obtained for the Cooper et al. method by use of a fixed α corresponding to $S = 10^{-5}$. For all wells, a very good to good fit was obtained by an adjustment of α. There may be several reasons that a perfect fit is not possible. The most common problem in evaluation of slug tests is skin effects due to incomplete well development. The tested wells have only been developed by pumping. Development by water injection was not performed since the wells should also be used for water sampling. Substituting the aquifer thickness by the effective well screen length (assumed being equal to the nominal screen length) may also be invalid for some wells. Furthermore, for some wells it is difficult to determine whether confined, semi-confined or unconfined conditions prevail. The equations developed for the evaluation of slug tests are also associated with a number of assumptions, e.g. regarding homogeneity and radial flow. These assumptions may in some cases not be valid, which also provides an explanation for the difficulties to obtain a perfect fit to the type curves.

For the reporting to the SKB SICADA database, the values obtained with fixed $S = 10^{-5}$ were used. 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, and the agreement between the obtained and the calculated initial displacement. For some wells a concave-upwards shape curve was obtained in the semi-logarithmic plots used for the evaluation according to Hvorslev and Bouwer & Rice, rather than the theoretical straight line. Possible explanations to this phenomenon are the same as for the difficulties to fit measured data to the type curves of the Cooper et al. method. The K-values obtained from the evaluation according to Hvorslev and Bouwer & Rice are between $7.23 \cdot 10^{-9}$ and $2.26 \cdot 10^{-5}$ m/s. The T-values obtained from the Cooper et al. method, reported to the SICADA database, are between $1.29 \cdot 10^{-7}$ and $4.20 \cdot 10^{-5}$ m^2/s. The corresponding range for K is $3.23 \cdot 10^{-7}$-$4.20 \cdot 10^{-5}$ m/s. For the T-values reported to SICADA, the geometrical mean of the corresponding K-values is $8.12 \cdot 10^{-7}$ m/s, whereas the arithmetic mean and the median of K is $4.74 \cdot 10^{-6}$ and $5.04 \cdot 10^{-7}$ m/s, respectively. The standard deviation of log-K is 0.7208. Assuming a log-normally distributed K, the 95 % confidence interval for the mean hydraulic conductivity K is $2.96 \cdot 10^{-7} < 8.12 \cdot 10^{-7} < 2.36 \cdot 10^{-6}$ m/s. The 95 % confidence interval for a new measurement is wider, $3.14 \cdot 10^{-8} < 8.12 \cdot 10^{-7} < 2.10 \cdot 10^{-5}$ m/s. The uncertainty in the estimation of S is large. However, the results do not reject the assumption that S is in the order of 10^{-5}.

Sammanfattning

Denna rapport redovisar metodik, genomförande, resultat och analys av slugtester som genomfördes i 12 st grundvattenrör i jord (SFM0022, SFM0062-0063, SFM0065, SFM0067-0073 och SFM0075) i Forsmarksområdet under våren 2004. Slugtesterna kompletterar motsvarande tester som genomfördes i 36 st grundvattenrör i Forsmark under våren 2003. Många av de tidigare testade rören har intagsdelen i gränsskiktet jord-berg, medan flertalet av de nu aktuella rören har intagsdelen i ytligare jordlager. Målsättningen med de genomförda slugtesterna är att erhålla data för bedömning av transmissiviteten (T) och storativiteten (S) för jordlagren i de undersökta punkterna. Data från slugtesterna analyserades med tre olika metoder: Cooper et al., Hvorslev samt Bouwer & Rice. Cooper et al.-metoden ger möjlighet för bestämning av både T och S medan de båda andra metoderna endast ger värden för T.

För de flesta av grundvattenrören erhölls en god till acceptabel passning med de typkurvor som används i Cooper et al.-metoden vid användning av ett fast α motsvarande $S = 10^{-5}$. För alla rör erhölls en mycket god till god passning om α varierades. Skälen till att en perfekt passning inte kan erhållas kan vara flera. Det vanligaste problemet vid utvärdering av slugtester är s k skin-effekter på grund av otillräcklig rensning av röret. De undersökta rören har endast rensats genom pumpning. Rensning genom injektering av vatten utfördes inte eftersom rören också skulle användas för vattenprovtagning. Att för de ofullständiga brunnarna ersätta akviferens tjocklek med den effektiva längden av brunnsfiltret (lika med dess verkliga längd) kan också vara ogiltigt för vissa brunnar. Vidare var det för några av rören svårt att avgöra i vilken utsträckning slutna, läckande eller öppna förhållanden rådde. De ekvationer som utvecklats för utvärdering av slugtester är också förknippade med ett flertal antaganden, t ex avseende homogenitet och radiellt flöde. Eventuellt är dessa antaganden i vissa fall inte uppfyllda, vilket också kan förklara svårigheterna att passa uppmätta data till typkurvor.

För rapportering till SKB´s SICADA-databas användes de data som erhölls för $S = 10^{-5}$. Valet av inrapporterat T-värde styrdes också av vilken av ”falling-head” och ”rising-head”-testerna som gav bäst passning till typkurvorna samt av överensstämmelsen mellan beräknad och initiell höjning respektive sänkning av grundvattennivån. För vissa rör erhölls en konkav kurva vid lin-log-plottningen för utvärdering enligt Hvorslev och Bouwer & Rice istället för den räta linje som teoretiskt skall erhållas. Troliga skäl till detta är de samma som för svårigheterna att erhålla en passning till Cooper et al.-metodens typkurvor. De K-värden som erhölls enligt med Hvorslev och Bouwer & Rice är mellan $7.23 \cdot 10^{-9}$ and $2.26 \cdot 10^{-5}$ m/s. De T-värden som erhölls från Cooper et al.-metoden och som inrapporterats till SICADA-databasen är mellan $1,29 \cdot 10^{-7}$ och $4,20 \cdot 10^{-5}$ m^2/s. Motsvarande intervall för K är $3,23 \cdot 10^{-7}$- $4,20 \cdot 10^{-5}$ m/s. För de T-värden som inrapporterats till SICADA är det geometriska medelvärdet av motsvarande K-värden $8,12 \cdot 10^{-7}$ m/s, och det aritmetiska medelvärdet och medianen av K är $4,74 \cdot 10^{-6}$ respektive $5,04 \cdot 10^{-7}$. Standardavvikelsen för log-K är 0,7208. Under antagande om ett lognormalfördelat K, så är det 95 %-iga konfidensintervallet för medelvärdet av K $2.96 \cdot 10^{-7} < 8.12 \cdot 10^{-7} < 2.36 \cdot 10^{-6}$ m/s. Det 95 %-iga konfidens intervallet för en ny observation är bredare, $3.14 \cdot 10^{-8} < 8.12 \cdot 10^{-7} < 2.10 \cdot 10^{-5}$ m/s. Osäkerheten i uppskattningen av S är stor. Resultaten motsäger emellertid inte antagandet om ett S i storleksordningen 10^{-5}.

Contents

1 Introduction

This report presents the methodology, results and analysis of slug tests performed in the Forsmark area during the period February 11 to April 7, 2004. The tests are part of the activities performed within the site investigation at Forsmark. During spring 2003, slug tests were conducted in 36 groundwater monitoring wells /1/. The present tests have been performed in accordance with activity plan AP PF 400-04-14 for supplementary slug tests in groundwater monitoring wells in soil in Forsmark. A total of 12 supplementary groundwater monitoring wells, installed during spring 2004 /2/, were tested. No other tests have been carried out in these wells before the slug tests were performed. The locations of the tested groundwater monitoring wells are shown in Figure 1-1. For information on soil profiles at the groundwater monitoring wells, see /2/.

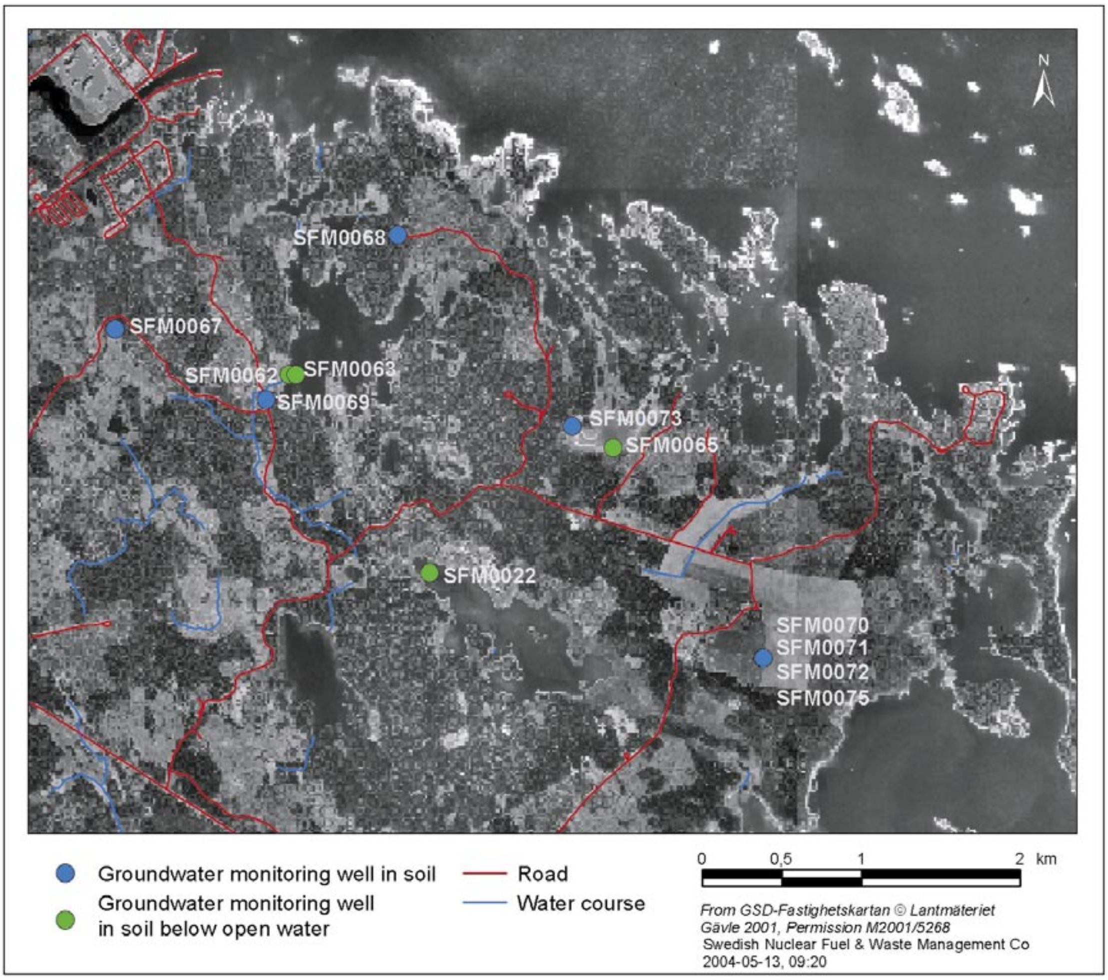

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Figure 1-1. *Map showing the locations of the groundwater monitoring wells in which slug tests were performed.*

In Table 1-1 controlling documents for performing this activity are listed. Both activity plans and method descriptions are SKB's internal controlling documents.

