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Forsmark site investigation

Slug tests in groundwater monitoring wells in soil

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SWECO VIAK

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Abstract

The methodology, results and analysis of slug tests performed during spring 2003 in 36 monitoring wells (SFM0001–0006, SFM0008–0021, SFM0023–0037, and SFM0049) in the Forsmark area are presented. The objective of the slug tests was to obtain data for the estimation of the transmissivity (T) and the storativity (S) of the contact zone between the soil and the bedrock. The data from the tests were evaluated using three separate methods: the Cooper et al method, the Hvorslev method, and the Bouwer & Rice method. The Cooper et al method allowed for the estimation of both T and S, whereas the other methods gave estimates of the hydraulic conductivity (K).

For most wells a good to acceptable fit was obtained for the Cooper et al method applying a fixed α (corresponding to $S = 10^{-5}$). For some wells a somewhat better fit was obtained by varying α. For some wells it was not possible to obtain an acceptable fit. There could be several reasons for this. The most common problem in evaluation of slug tests is skin effects due to incomplete well-development. The tested wells had only been developed by pumping. Some of the wells gave very little water and therefore the well development was not very effective. Development by water injection was not performed since the wells should also be used for water sampling. 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, radical flow etc. that can explain the difficulties to fit measured values to the type curves.

For the reporting to the SICADA database, the values obtained with the fixed $S=10^{-5}$ were used. The selection of the T-value to be reported was also based on which of the falling- or rising-head tests that gave the best fit to the type curves and to what extent the obtained and calculated initial displacement agreed.

For some wells a concave-upward shape curve was obtained in the semi-logarithmic plots used for the evaluation according to Hvorslev and Bouwer & Rice. Theoretically, a straight line should be obtained. Possible explanations to this are the same as for the difficulties to fit measured data to the types curves of the Cooper et al method.

The T-values obtained from the Cooper et al method which were reported to the SICADA database varied between $5.62 \cdot 10^{-8}$ and $5.50 \cdot 10^{-4}$ m^2/s. The geometric mean of all wells was $1.18 \cdot 10^{-5}$ m^2/s and the standard deviation was $1.26 \cdot 10^{-4}$. The uncertainty in the estimation of S is large. However, the results did not reject the assumption that S is in the order of 10^{-5}.

The T-values obtained from the Hvorslev and Bouwer & Rice methods varied between $8.10 \cdot 10^{-9}$ and $8.41 \cdot 10^{-4}$ m^2/s. The geometric means were somewhat lower than for the Cooper et al evaluation; from $5.05 \cdot 10^{-6}$ m^2/s for the rising head evaluations according to Bouwer & Rice up to $6.56 \cdot 10^{-6}$ m^2/s for the falling head evaluation according to Hvorslev. The standard deviations were very similar to those obtained from the evaluation by the Cooper et al method.

Sammanfattning

Metodik, genomförande, resultat och analys från de slugtester som genomfördes i 36 st grundvattenrör i jord (SFM0001–0006, SFM0008–0021, SFM0023–0037, and SFM0049) i Forsmarksområdet under våren 2003 redovisas i rapporten. Målet med slugtesterna var att erhålla data för bestämning av transmissiviteten (T) och storativiteten (S) för kontaktzonen mellan jord och berg. Data analyserades med tre olika metoder: the Cooper et al, Hvorslev och Bouwer & Rice metoderna. Cooper et al metoden ger möjlighet för bestämning av både T och S medan de båda andra metoderna endast ger värden för T.

För huvuddelen 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 vissa rör erhölls en något bättre passning om α varierades. För några rör var det inte möjligt att få en acceptabel passning. Skälen till detta 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. Några av rören gav mycket lite vatten och därför blev inte rensningen effektiv. Rensning genom injektering av vatten utfördes inte eftersom rören också skulle användas för vattenprovtagning. Antagandet att för de ofullständiga brunnarna ersätta akviferens tjocklek med en effektiv längd av brunnsfiltret lika med dess verkliga längd kan också vara ogiltigt för vissa brunnar. Vidare var det för flera av rören svårt att avgöra i vilken utsträckning slutna, läckande eller öppna förhållanden rådde. I de ekvationer som utvecklats för metoden finns också ett flertal antaganden, som t ex homogenitet, radiellt flöde etc som kanske inte är uppfyllda och som kan förklara svårigheterna att passa uppmätta data till metodens typkurvor.

För rapportering till SICADA användes de data som erhölls för $S = 10^{-5}$. Valet av det T-värde som inrapporterades 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 resp sänkning av grundvattennivån.

För vissa rör erhölls en konkav kurva vid 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 T-värden som erhölls från Cooper et al metoden och som inrapporterats till SICADA-databasen varierade mellan $5.62 \cdot 10^{-8}$ and $5.50 \cdot 10^{-4}$ m^2/s. Det geometriska medelvärdet var $1.18 \cdot 10^{-5}$ m^2/s och standardavvikelsen $1.26 \cdot 10^{-4}$. Osäkerheten i uppskattningen av S är stor. Resultaten motsade emellertid inte antagandet om ett S i storleksordningen 10^{-5}.

De T-värden som erhölls från utvärderingen enligt Hvorslev och Bouwer & Rice varierade mellan $8.10 \cdot 10^{-9}$ och $8.41 \cdot 10^{-4}$ m^2/s. De geometriska medelvärdena var något lägre än för utvärderingen enligt Cooper et al; från $5.05 \cdot 10^{-6}$ m^2/s för ”rising head” utvärderingen enligt Bouwer & Rice upp till $6.56 \cdot 10^{-6}$ m^2/s för ”falling head” utvärderingen enligt Hvorslev. Standardavvikelserna var i stort desamma som de som erhölls vid utvärderingen enligt Cooper et al.

Contents

1 Introduction

This report presents the methodology, results and analysis of slug tests performed in the Forsmark area during the period March 26 to April 16, 2003. The tests have been performed according to the Activity Plan AP PF 400-03-23 for slug tests in groundwater monitoring wells in soil in Forsmark. A total of 36 observation wells, installed during spring 2003 /1/, 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.

Most tested wells are placed in till, in the contact zone between soil and bedrock. The composition of the till varies from sandy, silty till to clayey till. At many locations the till is overlain by peat, gyttja, dy, and/or clay meaning that semi-confined to confined conditions prevail. At other locations the till extend to the ground surface or is overlain by relatively conductive sand deposits, and unconfined conditions prevail. For information on soil profiles at the groundwater monitoring wells, see /1/ and /2/.