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

Activity plan	**Number**	**Version**
Kompletterande slugtester i grundvattenrör i jord	AP PF 400-04-14	1.0
Method descriptions	**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

The data of the present activity is stored in SKB´s SICADA database, Field Note No. Forsmark 316.

2 Objective and scope

The overall objectives of the hydrogeological investigations in the Forsmark area are described in /3/ and /4/. The specific objective of the performed slug tests is to obtain data for the estimation of the transmissivity (T) and the storativity (S) of the soil as a supplement to earlier performed slug tests mainly of the contact zone between the soil and the upper parts of the bedrock /1/.

2.1 Boreholes tested

Table 2-2 presents basic technical data of the tested groundwater monitoring wells. The coordinates of the wells are given in Table 2-3.

Table 2-2. Technical data of the tested groundwater monitoring wells

Groundwater monitoring well		Stand pipe		Screen (test section)		
	Borehole diameter, d_w (mm)[1,2]	Inner diameter of stand pipe, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup (m)[3]	Depth to borehole seclow (m)[3]	Screen length, b (m)
SFM0022	60.3	51.3	0	5.30 (4.52)	5.80 (5.02)	0.50
SFM0062	60.3	51.3	0	3.25 (2.61)	3.65 (3.01)	0.40
SFM0063	60.3	51.3	0	3.22 (2.48)	3.72 (2.98)	0.50
SFM0065	60.3	51.3	0	4.45 (3.50)	4.85 (3.90)	0.40
SFM0067	103	50	0	1.00 (0.57)	2.00 (1.57)	1.00
SFM0068	103	50	0	0.80 (0.34)	1.80 (1.34)	1.00
SFM0069	103	50	0	1.00 (0.37)	2.00 (1.37)	1.00
SFM0070	103	50	0	1.68 (1.22)	2.68 (2.22)	1.00
SFM0071	103	50	0	5.00 (4.69)	6.00 (5.69)	1.00
SFM0072	103	50	0	8.50 (8.08)	9.50 (9.08)	1.00
SFM0073	103	50	0	3.50 (3.10)	4.50 (4.10)	1.00
SFM0075	103	50	0	7.66 (7.15)	8.66 (8.15)	1.00

[1] Wells SFM0022, 0062-63 and 0065 were installed in soil below open water using a hand-held Pionjär hammer drill. The effective borehole diameter (d_w) used for evaluation of T and S (see Section 6) for these wells was thus assumed to equal the outer diameter of the stand pipe (60.3 mm), as no filter sand was applied in these boreholes during drilling.

[2] Drilling of wells SFM0067-73 and 0075 was performed by air-rotary drilling with a casing driver system, Symmetrix N-82 (Ø 115 mm). The outer diameter of the drill casing was 103 mm. Filter sand was filled between the well casing and the drill casing while the latter was pulled out. The effective borehole diameter (d_w) used for evaluation of T and S (see Chapter 5) was therefore assumed to be 103 mm.

[3] Depth from the top of the stand pipe. Numbers within parentheses denote depth below ground surface/current ice level (wells installed below open water).

Table 2-3. Coordinates of the tested groundwater monitoring wells (coordinate system RT 90 2.5 gon V 0:-15 for X and Y, and RHB70 for Z)

Monitoring well	X	Y	Z[1]
SFM0022	6697597.55	1632697.18	1.49
SFM0062	6698838.75	1631807.99	1.18
SFM0063	6698839.05	1631851.49	1.28
SFM0065	6698380.94	1633841.58	0.97
SFM0067	6699120.60	1630713.36	2.54
SFM0068	6699706.12	1632489.56	2.07
SFM0069	6698680.22	1631662.25	2.50
SFM0070	6697069.55	1634783.49	3.72
SFM0071	6697069.45	1634785.08	3.60
SFM0072	6697069.33	1634789.30	3.69
SFM0073	6698513.24	1633585.10	0.63
SFM0075	6697069.45	1634786.84	3.78

[1] Top of the stand pipe (m.a.s.l.).

2.2 Tests

The performed slug tests are summarized in Table 2-4.

Table 2-4. Slug tests performed in the groundwater monitoring wells

Monitoring well	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[4] (s)	tF[4] (s)	Depth to water level in well prior to slug test[5] (m)	Tew[6] (°C)	Ecw[6] (mS/m)
SFM0022[2]	2004-02-11 15:49:43	5 041	4 572	0.85 (0.07)	6.71	35
SFM0062[2]	2004-02-12 14:06:20	7 541	3 982	0.56 (-0.08)	5.79	51
SFM0063[2]	2004-02-17 14:02:21	32 141	5 193	0.76 (0.02)	4.27	49
SFM0065[2]	2004-02-17 10:44:46	69 097	6 181	0.48 (-0.47)	5.47	22
SFM0067[3]	2004-04-06 10:42:45	10 922	3 645	0.49 (0.06)	2.98	
SFM0068[3]	2004-04-06 16:38:42	11 002	3 202	0.78 (0.32)	3.06	
SFM0069[3]	2004-04-06 09:25:32	171 (416)	261 (207)	0.88 (0.25)	1.85	
SFM0070[3]	2004-04-05 12:50:21	6 698	3 639	1.23 (0.77)	4.97	
SFM0071[3]	2004-04-05 17:35:59	2 410	3 630	1.15 (0.84)	5.24	
SFM0072[3]	2004-04-05 16:35:50	75 018	3 727	1.72 (1.30)	5.73	
SFM0073[3]	2004-04-05 15:18:53	427	346	0.21 (-0.19)	5.19	
SFM0075[3]	2004-04-06 18:47:34	39 891	3 816	1.33 (0.82)	3.89	

[1] Start of falling-head test.

[2] Times are given in Swedish Standard Time (SStT).

[3] Times are given in Swedish Summer Time (SStT + 1 h).

[4] tp denotes duration of falling-head test, and tF duration of rising-head test. Numbers in parentheses indicate that two falling-head tests and/or two rising-head tests were performed.

[5] The reference point is the top of the stand pipe. Numbers within parentheses denote depth below ground surface/current ice level (wells installed below open water).

[6] Tew and Ecw denote well water temperature and electrical conductivity, respectively. Tew is the well water temperature at sensor depth measured by the Diver® (see Section 2.3) at the start of the falling-head test. In accordance with activity plan AP PF 400-04-09 for supplementary soil drilling, soil sampling and installation of groundwater monitoring wells and surface water level, electrical conductivity (Ecw) was only measured in the wells installed below open water (SFM0022, 0062-63 and 0065).

Prior to each slug test, all equipment that was lowered into the observation well was cleaned with a soft cloth containing 70 % denatured alcohol according to level 2 in method description SKB MD 600.004. Subsequently, the depth to the water level and the depth to the bottom of the well were measured. Further, the electrical conductivity of the water in the well was measured. In order to observe the displacement of the water level in the well during the test, apart from the continuous recording by the pressure transducer, the water level in the well was also measured with a manual water-level meter several times during each test.

2.3 Equipment check

The equipment that was used for logging of water pressure head and temperature during the slug tests (Van Essen Instruments Diver®) was calibrated before the testing campaign, and the conductivity meter was checked after the campaign was finished (see Section 5.1). In addition, prior to each slug test, the Diver was lowered to two known depths in the monitoring well for measurement of the undisturbed water pressure head. These data, combined with the measured depth to the water level in the well, were used as part of the evaluation of the tests for data checking. For all tests, these checks gave satisfying results.

3 Equipment

3.1 Description of equipment

For the slug tests, the following equipment was used:

1. Van Essen Instruments Diver® with built-in pressure transducer and temperature sensor, with connecting cable.
2. Portable PC.
3. Slug and wire made of stainless steel (Figure 4-1).
4. Wire stopper (spanner wrench).
5. Folding rule.
6. Elwa PLS 50A -level water meter, with light and sound indicator.
7. WTW COND 315i conductivity meter with TetraCon® 325 conductivity cell.

Basic sensor data of the Diver® and the WTW conductivity meter are given in Tables 3-4 and 3-5.

The Diver® has a built-in pressure transducer with a resistor bridge for pressure measurements, and a semiconductor sensor for temperature measurements. The temperature is used to automatically compensate the depth measurements for temperature effects.

Table 3-4. Sensor data of the Diver®

	Name	Unit	Value/range
Pressure	Measurement range	cm wc[1]	0 to 1000
	Resolution	cm wc	0.2
	Accuracy	% of measurement range	0.1
Temperature	Measurement range	°C	-20 to +80
	Resolution	°C	0.01
	Accuracy	°C	±0.1

[1] Centimetres water column.

Table 3-5. Sensor data of the WTW conductivity meter

Name	Unit	Value/range
Measurement range	µS/cm	0-500 000
Resolution	µS/cm	1[1]
Accuracy	% of measured value	±0.5

[1] Resolution for the indicated measurement range.

The diameter of the equipment lowered into each groundwater monitoring well was as follows:

Outer diameter of signal cable:	3 mm
Outer diameter of wire:	5 mm
Outer diameter of slug:	40 mm

Table 3-6 provides the position of the pressure transducer in the Diver®, and the wire and slug length for each slug test. Positions are given in metres from the top of the stand pipe.

Table 3-6. Position (measured as depth from the top of the stand pipe) of pressure transducer in Diver®, and wire and slug length in the performed slug tests

Borehole	Diver® depth during slug test (m)	Wire length (m)	Slug length (m)
SFM00022	3.50	2.10	0.75
SFM00062	3.50	1.35	0.50
SFM00063	3.00	1.31	0.50
SFM00065	4.00	1.00	0.50
SFM00067	2.40	1.00	0.50
SFM00068	2.00	1.30	0.50
SFM00069	2.40	1.40	0.75
SFM00070	3.20	1.70	1.00
SFM00071	5.00	1.70	1.00
SFM00072	5.00	2.20	1.00
SFM00073	4.00	0.70	0.25
SFM00075	4.00	1.80	1.00

4 Execution

4.1 General

The slug tests were performed according to the specifications given in the method description for slug tests in open groundwater monitoring wells (Metodbeskrivning för slugtester i öppna grundvattenrör), SKB MD 325.001, version 1.0 (SKB internal document).

4.2 Preparations

Prior to the tests, the Divers® were tested at SWECO VIAK's office in Stockholm. The test procedure is described in the method description SKB MD 325.001. The tests showed that the water pressure head measured by the Divers® was equal (with a resolution of 0.01 m) to the height of the water column above the pressure transducer when the Divers® were lowered to two known depths into a water-filled plastic bucket.

Function checks of the Divers® were also performed in connection to each slug test (see Section 2.3).

4.3 Execution of field work

4.3.1 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) /5/. In the majority of the present tests, 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 the 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, additional tests are 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 400-04-14.

Figure 4-1. *Falling-head test in groundwater monitoring well SFM0065, installed in soil below open water. The slug (connected to a stainless-steel wire) is lowered into the well. The Diver®, hanging at a known depth in the well, is connected by the black cable to the portable PC on the sledge. A spanner wrench is utilized as wire stop. All wells installed in soil below open water (SFM0022, 0062-63, and 0065) were tested when the lakes were ice covered. As a consequence, the frozen water in the near-surface section of the stand pipe had to be melted using a LPG burner prior to initiation of the slug tests in these wells.*

4.3.2 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 groundwater 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 or 1.00 m, in order to prevent water from rising over the top of the stand pipe in the falling-head tests.

5. Logging of pressure in air, and thereafter at two known depths in the well, with the Diver®.
6. Performance of falling-head test: Rapid lowering of slug into the well (fixed with a wire stop). Sampling frequency of the Diver®: 1 measurement per second.
7. Measurement of the recovery of the water level in the well using a water-level meter.
8. Changing of the sampling frequency of the Diver® for wells with a slow recovery of the water level (see Table 4-1). Before changing the sampling frequency, the Diver® is stopped with the PC, and data are saved in a separate raw data file (cf. Appendix 1).
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 Diver®: 1 measurement per second. The practical performance of a rising-head test is demonstrated in Figure 4-2.
10. Termination of slug test approximately 1 h after start of the rising-head test (according to activity plan AP PF 400-04-14 for performance of supplementary slug tests in Forsmark).

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

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

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

Figure 4-2. *Initiation of the rising-head test in groundwater monitoring well SFM0067, installed in soil. The evaluation of slug tests is facilitated if the data demonstrate a distinct change of the water-pressure head at the initiation of the tests. This is particularly important for wells where the screens are installed in permeable soil layers, as the subsequent transient response of the water level is relatively fast in such wells. In order to achieve such a distinct change of the water-pressure head, the slug must be raised from the well as quickly as possible when the test is initiated.*

4.4 Data handling and post processing

Raw data from the Diver® (internal *.mon format) were saved on a portable PC, using the computer programme EnviroMon Ver. 1.45. After each test, the saved *.mon files were exported from EnviroMon to *.csv (comma-separated format).

Prior to the data evaluation for the generation of primary data files, all files in *.csv format 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 (see Section 4.5 and Chapter 5). The data processing performed in MS Excel involved (1) correction of the pressure data for the barometric pressure (obtained by keeping the Diver® in the open air prior to each slug test), and (2) identification of the exact starting time of the test for the analysis (removal of initial oscillation effects, usually lasting in the order of 1-10 seconds after lowering the slug into the well). For tests lasting more than 0.5 hour, the pre-test air-pressure data from the Diver® were adjusted, using air-pressure data (available from www.skb.se) from one of the on-site meteorological stations; this station measures the atmospheric air pressure twice per hour. In addition, a few outliers (obvious erroneous measurements) in some of the raw data files were removed prior to the data analysis.

A list of all generated raw and primary data files is given in Appendix 1. The raw data files (*.mon and *.csv) were delivered in digital form to the Activity Leader as well as the results of the evaluation (HY670 - PLU Slug test_2004.xls) for quality control and storage in the SICADA database, Field Note No. Forsmark 316.

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 /5/ and /6/.

All tested wells are only partially penetrating the aquifer. In the evaluation the aquifer thickness is substituted by the effective well screen length which is 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 standpipe is assumed to be equal to the outer diameter of the drill casing, 103 mm. For the wells where no sand filter is installed, the effective well screen and standpipe diameter is assumed to be the nominal outer diameter of the screen and standpipe, 60.3 mm.

4.5.1 Cooper et al. method

The Cooper et al. method is designed to estimate the transmissivity T 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 partly penetrating wells. If a close match can be obtained with a type curve applying a physically plausible α, the method can also be applied in unconfined aquifers (see /5/). The Cooper et al. method is also recommended as “the first choice” method by Butler /5/.

In the method, a plot of the normalized displacement versus the logarithm of $\beta = Tt/r^2$ (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 $\alpha = r_w^2 S/r_c^2$ (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, a computer program in Excel developed by the U.S. Geological Survey 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 α.

As is also discussed in /5/, 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 is designed to estimate the hydraulic conductivity of an aquifer /9/. 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 are 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 /5/.

For the present analysis according to the Hvorslev method, the computer program Aquifer Test Ver 3.0 was used /10/. 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 /1/. As also discussed and shown in /1/, 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 /5/. 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 /5/ is designed to estimate the hydraulic conductivity 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 /5/.

For the present analysis according to the Bouwer & Rice method, the computer program Aquifer Test Ver 3.0 was used /10/. 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 /1/. As also discussed and shown in /1/, 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 /5/.

4.6 Nonconformities

There were no nonconformities compared to the controlling activity plan or method descriptions.

5 Results

5.1 Nomenclature and symbols

The nomenclature and symbols used for the results presented in the following sections are given below.

dh$_0$* (m):	Expected initial displacement (both falling- and rising-head test)
h$_0$_p (m):	Water pressure head at the measurement point prior to initiation of falling-head test
h$_0$_F (m)	Water pressure head at the measuring point prior to initiation of rising-head test
dh$_0$_p (m):	Initial displacement for falling-head test
dh$_0$_F (m):	Initial displacement for rising-head test
dh$_0$*/dh$_0$_p:	Inverse of the normalized initial displacement for falling-head test
dh$_0$*/dh$_0$_F:	Inverse of the normalized initial displacement for rising-head test
hp (m):	Water pressure head at the measuring point at end of falling-head test
hF (m):	Water pressure head at the measuring point at end of rising-head test
T$_s$_measl_L (m^2/s):	Lower measurement limit of transmissivity for slug test

5.2 Results

The results of the performed slug tests (for nomenclature and symbols, see above) are summarized in Table 5-1 below.

Table 5-1. Summary of the results of the slug tests

Well	dh$_0$* (m)	h$_0$_p (m)	dh$_0$_p (m)	dh$_0$*/dh$_0$_p (-)	hp (m)	h$_0$_F (m)	dh$_0$_F (m)	dh$_0$*/dh$_0$_F (-)	hF (m)	T$_s$_measl_L (m^2/s)[2]
SFM00022	0.46	2.75	0.45	1.02	2.75	2.68	-0.48	0.96	2.59	$2.05\cdot10^{-8}$
SFM00062	0.31	2.93	0.31	1.00	2.93	2.93	-0.34	0.91	2.67	$1.37\cdot10^{-8}$
SFM00063	0.31	2.30	0.31	1.00	2.36	2.37	-0.30	1.03	2.13	$3.22\cdot10^{-9}$
SFM00065	0.31	3.51	0.30	1.03	3.54	3.55	-0.32	0.97	3.29	$1.50\cdot10^{-9}$
SFM00067	0.32	2.09	0.29	1.10	2.09	2.08	-0.32	1.00	1.89	$8.99\cdot10^{-9}$
SFM00068	0.32	1.41	0.30	1.07	1.41	1.39	-0.33	0.97	1.32	$8.92\cdot10^{-9}$
SFM00069[1]	0.48	1.63	0.33	1.45	1.65	1.65	-0.43	1.12	1.63	$5.74\cdot10^{-7}$
		(1.63)	(0.34)	(1.41)	(1.65)	(1.66)	(-0.43)	(1.12)	(1.64)	
SFM00070	0.64	2.06	0.58	1.10	2.06	2.01	-0.62	1.03	1.88	$1.47\cdot10^{-8}$
SFM00071	0.64	3.97	0.48	1.33	3.97	3.79	-0.58	1.10	3.74	$4.07\cdot10^{-8}$
SFM00072	0.64	3.45	0.61	1.05	3.57	3.57	-0.64	1.00	3.01	$1.31\cdot10^{-9}$
SFM00073	0.16	3.94	0.15	1.07	3.95	3.94	-0.15	1.07	3.92	$2.30\cdot10^{-7}$
SFM00075	0.64	2.89	0.61	1.05	2.91	2.91	-0.60	1.07	2.60	$2.46\cdot10^{-9}$

[1] Two falling- and rising head tests were performed according to the guidelines in the method description SKB MD 325.001 (SKB internal controlling document).

[2] T$_s$_measl_L for the test from which the T-value was delivered for storage in the SICADA database (see Table 5-2).

5.3 Interpreted parameters

5.3.1 Cooper et al. method

Table 5-2 presents the results of the slug-test analysis according to the Cooper et al. method (see description of the method in Section 4.5.1). The left and right main columns present the obtained values of T (and the corresponding value of K within parentheses for the screen length b of each well) and S for the falling-head tests and the rising-head tests, respectively. In each major column, the first two minor columns ("best fit") gives the results for the case when both T and S are varied, whereas the rightmost minor column is for the case with an assumed storativity of S = 10^{-5}.