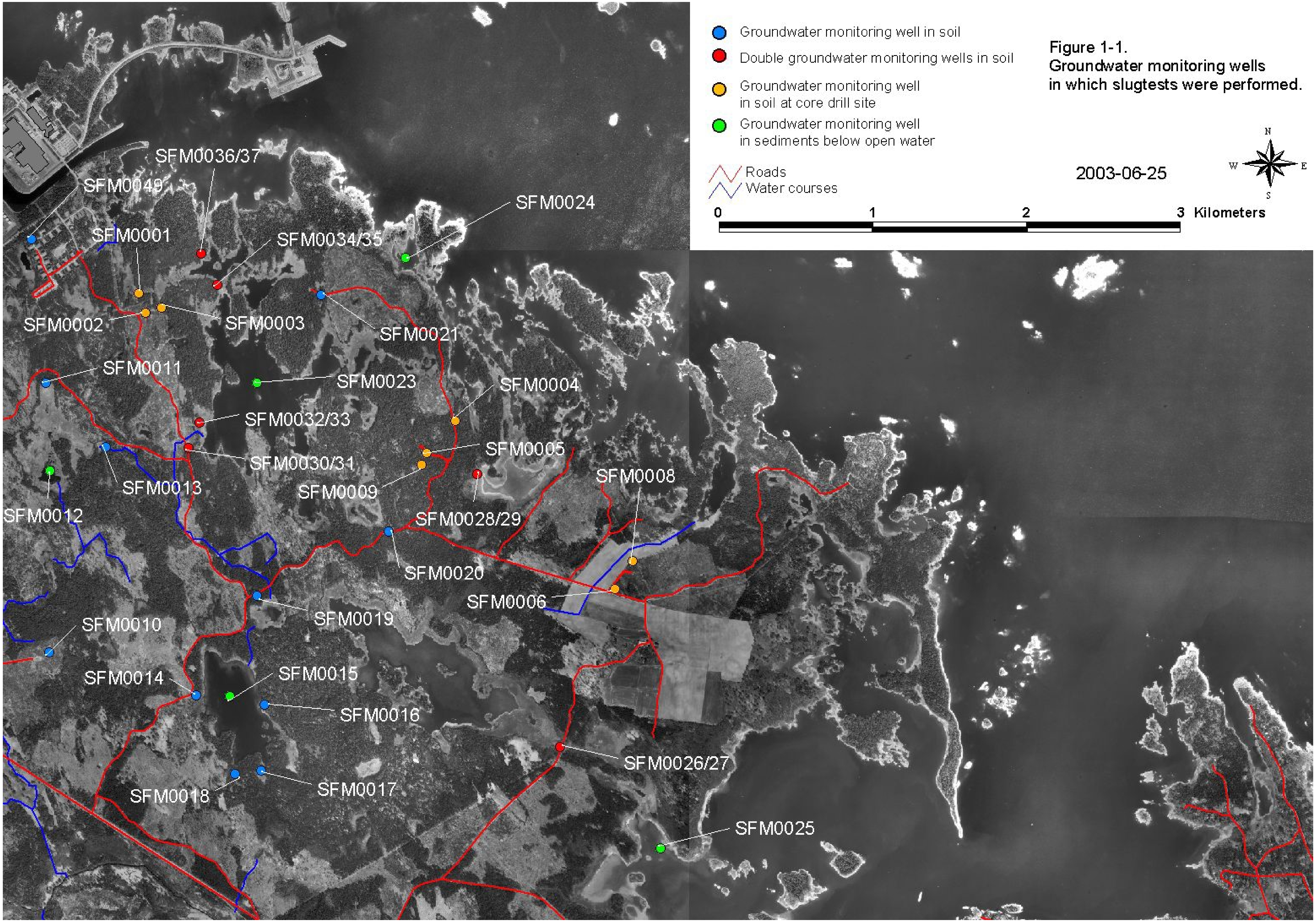

Figure 1-1.
Groundwater monitoring wells in which slugtests were performed.

2 Objectives

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 contact zone between the soil and the upper parts of the bedrock /1/.

3 Scope

3.1 Boreholes tested

Basic technical data of the groundwater monitoring wells in which the slug tests were performed are given in Table 3-1. The observation wells SFM0012, SFM0015, and SFM0023–0025 are installed in soil below open water. In these wells, the stand pipe is made of steel. All other wells have a stand pipe made of HDPE, and a cover pipe at the for protection of the stand pipe above ground. In the table below, the reference point is the top of the stand pipe (ToSP).

Table 3-1. Technical data of the tested observation wells SFM0001–0006, SFM0008–0021, SFM0023–0037, and SFM0049.

Groundwater monitoring well		Stand pipe		Screen (test section)		
	Borehole diameter[1], d_w (mm)	Inner diameter of stand pipe, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[2] (m)	Depth to borehole seclow[2] (m)	Screen length, b (m)
SFM0001[4]	168	50	0	3.95	4.95	1
SFM0002[4]	168	50	0	4.20	5.20	1
SFM0003[4]	168	50	0	9.00	11.00	2
SFM0004[4]	193.7	76	0	5.00	6.00	1
SFM0005[4]	193.7	76	0	2.10	3.10	1
SFM0006[4]	193.7	76	0	3.10	4.10	1
SFM0008[4]	193.7	76	0	5.10	6.10	1
SFM0009	103	50	0	2.05	3.05	1
SFM0010	103	50	0	1.34	2.34	1
SFM0011	103	50	0	3.49	4.49	1
SFM0012	60.3[3]	51.3	~2	5.37	6.37	1
SFM0013	103	50	0	4.50	5.50	1
SFM0014	103	50	0	2.00	3.00	1
SFM0015	60.3[3]	51.3	~5	6.34	7.34	1
SFM0016	103	50	0	7.50	8.50	1
SFM0017	103	50	0	4.00	5.00	1
SFM0018	103	50	0	4.50	5.50	1
SFM0019	103	50	0	4.50	5.50	1
SFM0020	103	50	0	3.00	4.00	1
SFM0021	103	50	0	2.00	3.00	1
SFM0023	60.3[3]	51.3	0	4.45	5.45	1
SFM0024	60.3[3]	51.3	0	2.72	3.22	0.5
SFM0025	60.3[3]	51.3	0	6.06	7.06	1

Table 3-1. Continued.

Groundwater monitoring well		Stand pipe		Screen (test section)		
	Borehole diameter[1], d_w (mm)	Inner diameter of stand pipe, d_c (mm)	Estimated inclination from vertical plane (°)	Depth to borehole secup[2] (m)	Depth to borehole seclow[2] (m)	Screen length, b (m)
SFM0026	103	50	0	16.00	17.00	1
SFM0027	103	50	0	7.04	8.04	1
SFM0028	103	50	0	7.00	8.00	1
SFM0029	103	50	0	7.00	8.00	1
SFM0030	103	50	0	4.00	5.00	1
SFM0031	103	50	0	3.50	4.50	1
SFM0032	103	50	0	3.00	4.00	1
SFM0033	103	50	0	3.00	4.00	1
SFM0034	103	50	0	2.00	3.00	1
SFM0035	103	50	0	2.00	3.00	1
SFM0036	103	50	0	2.00	3.00	1
SFM0037	103	50	0	2.00	3.00	1
SFM0049	103	50	0	4.00	5.00	1

[1]Drilling 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 used for evaluation of T and S (see Section 6) was therefore assumed to be 103 mm.

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

[3]Assumed equal to the outer diameter of the standpipe, as no filter sand was applied in these boreholes during drilling.

[4]Data supplied by SKB.

3.2 Tests

The performed slug tests are summarized in Table 3-2.

Table 3-2. Slug tests performed in the observation wells SFM0001–0006, SFM0008–0021, SFM0023–0037, and SFM0049.

Obs. well	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[2] (s)	tF[2] (s)	Depth to water level in well prior to slug test[3] (m)	Tew[4] (°C)	ECw[4] (mS/m)
SFM0001	2003-04-03 13:29:29	49	64	0.47	3.01	19.91
SFM0002	2003-04-07 12:59:23	850	1571	0.71	4.56	5.22
SFM0003	2003-04-03 16:59:40	640		0.51	3.35	4.56
SFM0004	2003-04-08 09:39:30	75682	5339	1.25	3.52	4.08
SFM0005	2003-04-16 07:25:23	306	265	1.77	4.14	2.94
SFM0006	2003-04-08 08:42:43	63148	5116	1.76	4.44	47.28
SFM0008	2003-04-08 08:18:41	1184	813	3.25	3.77	4.63
SFM0009	2003-04-02 08:22:42	457 (422)	388 (363)	0.48	3.11	4.14
SFM0010	2003-04-03 07:17:05	937	1051	0.57	2.94	3.43
SFM0011	2003-04-02 15:16:35	936	1345	0.62	4.63	58.63
SFM0012	2003-04-24 15:47:55	28320	660	0.94	7.13	50.02
SFM0013	2003-04-02 15:47:17	1819	2999	0.64	3.83	39.82
SFM0014	2003-03-27 13:13:52	342	434	1.16	4.59	4.55
SFM0015	2003-03-27 10:33:24	3655	4154	0.41	6.79	17.27
SFM0016	2003-04-14 12:43:09	28	77	0.90	5.39	4.48
SFM0017	2003-04-14 14:10:09	156	47	1.18	2.96	5.97

Table 3-2. Continued.