Table 5-2. Parameters evaluated by the Cooper et al. method

Well	Falling-head test				Rising-head test			
	Test no.	T (m^2/s), best fit (K (m/s), best fit)	S (-), best fit	T (m^2/s), S = 10^{-5} (K (m/s), S = 10^{-5}	Test no.	T (m^2/s), best fit (K (m/s), best fit)	S (-), best fit	T (m^2/s), S = 10^{-5} (K (m/s), S = 10^{-5})
SFM00022	1	$9.82\cdot10^{-7}$ ($1.96\cdot10^{-6}$)	$3.3\cdot10^{-5}$	$1.05\cdot10^{-6}$ ($2.1\cdot10^{-6}$)	1	$7.11\cdot10^{-7}$ ($1.42\cdot10^{-6}$)	$9.11\cdot10^{-5}$	[1]$7.80\cdot10^{-7}$ ($1.56\cdot10^{-6}$)
SFM00062	1	$7.44\cdot10^{-7}$ ($1.86\cdot10^{-6}$)	$4.46\cdot10^{-5}$	$6.06\cdot10^{-7}$ ($1.52\cdot10^{-6}$)	1	$1.03\cdot10^{-7}$ ($2.58\cdot10^{-7}$)	$6.45\cdot10^{-5}$	[1]$1.32\cdot10^{-7}$ ($3.30\cdot10^{-7}$)
SFM00063	1	$8.75\cdot10^{-8}$ ($1.75\cdot10^{-7}$)	$5.5\cdot10^{-3}$	$2.10\cdot10^{-7}$ ($4.20\cdot10^{-7}$)	1	$3.82\cdot10^{-8}$ ($7.64\cdot10^{-8}$)	$1.1\cdot10^{-3}$	[1]$6.17\cdot10^{-8}$ ($1.23\cdot10^{-7}$)
SFM00065	1	$8.96\cdot10^{-8}$ ($2.24\cdot10^{-7}$)	$2.1\cdot10^{-4}$	[1]$1.29\cdot10^{-7}$ ($3.23\cdot10^{-7}$)	1	$3.57\cdot10^{-8}$ ($8.93\cdot10^{-8}$)	$7.9\cdot10^{-4}$	$8.75\cdot10^{-8}$ ($2.19\cdot10^{-7}$)
SFM00067	1	$2.70\cdot10^{-7}$ ($2.70\cdot10^{-7}$)	$1.6\cdot10^{-4}$	$3.57\cdot10^{-7}$ ($3.57\cdot10^{-7}$)	1	$1.21\cdot10^{-7}$ ($2.42\cdot10^{-7}$)	$1.1\cdot10^{-3}$	[1]$2.58\cdot10^{-7}$ ($2.58\cdot10^{-7}$)
SFM00068	1	$5.27\cdot10^{-7}$ ($5.27\cdot10^{-7}$)	$9.6\cdot10^{-5}$	[1]$5.78\cdot10^{-7}$ ($5.78\cdot10^{-7}$)	1	$9.16\cdot10^{-7}$ ($9.16\cdot10^{-7}$)	$7.1\cdot10^{-4}$	$1.87\cdot10^{-6}$ ($1.87\cdot10^{-6}$)
SFM00069	1	$4.26\cdot10^{-5}$ ($4.26\cdot10^{-5}$)	$1.1\cdot10^{-6}$	$3.23\cdot10^{-5}$ ($3.23\cdot10^{-5}$)	1	$6.98\cdot10^{-}$ ($6.98\cdot10^{-5}$)	$1.7\cdot10^{-8}$	[1]$4.20\cdot10^{-5}$ ($4.20\cdot10^{-5}$)
	2	$2.62\cdot10^{-5}$ ($2.62\cdot10^{-5}$)	$2.6\cdot10^{-5}$	$2.87\cdot10^{-5}$ ($2.87\cdot10^{-5}$)	2	$6.47\cdot10^{-5}$ ($6.47\cdot10^{-5}$)	$3.4\cdot10^{-8}$	$4.08\cdot10^{-5}$ ($4.08\cdot10^{-5}$)
SFM00070	1	$6.20\cdot10^{-7}$ ($6.20\cdot10^{-7}$)	$4.3\cdot10^{-5}$	[1]$6.20\cdot10^{-7}$ ($6.20\cdot10^{-7}$)	1	$6.06\cdot10^{-7}$ ($6.06\cdot10^{-7}$)	$1.2\cdot10^{-4}$	$7.45\cdot10^{-7}$ ($7.45\cdot10^{-7}$)
SFM00071	1	$8.37\cdot10^{-7}$ ($8.37\cdot10^{-7}$)	$5.0\cdot10^{-5}$	$1.27\cdot10^{-6}$ ($1.27\cdot10^{-6}$)	1	$8.95\cdot10^{-7}$ ($8.95\cdot10^{-7}$	$2.7\cdot10^{-5}$	[1]$8.95\cdot10^{-7}$ ($8.95\cdot10^{-7}$)
SFM00072	1	$5.92\cdot10^{-8}$ ($5.92\cdot10^{-8}$)	$2.1\cdot10^{-2}$	[1]$4.29\cdot10^{-7}$ ($4.29\cdot10^{-7}$)	1	$3.57\cdot10^{-8}$ ($3.57\cdot10^{-8}$	$8.0\cdot10^{-5}$	$6.49\cdot10^{-8}$ ($6.49\cdot10^{-8}$)
SFM00073	1	$9.95\cdot10^{-6}$ ($9.95\cdot10^{-6}$)	$9.2\cdot10^{-6}$	[1]$9.50\cdot10^{-6}$ ($9.50\cdot10^{-6}$)	1	$1.07\cdot10^{-5}$ ($1.07\cdot10^{-5}$	$8.4\cdot10^{-6}$	$9.79\cdot10^{-6}$ ($9.79\cdot10^{-6}$)
SFM00075	1	$2.10\cdot10^{-7}$ ($2.10\cdot10^{-7}$)	$5.5\cdot10^{-5}$	[1]$2.83\cdot10^{-7}$ ($2.83\cdot10^{-7}$)	1	$2.41\cdot10^{-7}$ ($2.41\cdot10^{-7}$	$1.1\cdot10^{-4}$	$2.77\cdot10^{-7}$ ($2.77\cdot10^{-7}$)

[1] Transmissivity value delivered for storage in the SICADA database.

5.3.2 Hvorslev and Bouwer & Rice methods

Table 5-3 presents the results of the slug-test analysis according to the Hvorslev and Bouwer & Rice methods (see description of these methods in Sections 4.5.2-3). The left and right main columns present the obtained values of K for the falling-head tests and the rising-head tests, respectively. Note that since T = K·b, the values of K (m/s) corresponds to the same value of T (m^2/s) for each slug test (b = 1 m; see Table 2-2), except for SFM0022, -0063, -0067, and -0069 (b = 0.5 m), and SFM0062 and -0065 (b = 0.4 m).

Table 5-3. Values of hydraulic conductivity K (m/s) evaluated by the Hvorslev and Bouwer & Rice methods

Well	Falling-head test			Rising-head test		
	Test no.	Hvorslev method	Bouwer & Rice method	Test no.	Hvorslev method	Bouwer & Rice method
SFM00022	1	$9.16 \cdot 10^{-7}$	$9.07 \cdot 10^{-7}$	1	$5.57 \cdot 10^{-7}$	$5.45 \cdot 10^{-7}$
SFM00062	1	$8.73 \cdot 10^{-7}$	$7.10 \cdot 10^{-7}$	1	$1.18 \cdot 10^{-7}$	$1.08 \cdot 10^{-7}$
SFM00063	1	$4.83 \cdot 10^{-8}$	$7.48 \cdot 10^{-8}$	1	$6.60 \cdot 10^{-8}$	$6.55 \cdot 10^{-8}$
SFM00065	1	$6.28 \cdot 10^{-8}$	$6.00 \cdot 10^{-8}$	1	$6.05 \cdot 10^{-8}$	$5.78 \cdot 10^{-8}$
SFM00067	1	$2.34 \cdot 10^{-7}$	$1.42 \cdot 10^{-7}$	1	$1.18 \cdot 10^{-7}$	$7.54 \cdot 10^{-8}$
SFM00068	1	$3.15 \cdot 10^{-7}$	$2.06 \cdot 10^{-7}$	1	$2.52 \cdot 10^{-7}$	$1.79 \cdot 10^{-7}$
SFM00069	1	$1.13 \cdot 10^{-5}$	$7.32 \cdot 10^{-6}$	1	$2.26 \cdot 10^{-5}$	$1.88 \cdot 10^{-5}$
	2	$1.24 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	2	$2.22 \cdot 10^{-5}$	$1.10 \cdot 10^{-5}$
SFM00070	1	$5.43 \cdot 10^{-7}$	$3.97 \cdot 10^{-7}$	1	$4.06 \cdot 10^{-7}$	$2.88 \cdot 10^{-7}$
SFM00071	1	$3.49 \cdot 10^{-7}$	$4.22 \cdot 10^{-7}$	1	$1.32 \cdot 10^{-7}$	$1.48 \cdot 10^{-7}$
SFM00072	1	$7.23 \cdot 10^{-9}$	$9.65 \cdot 10^{-9}$	1	$2.60 \cdot 10^{-8}$	$2.42 \cdot 10^{-8}$
SFM00073	1	$7.51 \cdot 10^{-6}$	$5.40 \cdot 10^{-6}$	1	$4.56 \cdot 10^{-6}$	$4.32 \cdot 10^{-6}$
SFM00075	1	$7.10 \cdot 10^{-8}$	$7.83 \cdot 10^{-8}$	1	$1.46 \cdot 10^{-7}$	$1.33 \cdot 10^{-7}$

6 Summary and discussions

Slug tests were performed in 12 groundwater monitoring wells in Forsmark during spring 2004. These tests were evaluated according to the methods of Cooper et al. /5/ and /7/, Hvorslev /9/, and Bouwer & Rice /10/.

Fore most of the wells a good to acceptable fit was obtained for the Cooper et al. method by use of a fixed α corresponding to $S = 10^{-5}$. For all wells a very good to good fit was obtained by an adjustment of α. One common problem in the evaluation of slug tests is skin effects due to incomplete well development. The tested wells have only been developed by pumping; development by water injection was not performed since the wells should also be used for water sampling. Further, substituting the aquifer thickness by the nominal screen length may also be invalid for some wells. Furthermore, for some wells it is difficult to determine whether confined, semi-confined or unconfined conditions prevail.

The equations developed for the evaluation of slug tests are also associated with assumptions of, for instance, homogeneity and radial flow. These assumptions may in some cases not be valid, which also provides an explanation for the difficulties to obtain a perfect fit to the type curves (see /5/, /6/ and /7/ for a more thorough discussion of the restrictions on the applicability of the method).

For the reporting to SKB´s SICADA database, the values obtained with fixed $S = 10^{-5}$ were used. 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, and the agreement between the obtained and the calculated initial displacement. For some wells a concave-upwards shape curve was obtained in the semi-logarithmic plots used for the evaluation according to Hvorslev and Bouwer & Rice, rather than the theoretical straight line. Possible explanations to this phenomenon are the same as for the difficulties to fit measured data to the type curves of the Cooper et al. method. The K-values obtained from the evaluation according to Hvorslev and Bouwer & Rice are between $7.23 \cdot 10^{-9}$ and $2.26 \cdot 10^{-5}$ m/s.

The T-values obtained from the Cooper et al. method, reported to the SICADA database, are between $1.29 \cdot 10^{-7}$ and $4.20 \cdot 10^{-5}$ m^2/s. The geometrical mean of the corresponding K-values is $8.12 \cdot 10^{-7}$ m/s, whereas the arithmetic mean and the median of K is $4.74 \cdot 10^{-6}$ and $5.04 \cdot 10^{-7}$ m/s, respectively. The standard deviation of log-K is 0.7208. Assuming a log-normally distributed K, the 95 % confidence interval for the mean hydraulic conductivity is $2.96 \cdot 10^{-7} < 8.12 \cdot 10^{-7} < 2.36 \cdot 10^{-6}$ m/s. The 95 % confidence interval for a new measurement is wider, $3.14 \cdot 10^{-8} < 8.12 \cdot 10^{-7} < 2.10 \cdot 10^{-5}$ m/s.

The uncertainty in the estimation of S is large. However, the results do not reject the assumption that S is in the order of 10^{-5}.

7 References

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/9/ **Hvorslev M J, 1951.** Time lag and soil permeability in ground-water observations. Bull. 26, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, MS.

/10/ **Waterloo Hydrogeologic, Inc, 2000.** User's guide for Aquifer Test. Waterloo Hydrogeologic, Inc., Waterloo, Ont., Canada.