Obs. well	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[2] (s)	tF[2] (s)	Depth to water level in well prior to slug test[3] (m)	Tew[4] (°C)	ECw[4] (mS/m)
SFM0018	2003-04-15 08:00:39	391	832	1.33	4.37	4.53
SFM0019	2003-04-03 15:06:54	3728	2133	1.54	4.41	6.87
SFM0020	2003-03-26 16:06:51	44 (49)	55 (62)	0.72	3.97	5.97
SFM0021	2003-04-02 10:06:42	190	66	0.82	3.4	3.68
SFM0023	2003-04-15 15:10:41	13412	153	0.52	7.88	81.13
SFM0024	2003-03-26 14:25:58	5 (11)	7	0.76	5.03	55.94
SFM0025	2003-04-15 12:46:45	961	503	1.11	5.74	27.03
SFM0026	2003-04-03 11:54:40	921	1299	0.43	3.58	9.36
SFM0027	2003-04-14 16:25:25	7882	5447	0.70	4.56	5.62
SFM0028	2003-03-28 08:12:51	243	206	0.73	4.15	6.23
SFM0029	2003-04-01 16:58:18	139 (148)	170 (164)	0.95	3.9	6.87
SFM0030	2003-04-02 12:09:25	5513		1.24	2.91	8.82
SFM0031	2003-03-27 15:47:26	5340	3844	1.07	3.1	7.28
SFM0032	2003-04-02 12:54:52	16	15	0.97	3.47	6.37
SFM0033	2003-04-02 13:17:37	3	27	1.03	3.01	6.02
SFM0034	2003-04-04 08:53:21	9479	3537	0.98	2.77	11.90
SFM0035	2003-04-16 12:18:11	225480	456	0.88	3.54	7.47
SFM0036	2003-04-04 07:27:59	192	195	0.89	2.62	8.71

Table 3-2. Continued.

Obs. well	Test start[1] (YYYY-MM-DD hh:mm:ss)	tp[2] (s)	tF[2] (s)	Depth to water level in well prior to slug test[3] (m)	Tew[4] (°C)	ECw[4] (mS/m)
SFM0037	2003-04-04 07:56:25	512	363	0.96	2.18	9.11
SFM0049	2003-04-03 08:20:54	73	93	1.10	1.15	3.73

[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. Numbers in parentheses indicate that two falling-head tests and/or two rising-head test were perfomed.

[3]The reference point is ToSP.

[4] Tew and Ecw denotes well water temperature and electrical conductivity, respectively.

Prior to each slug test, all equipment that was lowered into the observation well was cleaned with a soft cloth containing 70% denaturated alcohol /5/. 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, at a depth of 3.3 m below the top of the cover pipe. In order to observe the displacement of the water level in the well during the test, beside the continuous recording by a pressure transducer, the water level in the well was also measured with a manual water-level meter several times during each test.

3.3 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 observation well for logging 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.

4 Equipment

4.1 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 in stainless steel (Figure 4-1).
4. Slug made of a HDPE pipe (filled with sand and an iron rod) and wire in stainless steel (slug tests in SFM0004–0008, which have a 3-inch stand pipe).
5. Wire stopper (spanner wrench).
6. Folding rule.
7. Elwa PLS 50A water-level meter, with light- and sound indicator.
8. WTW LF 320 conductivity meter with TetraCon® Standard-conductivity cell.

Figure 4-1. *The stainless-steel slug that was used to create the water-level displacement in all 2-inch observation wells. The length of the slug can be adjusted by adding or removing 0.25- and 0.50-m sections.*

4.2 Sensors

Basic sensor data of the Diver® and the conductivity meter are given in Tables 4-1a and b.

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 4-1a. Sensor data of the Diver®.

	Name	Unit	Value/range
Pressure	Measurement range	cm wc[1]	0 to 1000[2]
	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.

[2]A Diver® with a measurement range of 0 to 3000 cm wc was used in SFM0006 due to technical problems.

Table 4-1b. Sensor data of the WTW conductivity meter.

Name	Unit	Value/range
Measurement range	µS/cm	0–199.9
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
Outer diameter of slug used in SFM0004–0006 and 0008: 63 mm

Table 4-2 shows 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 (ToSP).

Table 4-2. Position (from ToSP) of pressure transducer in Diver® and slug in the performed slug tests.

Borehole	Diver® depth[1] during slug test (m)	Wire length[1] (m)	Slug length (m)
SFM0001	2.85	1.75	0.75
SFM0002	3.90	1.40	0.75
SFM0003	2.80	1.00	0.75
SFM0004	3.90	1.40	1.00[2]
SFM0005	2.90	1.65	1.00[2]
SFM0006	3.85	1.85	1.00[2]
SFM0008	5.85	3.35	1.00[2]
SFM0009	2.30	0.98	0.50
SFM0010	2.87	1.07	0.75
SFM0011	3.76	1.66	0.75
SFM0012	3.00	1.65	0.75
SFM0013	3.80	1.40	0.75
SFM0014	3.16	1.66	1.00
SFM0015	1.91	0.91	0.50
SFM0016	3.85	1.33	0.75
SFM0017	4.00	1.48	0.75
SFM0018	3.79	2.14	0.75
SFM0019	4.32	1.72	2.00
SFM0020	2.72	1.22	1.00
SFM0021	1.82	1.14	0.75
SFM0023	4.00	1.65	0.75
SFM0024	2.84	1.26	1.00
SFM0025	4.00	1.65	0.75
SFM0026	2.83	1.03	0.75
SFM0027	4.00	1.95	0.75
SFM0028	2.73	1.23	1.00
SFM0029	2.95	1.45	1.00
SFM0030	4.24	1.74	2.00
SFM0031	3.07	1.57	1.00
SFM0032	3.83	1.73	1.25
SFM0033	3.82	1.72	1.25
SFM0034	2.83	1.03	0.75
SFM0035	2.81	1.01	0.75
SFM0036	2.81	1.01	0.75
SFM0037	2.86	1.06	0.75
SFM0049	4.35	1.75	2.00

[1]The reference point is the top of the stand pipe (ToSP).

[2]The slug used in SFM0004–0006 and 0008 consisted of an HDPE pipe (filled with filter sand and an iron rod), having an outer diameter of 0.063 m. In addition to the given slug length, the lower end of the slug used in SFM0004–0006 and 0008 consisted of a 0.049 m long end plus a 0.03 m long cone. The volume of the end plus the cone was approximately $1.84 \cdot 10^{-4}$ m^3.

5 Performance

5.1 Preparations

Prior to the tests, the Divers® were tested at SWECO's engineering workshop in Vinsta, Stockholm. The test procedure is described in /6/. The tests showed that the water pressure head mesured 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 PVC-pipe.

Function checks of the equipment were also performed in connection to each slug test (see Section 3.3).

5.2 Performance of tests

5.2.1 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 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) /7/. In the majority of the present tests, both falling-head tests and rising-head tests were performed /6/. 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 /6/.

Figure 5-1 illustrates the practical performance of slug tests.

Figure 5-1. *Initiation of falling-head test in groundwater monitoring well SFM0012. One of the operators is holding the slug connected to the wire, and the black cable connected to the Diver® (already lowered into the well) is hanging on top of the well. After trying out different types of wire stops, it was found that a spanner wrench was most suited for this purpose. For security reasons, two persons had to perform the slug tests in wells installed in soil below open water.*

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 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 /6/.

5.2.2 Test procedure

The test procedure is briefly described below:

1. Cleaning of equipment that is lowered into the well /5/.

2. Measurement of the depth from the top of the standpipe to the bottom of the well. With exception of two wells none of only a few centimetres of sediments were present in the sump. In SFM0013 and SFM0049 the sump was almost filled up to the screen.

3. Measurement of the electrical conductivity.

4. Determination of the slug- and wire length.
   The objective is to cause a 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 0.75 m or 1.00 m, in order to prevent water from rising over the top of the rising 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. Following failure of the pressure sensor in the Diver® during the falling-head test in well SFM0029, it was agreed by the Activity Leader to lower the slug into the wells in a more controlled manner in the falling-head tests. Prior to this decision, the slug was lowered in a more or less free fall into the well.

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 5-1). Before changing the sampling frequency, the Diver® is stopped with the PC, and the data is 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.

10. Termination of slug test approximately 1 h after start of the rising-head test (according to the Activity Plan AP PF 400-03-23 for performance of slug tests in Forsmark).

In general, the sampling interval of the Diver® during the slug tests was according to Table 5-1.

Table 5-1. 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

5.3 Data handling

Raw data from the Diver® (internal *.mon format) was 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 Sections 5.4 and 6). 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 intial oscillation effects, usually lasting on the order of 1–10 seconds after lowering the slug into the well).

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 (*slugtester_Forsmark_resultat_030521.xls*) for quality control and storage in the SICADA database.

5.4 Analyses and interpretation

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 /7/, /8/ and /9/.

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.

5.4.1 Cooper et al method

The Cooper et al method is designed to estimate the transmissivity and storativity of an aquifer /9/. 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 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 /7/). The Cooper et al method is also recommended as "the first choice" method in /5/.

In the method, a plot of the normalized displacement versus the logarithm of $\beta = Tt/r_c^2$ (t denotes time) forms a series of type curves for different values of $\alpha = r_w^2 S/r_c^2$. 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 /10/. 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.

The two cases are illustrated in Figures 5-1a and b below. Figure 5-1a shows the result of the curve fitting to the recovery data from the falling-head test in observation well SFM0025 for $S = 10^{-5}$ ($\alpha \sim 1.41 \cdot 10^{-5}$). Figure 5-1b shows the corresponding result when α was varied to obtain the best fit to a particular type curve.

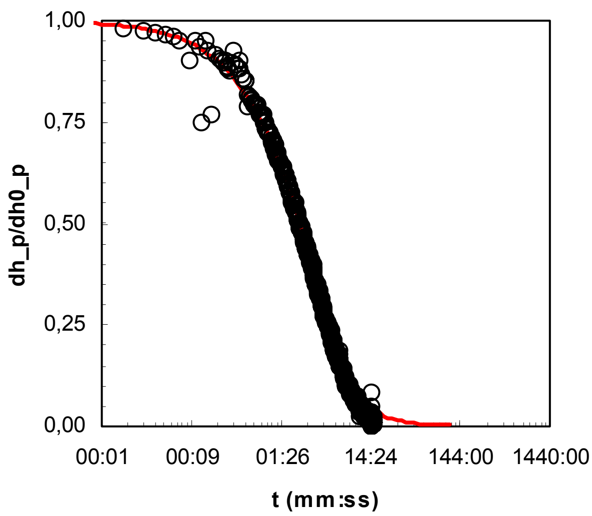

Figure 5-1a. *Result of the curve fitting for the falling-head test in SFM0025. Assumed storativity $S = 10^{-5}$ ($\alpha \sim 1.41 \cdot 10^{-5}$), producing the result $T = 9.75 \cdot 10^{-6}$ m^2/s. (See Section 6.1 for nomenclature.)*

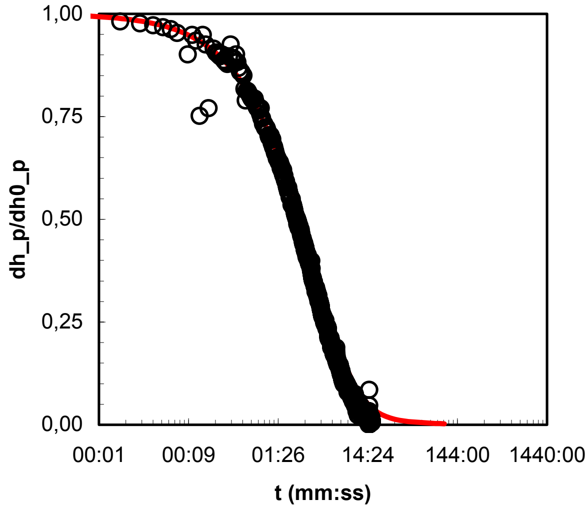

Figure 5-1b. *Result of the curve fitting for the falling-head test in SFM0025. Both T and S are varied to obtain the best fit, producing the result* $T = 1.07 \cdot 10^{-5}$ *m*^{2}*/s, and* $S = 2.04 \cdot 10^{-6}$ *(*$\alpha \sim 2.82 \cdot 10^{-6}$*).*

As is also discussed in /7/, the sensitivity of T to the curve-fitting procedure is relatively small compared to the sensitivity of S. A comparison shows that S obtained for the best-fit case (Figure 5-1b) is 80% smaller than the assumed S (Figure 5-1a), whereas the corresponding difference for T is < 9%. Hence, the values of S that are obtained by the Cooper et al method are relatively uncertain, compared to the obtained values of T.

5.4.2 Hvorslev method

The Hvorslev method is designed to estimate the hydraulic conductivity of an aquifer /11/. 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 5.4.3) is based on the same principle. The theory of the Hvorslev method and practical recommendations for its application are given in /7/.

For the present analysis according to the Hvorlev method, the computer program Aquifer Test Ver 3.0 was used /12/. The program allows for both automatic (based on linear regression analysis) and manual fitting of a straight-line plot to the measured data. Figures 5-2a to c show the principles of both automatic and manual fitting procedures and their implications. Figure 5-2a illustrates the underlying principle of the Hvorslev and Bouwer & Rice methods (the Hvorslev method was used to produce the particular plot in the figure), for an ideal case where a very good fit between the measured data and a straight-line plot may be obtained.

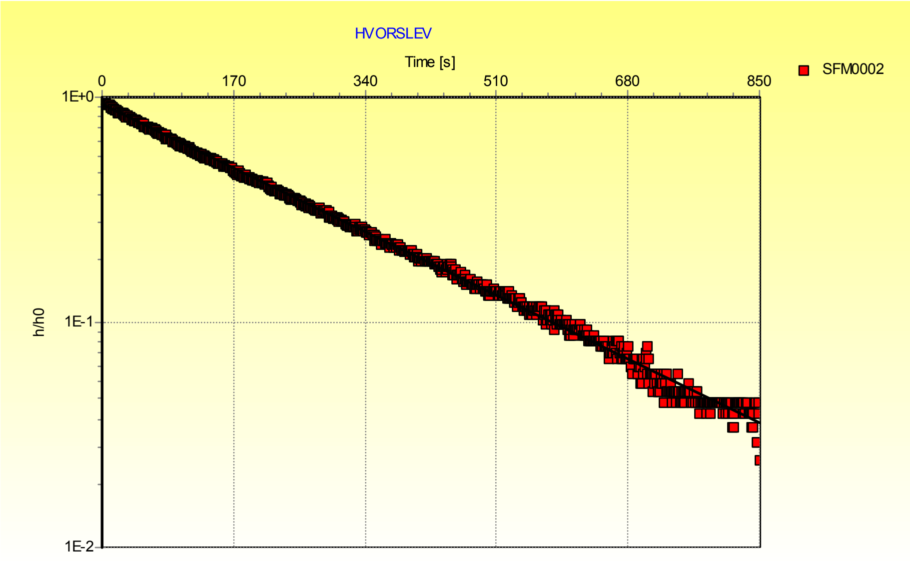

__Figure 5-2a.__ Principle of the Hvorslev method and the Bouwer & Rice method (the Hvorslev method was used to produce the plot, data from the falling-head test in SFM0002).

Figure 5-2b shows a case where a semi-logarithmic plot of the measured data demonstrates a concave-upward shape. As indicated in the figure, automatic fitting is inappropriate in this case, and some manual curve-fitting procedure is required. Guidelines for manual fitting of upward-concave plots are given in /7/. 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 (see Figure 5-2c).