Appendix 1

List of generated raw data files and primary data files

Table A1. List of generated raw data files and primary data files. The symbol * denotes file names including “S_est” for curve fitting using the assumed value of S (= 10^{-5}), and files names including “best_fit” for curve fitting, where both S and T were varied to obtain the best fit**

Obs. well	**Raw data files:** ***.mon** ***.csv**	**Data processing files:** ***.xls**	**Primary data files**	
			Cooper et al. method: ***.xls**	**Hvorslev and Bouwer & Rice methods:** ***.mdb**
	Parameters: **Pressure and temperature**		**Parameters:** **Transmissivity and storativity**	**Parameter:** **Hydraulic conductivity**
SFM00022	SFM0022_steg1 SFM0022_steg2 SFM0022_aterhamtning	SFM0022_bearbetningsfil	SFM0022_slugtest_***_Slug_Cooper_Greene SFM0022_bailtest_***_Slug_Cooper_Greene	SFM0022
SFM00062	SFM0062_steg1 SFM0062_steg2 SFM0062_återhämtning	SFM0062_bearbetningsfil	SFM0062_slugtest_***_Slug_Cooper_Greene SFM0062_bailtest_***_Slug_Cooper_Greene	SFM0062
SFM00063	SFM0063_steg1 SFM0063_steg2 SFM0063_aterhamtning	SFM0063_bearbetningsfil	SFM0063_slugtest_***_Slug_Cooper_Greene SFM0063_bailtest_***_Slug_Cooper_Greene	SFM0063
SFM00065	SFM0065_steg1 SFM0065_steg2 SFM0065_aterhamtning	SFM0065_bearbetningsfil	SFM0065_slugtest_***_Slug_Cooper_Greene SFM0065_bailtest_***_Slug_Cooper_Greene	SFM0065
SFM00067	SFM0067_steg1 SFM0067_steg2 SFM0067_aterhamtning	SFM0067_bearbetningsfil	SFM0067_slugtest_***_Slug_Cooper_Greene SFM0067_bailtest_***_Slug_Cooper_Greene	SFM0067
SFM00068	SFM0068_steg1 SFM0068_steg2 SFM0068_aterhamtning	SFM0068_bearbetningsfil	SFM0068_slugtest_***_Slug_Cooper_Greene SFM0068_bailtest_***_Slug_Cooper_Greene	SFM0068
SFM00069	SFM0069	SFM0069_bearbetningsfil	SFM0069_slugtest_1_***_Slug_Cooper_Greene SFM0069_bailtest_1_***_Slug_Cooper_Greene SFM0069_slugtest_2_***_Slug_Cooper_Greene SFM0069_bailtest_2_***_Slug_Cooper_Greene	SFM0069

Table A1. Continued

SFM00070	SFM0070_steg1 SFM0070_steg2 SFM0070_aterhamtning	SFM0070_bearbetningsfil	SFM0070_slugtest_***_Slug_Cooper_Greene SFM0070_bailtest_***_Slug_Cooper_Greene	SFM0070
SFM00071	SFM0071_steg1 SFM0071_steg2 SFM0071_aterhamtning	SFM0071_bearbetningsfil	SFM0071_slugtest_***_Slug_Cooper_Greene SFM0071_bailtest_***_Slug_Cooper_Greene	SFM0071
SFM00072	SFM0072_steg1 SFM0072_steg2 SFM0072_aterhamtning	SFM0072_bearbetningsfil	SFM0072_slugtest_***_Slug_Cooper_Greene SFM0072_bailtest_***_Slug_Cooper_Greene	SFM0072
SFM00073	SFM0073	SFM0073_bearbetningsfil	SFM0073_slugtest_***_Slug_Cooper_Greene SFM0073_bailtest_***_Slug_Cooper_Greene	SFM0073
SFM00075[1]	SFM0071x_steg1 SFM0071x_steg2 SFM0071x_aterhamtning	SFM0075_bearbetningsfil	SFM0075_slugtest_***_Slug_Cooper_Greene SFM0075_bailtest_***_Slug_Cooper_Greene	SFM0075

[1] Monitoring well SFM0075 was temporarily named SFM0071X when the raw data files were generated.

Appendix 2

Diagrammes

Appendix 2 contains diagrammes of the results of the slug tests.

Figures A2-1 to A2-26 show semi-log plots of the normalized displacement versus time (the scale for the time is logarithmic). Further, the displacement data are fitted to type curves according to the Cooper et al. method, whereby the estimates of T and S (presented in Section 5.3.1) are obtained. Note that the results of the curve-fitting considers an adjustment of S. In the diagrammes, the nomenclature for the normalized displacement is as follows:

y/y0 = dh_p/dh0_p for falling-head test

y/y0 = abs(dh_F/dh0_F) for rising-head test

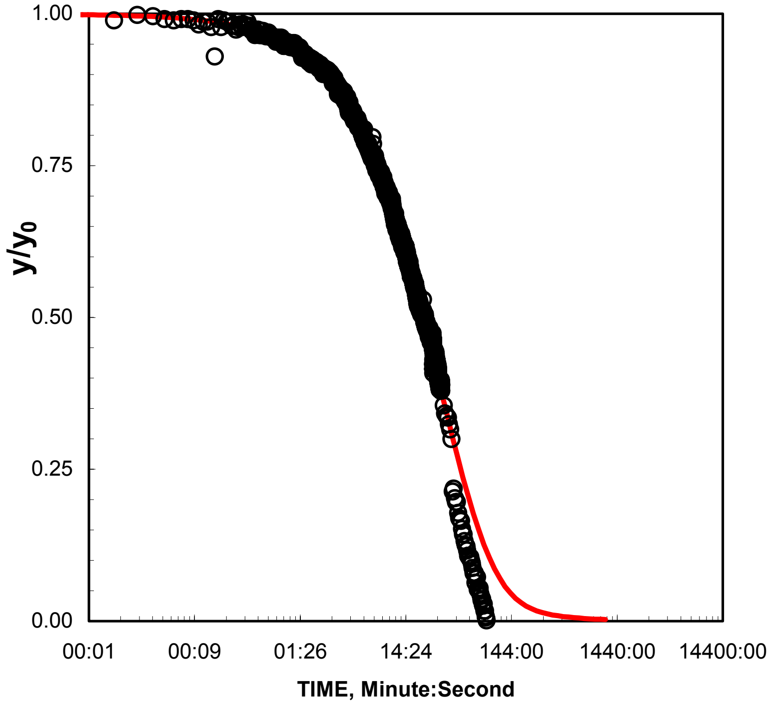

Figure A2-1. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the falling-head test in SFM0022.*

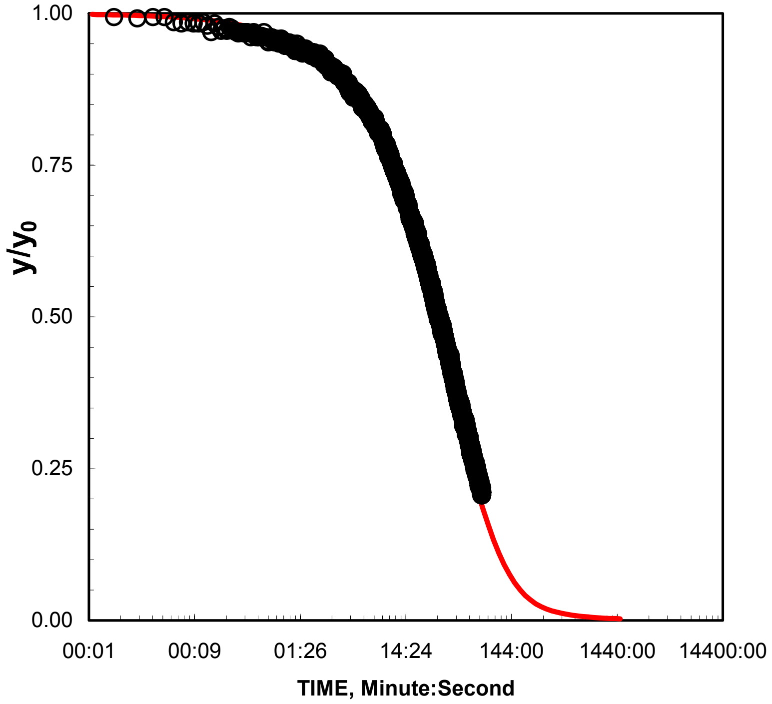

Figure A2-2. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the rising-head test in SFM0022.*

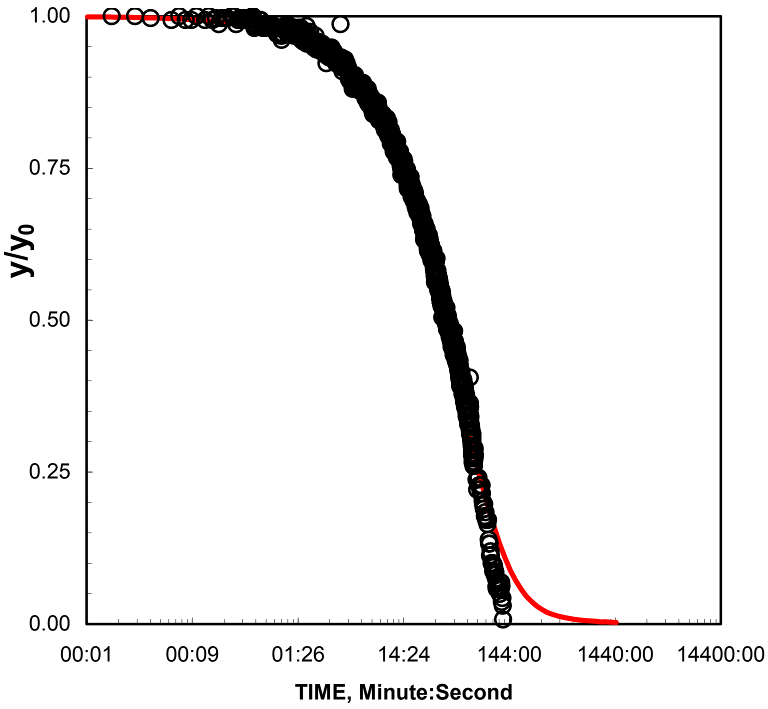

Figure A2-3. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the falling-head test in SFM0062.*

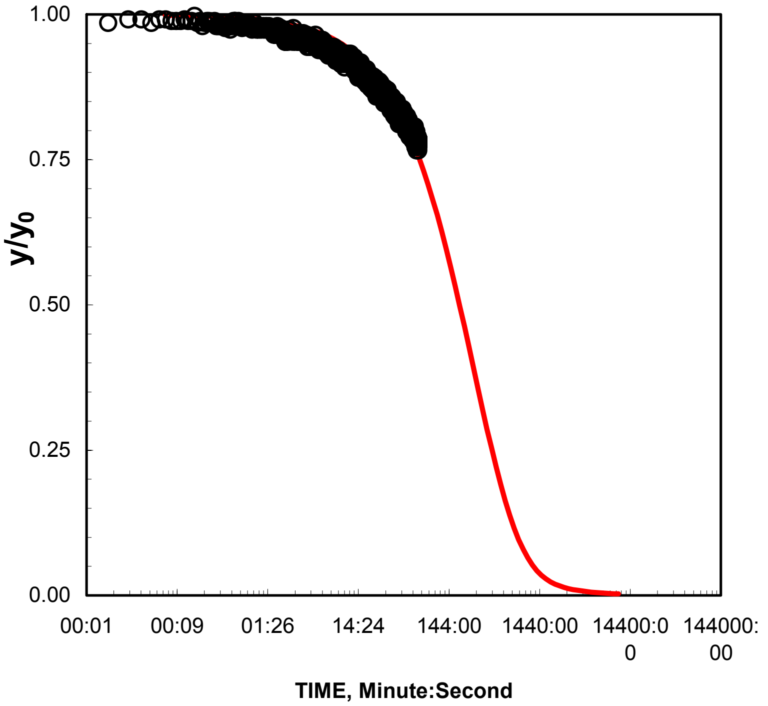

Figure A2-4. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the rising-head test in SFM0062.*