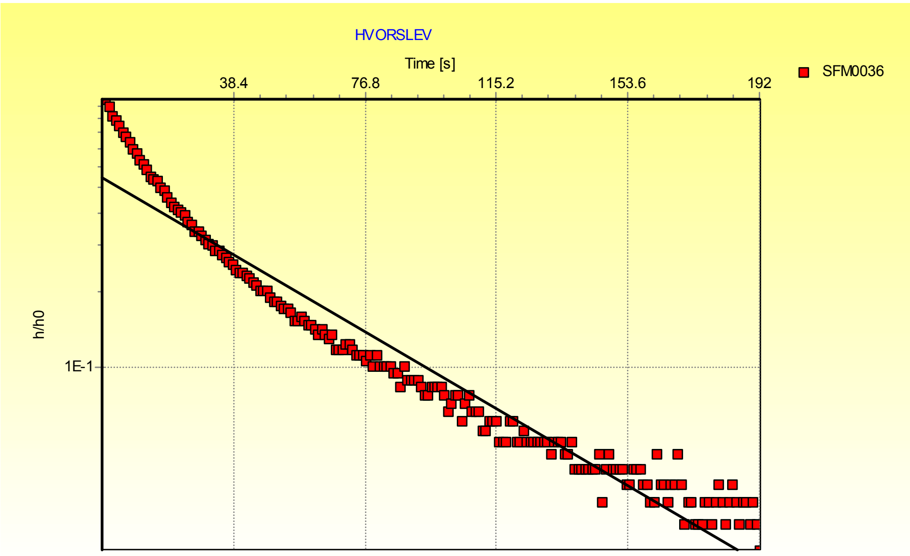

__Figure 5-2b.__ Illustration of automatic fitting of a straight line to measured data demonstrating a concave-upwards shape in a semi-logarithmic plot, producing the result $K = 1.59 \cdot 10^{-5}$ m/s (data from the falling-head test in SFM0036).

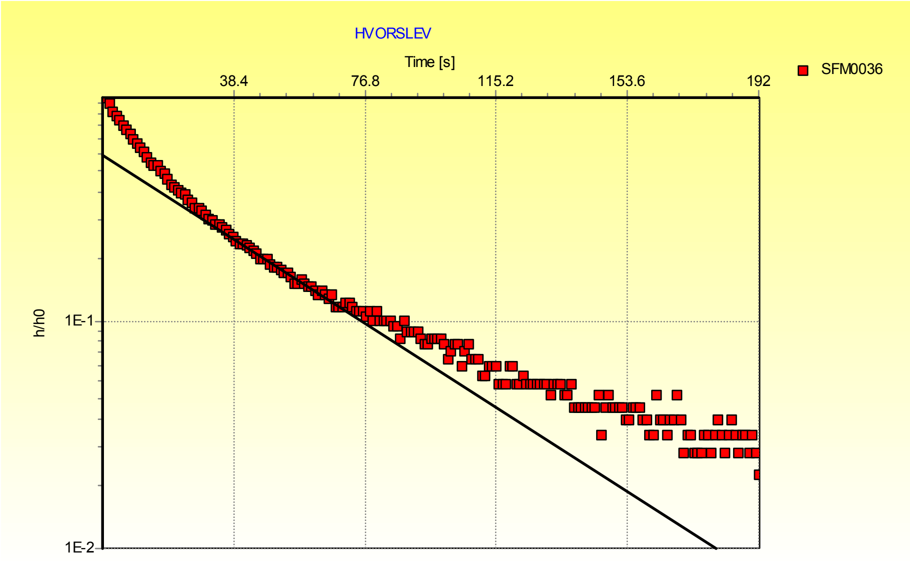

Figure 5-2c. *Illustration of the adopted principle of manual fitting of a straight line to measured data demonstrating a concave-upwards shape on a semi-logarithmic plot. The straight line is fitted for a normalized displacement in the interval 0.15–0.25, producing the result* $K = 2.07 \cdot 10^{-5}$ *m/s (data from the falling-head test in SFM0036).*

5.4.3 Bouwer & Rice method

The Bouwer & Rice method /12/ 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 Hvorlev 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 /7/.

For the present analysis according to the Bouwer & Rice method, the computer program Aquifer Test Ver 3.0 was used /12/. 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. Figures 5-3a and b show the principles of both automatic and manual fitting procedures and their implications in the Bouwer & Rice method.

Figure 5-3a shows a case where a semi-logarithmic plot of the measured data demonstrates a concave-upward shape (cf Figure 5-2b). For the Bouwer & Rice method, it is recommended to fit the straight line for a normalized displacement in the interval 0.20–0.30 /7/ (see Figure 5-2b).

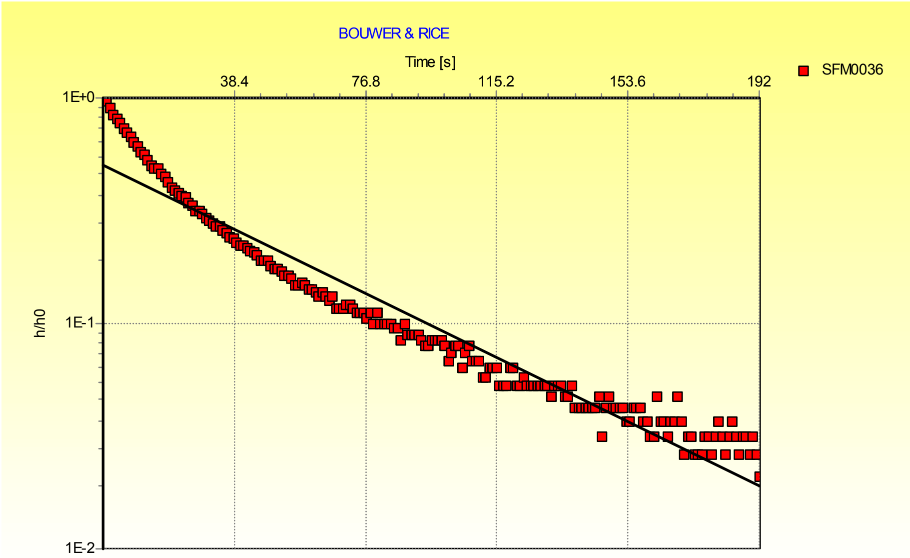

Figure 5-3a. *Illustration of automatic fitting of a straight line to measured data demonstrating a concave-upwards shape in a semi-logarithmic plot, producing the result $K = 1.16{\cdot}10^{-5}$ m/s (data from the falling-head test in SFM0036).*

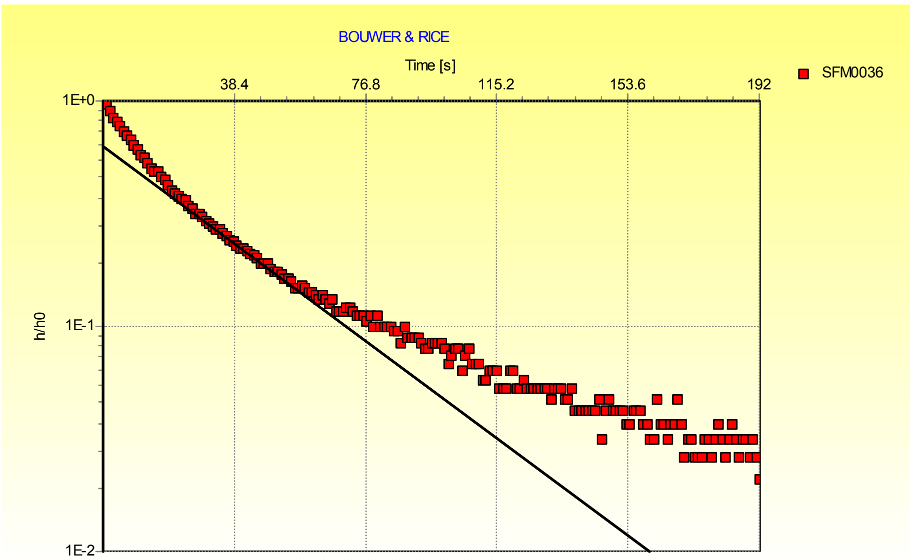

Figure 5-3b. *Illustration of the adopted principle of manual fitting of a straight line to measured data demonstrating a concave-upwards shape on a semi-logarithmic plot. The straight line is fitted for a normalized displacement in the interval 0.20–0.30, producing the result $K = 1.76{\cdot}10^{-5}$ m/s (data from the falling-head test in SFM0036).*

6 Results

6.1 Nomenclature and symbols

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

h_0 (m):	Water pressure head at the measuring point prior to initiation of slug test.
dh_0_p (m):	Initial displacement for falling-head test.
dh_0_F (m):	Initial displacement for rising-head test.
dh_0* (m):	Expected initial displacement.
dh_0*/dh_0_p:	Inserse of the normalized initial displacement for falling-head test.
dh_0*/dh_0_F:	Inserse 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 /6/.

6.2 Results

The results of the performed slug tests (for nomenclature and symbols, see above) are summarized in Table 6-1 below.

Table 6-1. Summary of the results of the slug tests.

Well	h_0 (m)	dh_0* (m)	dh_0_p (m)	dh_0_p*/dh_0_p	dh_0_F (m)	dh_0*/dh_0_F	hp (m)	hF (m)	T_s_measl_L (m^2/s)
SFM0001	2.44	0.48	0.21	2.29	-0.37	-1.30	2.44	2.43	$2.00\cdot10^{-6}$
SFM0002	3.19	0.48	0.41	1.17	-0.47	-1.02	3.19	3.17	$1.15\cdot10^{-7}$
SFM0003	2.42	0.48	0.35	1.37			2.42		$1.53\cdot10^{-7}$
SFM0004	2.65	0.73	0.71	1.03	-0.73	-1.00	2.77	2.14	$3.00\cdot10^{-9}$
SFM0005	1.14	0.73	0.55	1.33	-0.50	-1.46	1.14	1.13	$7.41\cdot10^{-7}$
SFM0006	2.14	0.73	0.68	1.07	-0.68	-1.07	2.15	1.91	$3.59\cdot10^{-9}$
SFM0008	2.56	0.73	0.68	1.07	-0.70	-1.04	2.57		$8.29\cdot10^{-8}$
SFM0009	1.49	0.32	0.30	1.07	-0.34	-1.06	1.49	1.48	$2.15\cdot10^{-7}$
SFM0010	2.39	0.48	0.41	1.17	-0.46	-1.04	2.39	2.38	$1.05\cdot10^{-7}$
SFM0011	3.14	0.48	0.45	1.07	-0.48	-1.00	3.12	3.11	$1.05\cdot10^{-7}$
SFM0012	2.08	0.46	0.46	1.00	-0.48	-0.96	2.07	1.70	$3.65\cdot10^{-9}$
SFM0013	3.23	0.48	0.46	1.04	-0.47	-1.02	3.22	3.22	$5.40\cdot10^{-8}$
SFM0014	2.02	0.64	0.49	1.30	-0.60	-1.07	1.99	1.99	$2.87\cdot10^{-7}$
SFM0015	1.59	0.30	0.19	1.58	-0.32	-0.94	1.57	1.46	$2.83\cdot10^{-8}$
SFM0016	2.93	0.48	0.25	1.92	-0.42	-1.14	2.93	2.92	$3.51\cdot10^{-6}$
SFM0017	2.82	0.48	0.28	1.71	-0.45	-1.07	2.83	2.82	$6.29\cdot10^{-7}$
SFM0018	2.48	0.48	0.41	1.17	-0.47	-1.02	2.48	2.44	$2.51\cdot10^{-7}$
SFM0019	2.84	1.28	0.96	1.33	-1.04	-1.23	2.82	2.59	$2.63\cdot10^{-8}$
SFM0020	2.09	0.64	0.32	2.00	-0.43	-1.49	2.08	2.07	$2.23\cdot10^{-6}$
SFM0021	1.99	0.48	0.12	4.00	-0.35	-1.37	1.99	1.99	$5.17\cdot10^{-7}$
SFM0023	3.51	0.46	0.51	0.90	-0.46	-1.00	3.47	3.04	$7.71\cdot10^{-9}$
SFM0024	2.24	0.61	0.03	20.33	-0.03	-20.33	2.24	2.24	$2.07\cdot10^{-5}$
SFM0025	3.04	0.46	0.49	0.94	-0.46	-1.00	3.04	3.04	$1.08\cdot10^{-7}$
SFM0026	2.46	0.48	0.38	1.26	-0.47	-1.02	2.47	2.46	$1.07\cdot10^{-7}$

Table 6-1. Continued.

Well	h_0 (m)	dh_0* (m)	dh_0_p (m)	dh_0_p*/dh_0_p	dh_0_F (m)	dh_0*/dh_0_F	hp (m)	hF (m)	T_s_measl_L (m^2/s)
SFM0027	3.32	0.48	0.46	1.04	-0.51	0.94	3.23	2.98	$1.25\cdot10^{-8}$
SFM0028	2.00	0.64	0.30	2.13	-0.56	-1.14	2.00	1.99	$4.04\cdot10^{-7}$
SFM0029	2.02	0.64	0.60	1.07	-0.54	-1.19	2.03	2.01	$7.06\cdot10^{-7}$
SFM0030	2.96	1.28	1.04	1.23			3.01		$1.78\cdot10^{-8}$
SFM0031	2.07	0.64	0.46	1.39	-0.59	-1.08	2.07	1.94	$1.84\cdot10^{-8}$
SFM0032	2.93	0.80	0.02	40.00	-0.42	-1.90	2.93	2.93	$6.14\cdot10^{-6}$
SFM0033	2.80	0.80	0.45	1.78	-0.30	-2.67	2.80	2.80	$3.27\cdot10^{-5}$
SFM0034	1.92	0.48	0.44	1.09	-0.47	-1.02	1.91	1.89	$1.04\cdot10^{-8}$
SFM0035	1.99	0.48	0.45	1.07	-0.69	-0.70	1.99	1.32	$4.35\cdot10^{-10}$
SFM0036	1.93	0.48	0.38	1.26	-0.44	-1.09	1.93	1.91	$5.11\cdot10^{-7}$
SFM0037	1.93	0.48	0.47	1.02	-0.45	-1.02	1.93	1.91	$1.92\cdot10^{-7}$
SFM0049	2.74	1.28	0.08	16.00	-0.10	-12.80	2.75	2.74	$1.34\cdot10^{-6}$

6.3 Interpreted parameters

6.3.1 Cooper et al method

Table 6-2 presents the results of the slug-test analysis according to the Cooper et al method (see description of the method in Section 5.4.1). The left and right main columns present the obtained values of T 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 6-2. Parameters evaluated by the Cooper et al method.