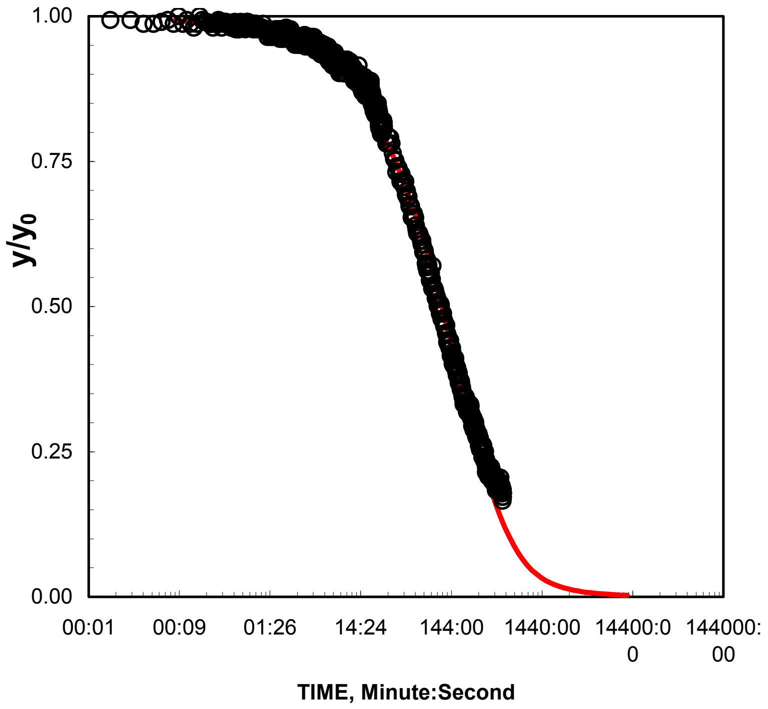

***Figure A2-5**. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0063.*

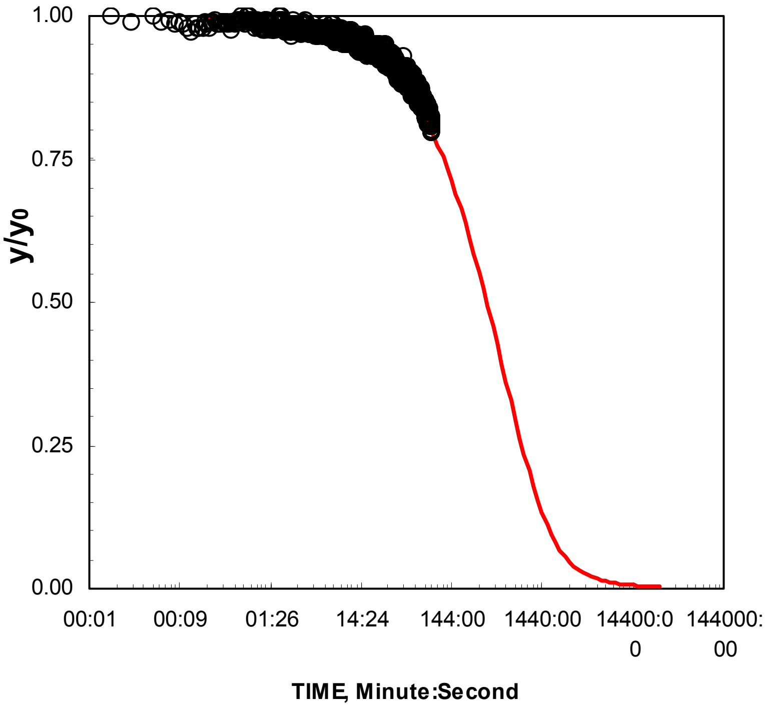

***Figure A2-6.** Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0063.*

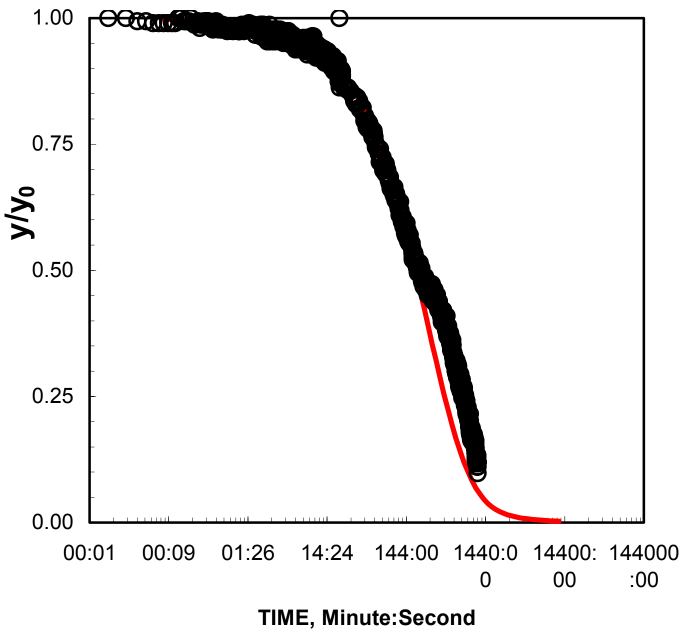

Figure A2-7. *Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0065.*

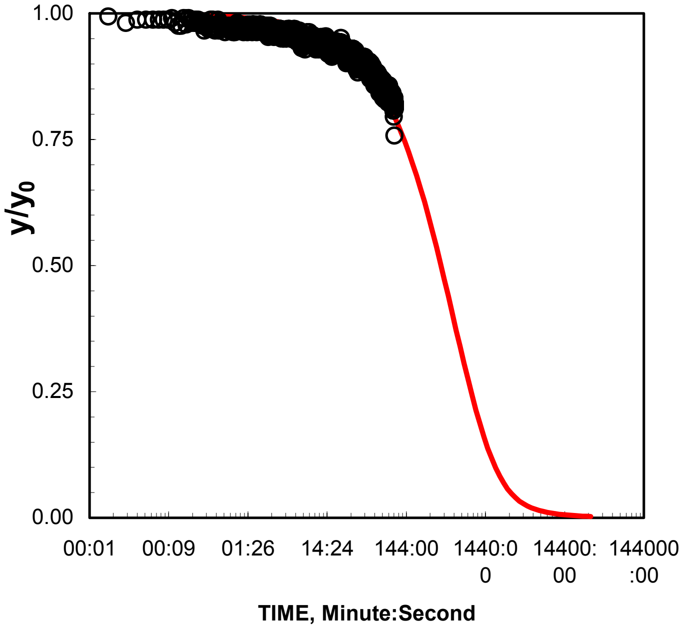

Figure A2-8. *Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0065.*

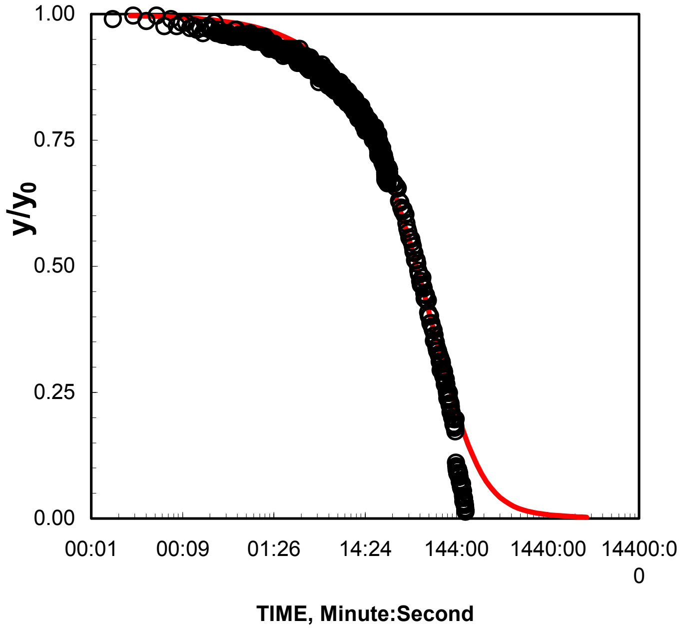

Figure A2-9. *Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0067.*

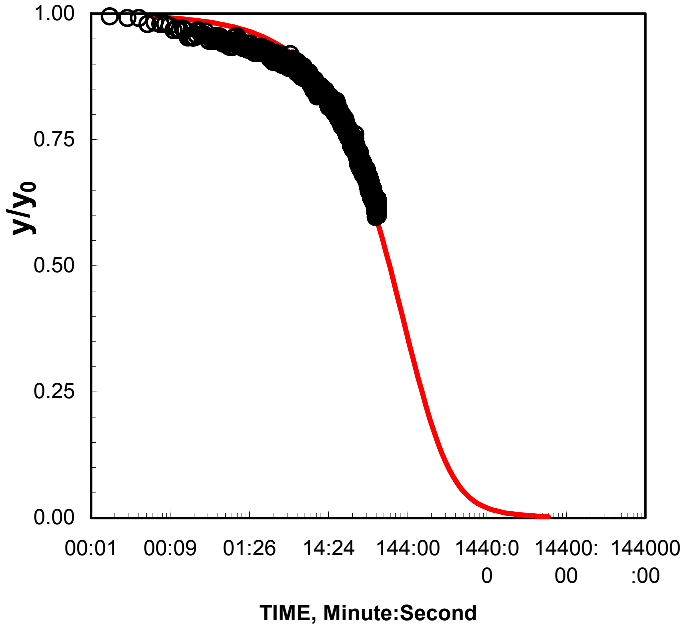

Figure A2-10. *Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0067.*

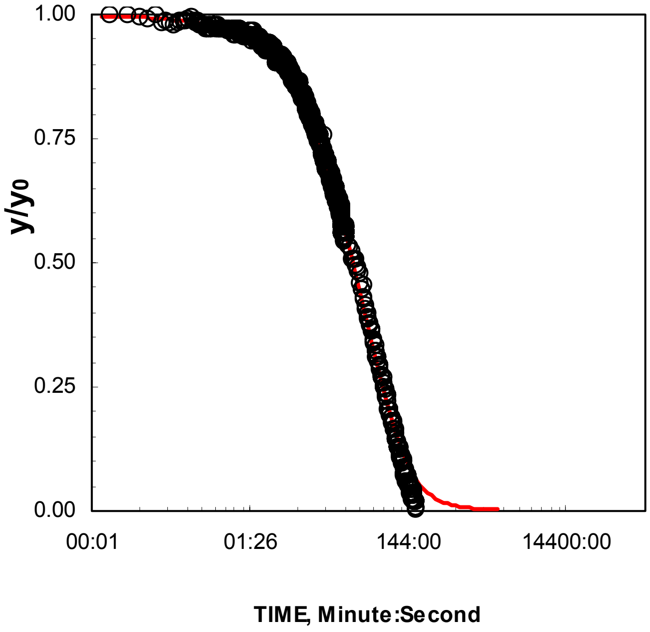

Figure A2-11. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the falling-head test in SFM0068.*