Obs. well	Falling-head test				Rising-head test			
	Test no.	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), $S = 10^{-5}$**	**Test no.**	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), $S = 10^{-5}$**
SFM0001	1	$1.23\cdot10^{-4}$	$1.00\cdot10^{-5}$	$1.23\cdot10^{-4}$	1	$1.41\cdot10^{-4}$	$1.00\cdot10^{-5}$	[1]$1.41\cdot10^{-4}$
SFM0002	1	$7.68\cdot10^{-6}$	$1.00\cdot10^{-5}$	[1]$7.68\cdot10^{-6}$	1	$5.16\cdot10^{-6}$	$1.00\cdot10^{-5}$	$5.16\cdot10^{-6}$
SFM0003	1	$1.77\cdot10^{-5}$	$1.00\cdot10^{-5}$	[1]$1.77\cdot10^{-5}$	1			
SFM0004	1	$7.80\cdot10^{-8}$	$1.07\cdot10^{-3}$	[1]$1.59\cdot10^{-7}$	1	$1.05\cdot10^{-8}$	$6.72\cdot10^{-3}$	$8.96\cdot10^{-8}$
SFM0005	1	$5.54\cdot10^{-5}$	$1.50\cdot10^{-6}$	$3.12\cdot10^{-5}$	1	$7.53\cdot10^{-5}$	$1.22\cdot10^{-5}$	[1]$8.07\cdot10^{-5}$
SFM0006	1	$5.65\cdot10^{-6}$	$1.00\cdot10^{-5}$	$5.65\cdot10^{-6}$	1	$2.97\cdot10^{-6}$	$1.00\cdot10^{-5}$	[1]$2.97\cdot10^{-6}$
SFM0008	1	$2.11\cdot10^{-5}$	$1.00\cdot10^{-5}$	$2.11\cdot10^{-5}$	1	$1.37\cdot10^{-5}$	$8.27\cdot10^{-4}$	[1]$2.27\cdot10^{-5}$
SFM0009	1	$1.13\cdot10^{-5}$	$8.36\cdot10^{-5}$	$1.45\cdot10^{-5}$	1	$1.64\cdot10^{-5}$	$2.10\cdot10^{-5}$	$1.64\cdot10^{-5}$
	2	$1.68\cdot10^{-5}$	$4.00\cdot10^{-6}$	[1]$1.50\cdot10^{-5}$	2	$1.56\cdot10^{-5}$	$1.96\cdot10^{-5}$	$1.67\cdot10^{-5}$
SFM0010	1	$1.02\cdot10^{-5}$	$7.80\cdot10^{-6}$	$9.70\cdot10^{-6}$	1	$9.92\cdot10^{-6}$	$1.00\cdot10^{-5}$	[1]$9.92\cdot10^{-6}$
SFM0011	1	$1.01\cdot10^{-6}$	$1.63\cdot10^{-4}$	$1.43\cdot10^{-6}$	1	$9.77\cdot10^{-6}$	$3.82\cdot10^{-6}$	[1]$8.71\cdot10^{-6}$
SFM0012	1	$2.01\cdot10^{-7}$	$2.40\cdot10^{-8}$	$1.42\cdot10^{-7}$	1	$6.23\cdot10^{-7}$	$5.62\cdot10^{-5}$	[1]$7.66\cdot10^{-7}$
SFM0013	1	$4.32\cdot10^{-6}$	$6.34\cdot10^{-6}$	[1]$4.42\cdot10^{-6}$	1	$3.14\cdot10^{-6}$	$4.10\cdot10^{-5}$	$3.69\cdot10^{-6}$
SFM0014	1	$2.68\cdot10^{-5}$	$1.59\cdot10^{-7}$	$1.79\cdot10^{-5}$	1	$2.48\cdot10^{-5}$	$7.45\cdot10^{-6}$	[1]$2.30\cdot10^{-5}$
SFM0015	1	$9.22\cdot10^{-7}$	$2.19\cdot10^{-6}$	$7.49\cdot10^{-7}$	1	$5.95\cdot10^{-7}$	$1.00\cdot10^{-5}$	[1]$5.95\cdot10^{-7}$
SFM0016	1	$4.87\cdot10^{-4}$	$5.65\cdot10^{-10}$	$2.80\cdot10^{-4}$	1	$1.43\cdot10^{-4}$	$1.79\cdot10^{-7}$	[1]$1.01\cdot10^{-4}$
SFM0017	1	$2.03\cdot10^{-4}$	$9.60\cdot10^{-5}$	[1]$2.80\cdot10^{-4}$	1	$3.54\cdot10^{-4}$	$1.71\cdot10^{-6}$	$2.94\cdot10^{-4}$
SFM0018	1	$7.44\cdot10^{-5}$	$7.45\cdot10^{-7}$	$5.15\cdot10^{-5}$	1	$6.91\cdot10^{-6}$	$1.10\cdot10^{-7}$	[1]$4.56\cdot10^{-6}$

Table 6-2. Continued.

Obs. well	Falling-head test				Rising-head test			
	Test no.	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), S = 10^{-5}**	**Test no.**	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), S = 10^{-5}**
SFM0019	1	$1.09\cdot10^{-6}$	$4.81\cdot10^{-3}$	[1]$3.46\cdot10^{-6}$	1	$1.32\cdot10^{-6}$	$1.96\cdot10^{-5}$	$1.44\cdot10^{-6}$
SFM0020	1	$2.90\cdot10^{-4}$	$4.59\cdot10^{-11}$	$1.26\cdot10^{-4}$	1	$2.12\cdot10^{-4}$	$1.29\cdot10^{-9}$	$1.14\cdot10^{-4}$
	2	$1.57\cdot10^{-4}$	$9.38\cdot10^{-11}$	[1]$9.88\cdot10^{-5}$	2	$1.46\cdot10^{-4}$	$1.59\cdot10^{-7}$	$1.19\cdot10^{-4}$
SFM0021	1	$2.25\cdot10^{-4}$	$2.36\cdot10^{-4}$	$4.29\cdot10^{-4}$	1	$4.81\cdot10^{-4}$	$6.64\cdot10^{-7}$	[1]$3.91\cdot10^{-4}$
SFM0023	1	$7.40\cdot10^{-7}$	$8.13\cdot10^{-10}$	[1]$3.01\cdot10^{-7}$	1	$4.16\cdot10^{-7}$	$1.00\cdot10^{-5}$	$4.16\cdot10^{-7}$
SFM0024	1	$4.58\cdot10^{-4}$	$1.00\cdot10^{-5}$	$4.58\cdot10^{-4}$	1	$1.88\cdot10^{-4}$	$1.00\cdot10^{-5}$	$1.88\cdot10^{-4}$
	2	$5.28\cdot10^{-4}$	$5.50\cdot10^{-9}$	[1]$3.49\cdot10^{-4}$				
SFM0025	1	$1.07\cdot10^{-5}$	$2.00\cdot10^{-6}$	[1]$9.75\cdot10^{-6}$	1	$2.04\cdot10^{-5}$	$2.57\cdot10^{-6}$	$1.77\cdot10^{-5}$
SFM0026	1	$6.75\cdot10^{-6}$	$6.06\cdot10^{-6}$	[1]$5.74\cdot10^{-6}$	1	$6.44\cdot10^{-6}$	$1.00\cdot10^{-5}$	$6.44\cdot10^{-6}$
SFM0027	1	$1.02\cdot10^{-6}$	$1.00\cdot10^{-5}$	[1]$1.02\cdot10^{-6}$	1	$3.54\cdot10^{-7}$	$1.00\cdot10^{-5}$	$3.54\cdot10^{-7}$
SFM0028	1	$3.72\cdot10^{-5}$	$1.24\cdot10^{-8}$	$2.35\cdot10^{-5}$	1	$3.90\cdot10^{-5}$	$1.00\cdot10^{-5}$	[1]$3.90\cdot10^{-5}$
SFM0029	1	$6.83\cdot10^{-5}$	$3.18\cdot10^{-4}$	$8.22\cdot10^{-5}$	1	$4.36\cdot10^{-5}$	$1.00\cdot10^{-5}$	[1]$4.36\cdot10^{-5}$
	2	$4.44\cdot10^{-5}$	$1.00\cdot10^{-5}$	$4.44\cdot10^{-5}$	2	$2.81\cdot10^{-5}$	$1.00\cdot10^{-5}$	$2.81\cdot10^{-5}$
SFM0030	1	$1.86\cdot10^{-6}$	$1.18\cdot10^{-4}$	[1]$1.86\cdot10^{-6}$				
SFM0031	1	$1.09\cdot10^{-6}$	$1.00\cdot10^{-5}$	[1]$1.09\cdot10^{-6}$	1	$6.15\cdot10^{-7}$	$6.20\cdot10^{-4}$	$7.75\cdot10^{-7}$
SFM0032	1	$7.68\cdot10^{-5}$	$1.00\cdot10^{-5}$	[1]$7.68\cdot10^{-5}$	1	$4.77\cdot10^{-4}$	$1.00\cdot10^{-5}$	$4.77\cdot10^{-4}$
SFM0033	1	$1.88\cdot10^{-4}$	$1.00\cdot10^{-5}$	$1.88\cdot10^{-4}$	1	$5.50\cdot10^{-4}$	$1.00\cdot10^{-5}$	[1]$5.50\cdot10^{-4}$
SFM0034	1	$6.75\cdot10^{-7}$	$1.79\cdot10^{-5}$	$6.15\cdot10^{-7}$	1	$2.69\cdot10^{-6}$	$5.78\cdot10^{-6}$	[1]$2.69\cdot10^{-6}$

Table 6-2. Continued.