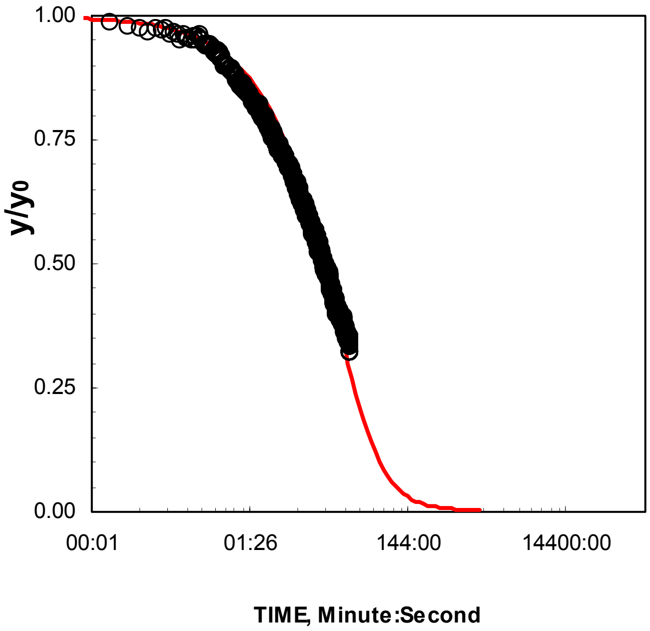

Figure A2-12. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the rising-head test in SFM0068.*

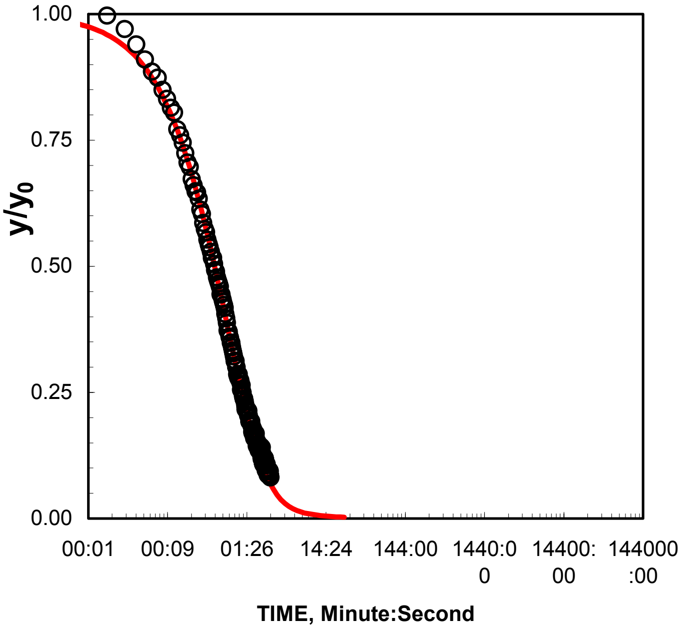

Figure A2-13. *Log-linear plot of the normalized displacement* y/y$_0$ *versus time for falling-head test no. 1 in SFM0069.*

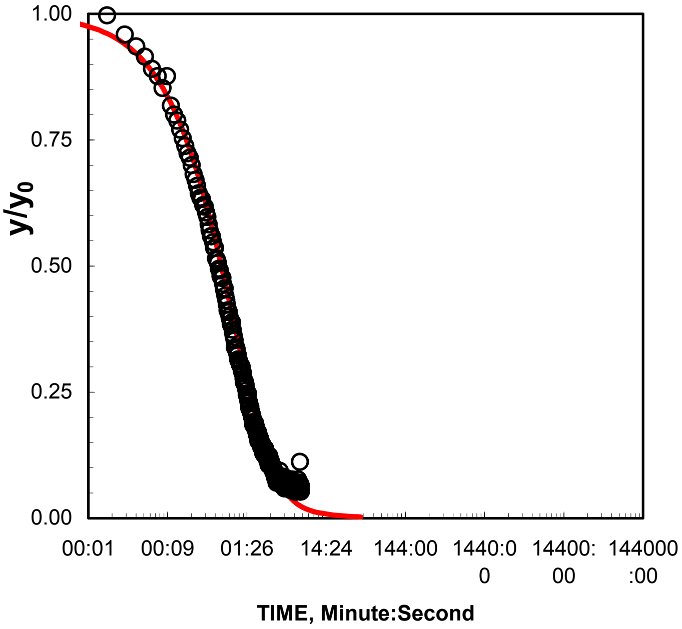

Figure A2-14. *Log-linear plot of the normalized displacement y/y$_0$ versus time for falling-head test no. 2 in SFM0069.*

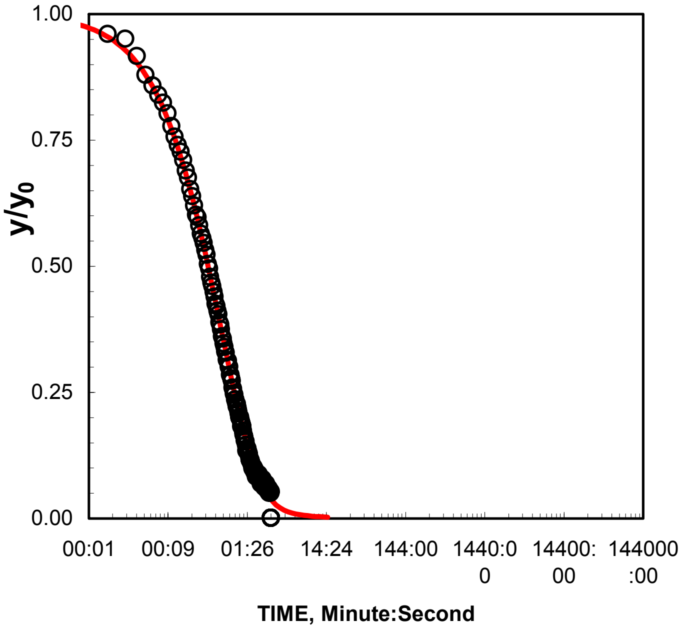

Figure A2-15. *Log-linear plot of the normalized displacement y/y*$_0$ *versus time for rising-head test no. 1 in SFM0069.*

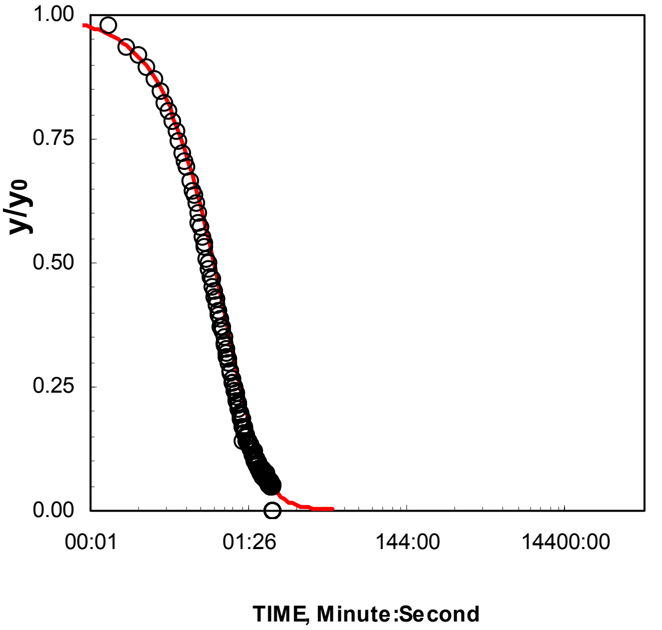

Figure A2-16. *Log-linear plot of the normalized displacement y/y*$_0$ *versus time for rising-head test no. 2 in SFM0069.*

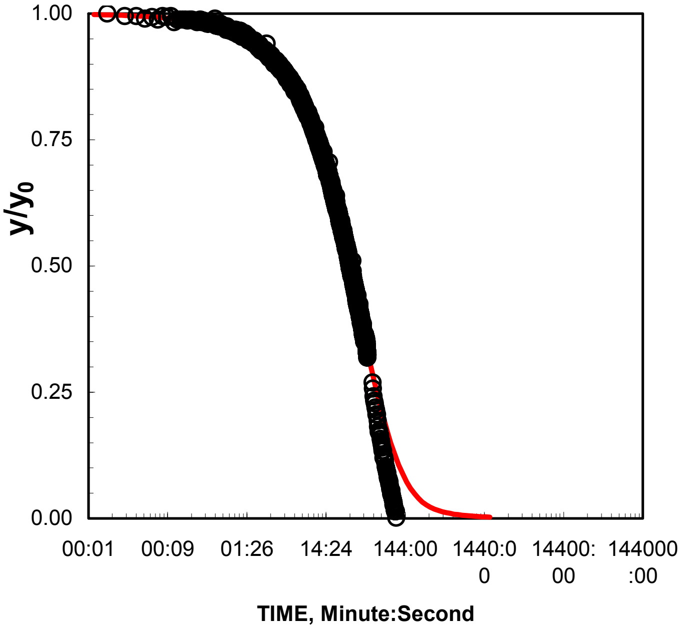

Figure A2-17. *Log-linear plot of the normalized displacement* y/y$_0$ *versus time for the falling-head test in SFM0070.*

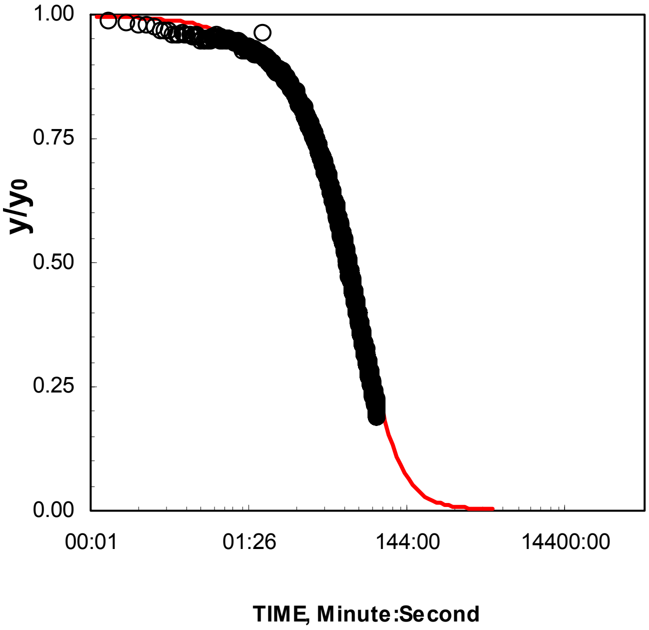

Figure A2-18. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the rising-head test in SFM0070.*

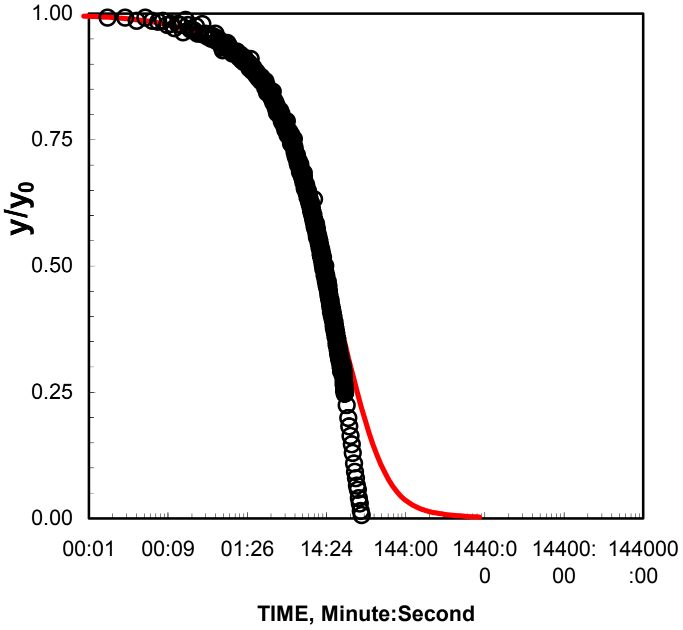

Figure A2-19. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the falling-head test in SFM0071.*

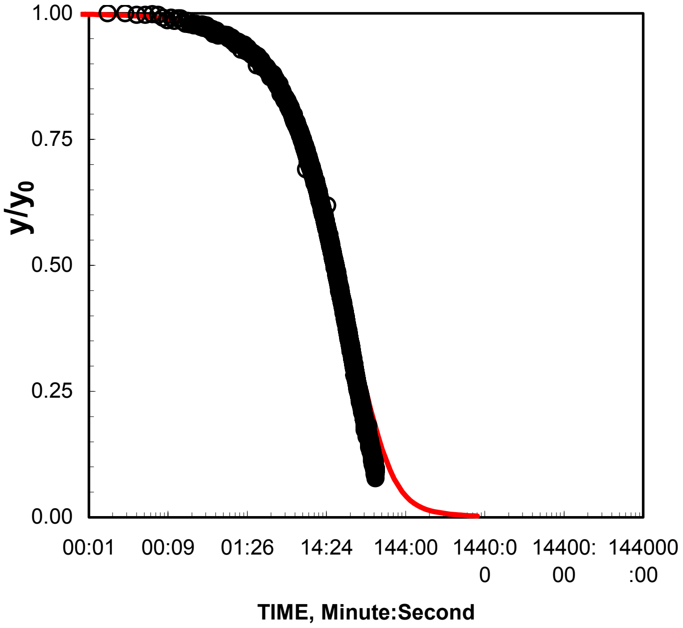

Figure A2-20. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the rising-head test in SFM0071.*

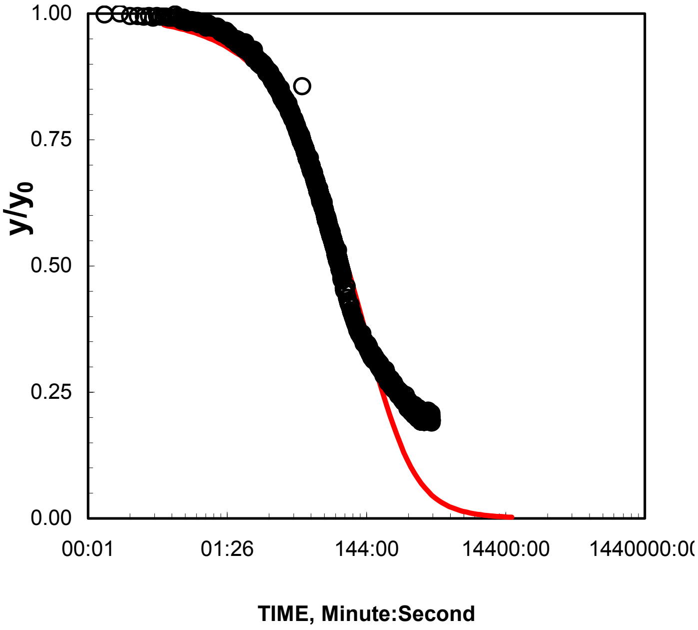

Figure A2-21. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the falling-head test in SFM0072.*

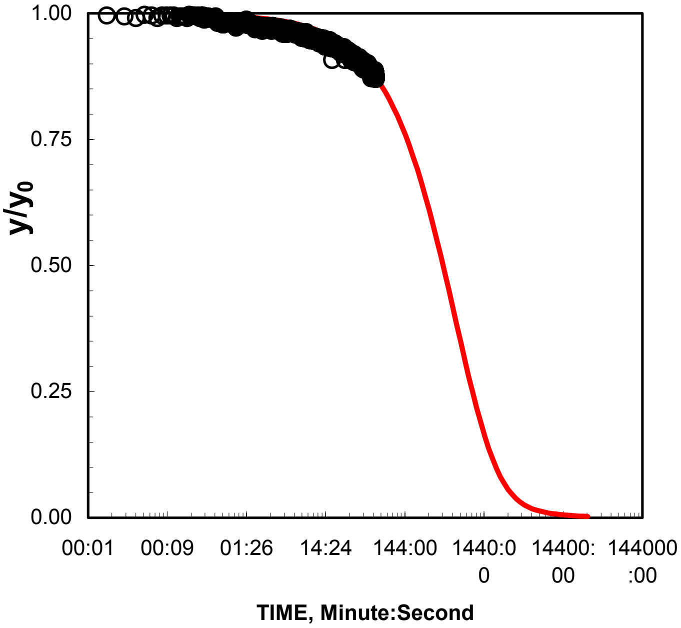

Figure A2-22. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the rising-head test in SFM0072.*

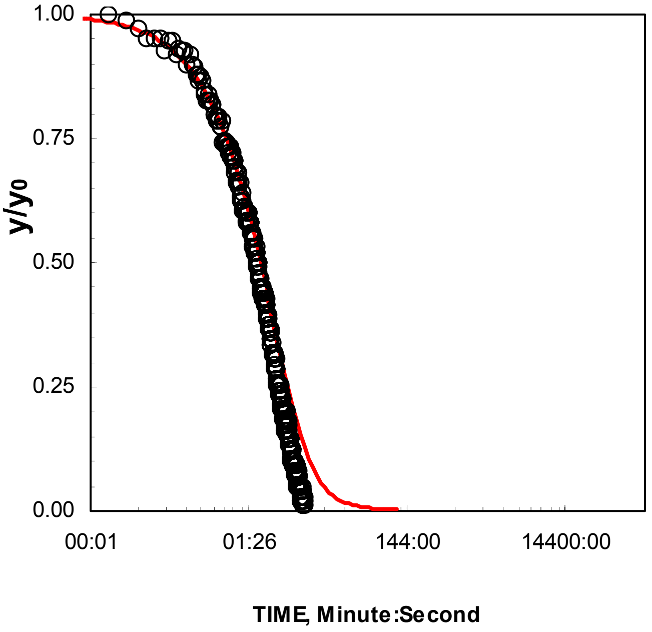

Figure A2-23. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the falling-head test in SFM0073.*

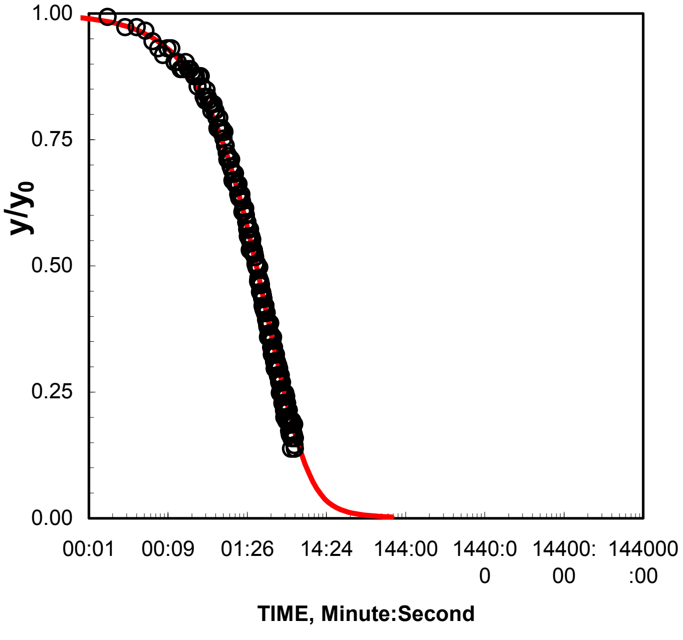

Figure A2-24. *Log-linear plot of the normalized displacement y/y$_0$ versus time for the rising-head test in SFM0073.*

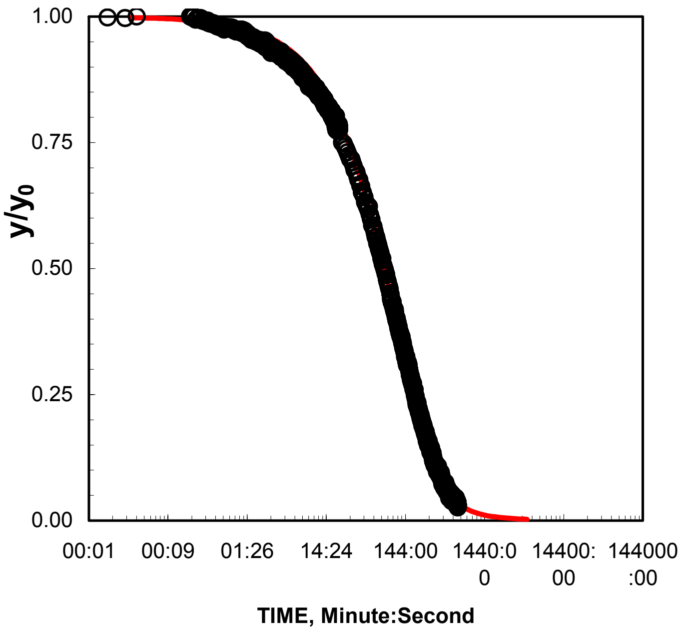

Figure A2-25. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the falling-head test in SFM0075.*

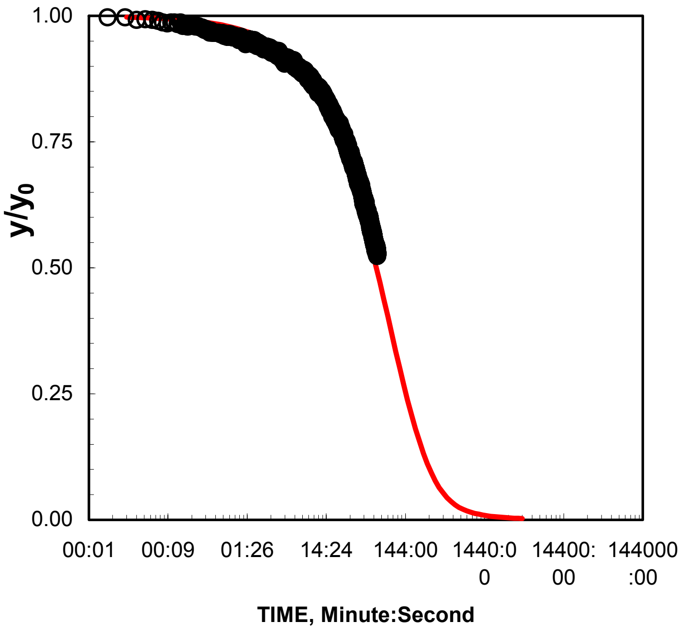

Figure A2-26. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the rising-head test in SFM0075.*