Obs. well	Falling-head test				Rising-head test			
	Test no.	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), $S = 10^{-5}$**	**Test no.**	**T (m^2/s), best fit**	**S (-), best fit**	**T (m^2/s), $S = 10^{-5}$**
SFM0035	1	$5.62 \cdot 10^{-8}$	$1.00 \cdot 10^{-5}$	[1]$5.62 \cdot 10^{-8}$	1	$9.32 \cdot 10^{-8}$	$1.00 \cdot 10^{-5}$	$9.32 \cdot 10^{-8}$
SFM0036	1	$7.17 \cdot 10^{-5}$	$1.00 \cdot 10^{-5}$	[1]$7.17 \cdot 10^{-5}$	1	$5.44 \cdot 10^{-5}$	$1.79 \cdot 10^{-4}$	$6.85 \cdot 10^{-5}$
SFM0037	1	$1.82 \cdot 10^{-5}$	$3.49 \cdot 10^{-6}$	$1.82 \cdot 10^{-5}$	1	$2.39 \cdot 10^{-5}$	$1.00 \cdot 10^{-5}$	[1]$2.39 \cdot 10^{-5}$
SFM0049	1	$9.82 \cdot 10^{-5}$	$1.00 \cdot 10^{-5}$	[1]$9.82 \cdot 10^{-5}$	1	$9.71 \cdot 10^{-5}$	$5.28 \cdot 10^{-4}$	$1.37 \cdot 10^{-4}$

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

6.3.2 Hvorslev and Bouwer & Rice methods

This section presents the reults of the slug-test analysis according to the.Hvorslev and Bouwer & Rice methods (see description of the methods in Sections 5.4.2–3).

Table 6-3 presents the results of the slug-test analysis according to the Hvorslev and Bouwer & Rice methods (see description of these methods in Sections 5.4.2–3). 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 3-1), except for SFM0003 (b = 2 m) and SFM0024 (b = 0.5 m).

Table 6-3. 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
SFM0001	1	$6.82 \cdot 10^{-5}$	$7.06 \cdot 10^{-5}$	1	$6.70 \cdot 10^{-5}$	$6.92 \cdot 10^{-5}$
SFM0002	1	$2.98 \cdot 10^{-6}$	$3.06 \cdot 10^{-6}$	1	$1.63 \cdot 10^{-6}$	$1.84 \cdot 10^{-6}$
SFM0003	1	$4.50 \cdot 10^{-6}$	$5.06 \cdot 10^{-6}$			
SFM0004	1	$4.39 \cdot 10^{-8}$	$4.61 \cdot 10^{-8}$	1	$3.79 \cdot 10^{-8}$	$3.94 \cdot 10^{-8}$
SFM0005	1	$3.93 \cdot 10^{-5}$	$2.97 \cdot 10^{-5}$	1	$2.22 \cdot 10^{-5}$	$1.70 \cdot 10^{-5}$
SFM0006	1	$9.04 \cdot 10^{-8}$	$8.37 \cdot 10^{-8}$	1	$1.05 \cdot 10^{-7}$	$9.26 \cdot 10^{-8}$
SFM0008	1	$5.76 \cdot 10^{-6}$	$5.47 \cdot 10^{-6}$	1	$6.06 \cdot 10^{-6}$	$6.11 \cdot 10^{-6}$
SFM0009	1 2	$7.40 \cdot 10^{-6}$ $6.94 \cdot 10^{-6}$	$5.64 \cdot 10^{-6}$ $5.29 \cdot 10^{-6}$	1 2	$6.22 \cdot 10^{-6}$ $7.91 \cdot 10^{-6}$	$4.92 \cdot 10^{-6}$ $5.90 \cdot 10^{-6}$
SFM0010	1	$4.12 \cdot 10^{-6}$	$2.83 \cdot 10^{-6}$	1	$3.55 \cdot 10^{-6}$	$2.42 \cdot 10^{-6}$
SFM0011	1	$3.36 \cdot 10^{-6}$	$2.74 \cdot 10^{-6}$	1	$3.31 \cdot 10^{-6}$	$2.54 \cdot 10^{-6}$
SFM0012	1	$1.43 \cdot 10^{-7}$	$1.46 \cdot 10^{-7}$	1	$4.61 \cdot 10^{-7}$	$4.73 \cdot 10^{-7}$
SFM0013	1	$1.84 \cdot 10^{-6}$	$1.49 \cdot 10^{-6}$	1	$1.50 \cdot 10^{-6}$	$1.22 \cdot 10^{-6}$
SFM0014	1	$9.90 \cdot 10^{-6}$	$7.26 \cdot 10^{-6}$	1	$1.06 \cdot 10^{-5}$	$7.68 \cdot 10^{-6}$
SFM0015	1	$7.14 \cdot 10^{-7}$	$7.12 \cdot 10^{-7}$	1	$2.90 \cdot 10^{-7}$	$3.01 \cdot 10^{-7}$
SFM0016	1	$1.90 \cdot 10^{-4}$	$1.70 \cdot 10^{-4}$	1	$5.41 \cdot 10^{-5}$	$4.83 \cdot 10^{-5}$
SFM0017	1	$1.44 \cdot 10^{-4}$	$1.10 \cdot 10^{-4}$	1	$1.78 \cdot 10^{-4}$	$1.42 \cdot 10^{-4}$
SFM0018	1	$4.39 \cdot 10^{-5}$	$3.95 \cdot 10^{-5}$	1	$3.82 \cdot 10^{-6}$	$3.20 \cdot 10^{-6}$
SFM0019	1	$9.21 \cdot 10^{-7}$	$7.66 \cdot 10^{-7}$	1	$6.29 \cdot 10^{-7}$	$5.19 \cdot 10^{-7}$

Table 6-3. Continued.

Well	Falling-head test			Rising-head test		
	Test no.	Hvorslev method	Bouwer & Rice method	Test no.	Hvorslev method	Bouwer & Rice method
SFM0020	1	$9.56 \cdot 10^{-5}$	$7.56 \cdot 10^{-5}$	1	$7.50 \cdot 10^{-5}$	$5.81 \cdot 10^{-5}$
	2	$6.41 \cdot 10^{-5}$	$5.20 \cdot 10^{-5}$	2	$6.05 \cdot 10^{-5}$	$4.89 \cdot 10^{-5}$
SFM0021	1	$2.26 \cdot 10^{-4}$	$1.68 \cdot 10^{-4}$	1	$1.78 \cdot 10^{-4}$	$1.34 \cdot 10^{-4}$
SFM0023	1	$3.20 \cdot 10^{-7}$	$3.22 \cdot 10^{-7}$	1	$1.71 \cdot 10^{-7}$	$1.71 \cdot 10^{-7}$
SFM0024	1	$2.82 \cdot 10^{-4}$	$2.82 \cdot 10^{-4}$	1	$1.08 \cdot 10^{-3}$	$1.08 \cdot 10^{-3}$
	2	$4.06 \cdot 10^{-4}$	$4.05 \cdot 10^{-4}$			
SFM0025	1	$5.46 \cdot 10^{-6}$	$5.57 \cdot 10^{-6}$		$8.12 \cdot 10^{-6}$	$8.35 \cdot 10^{-6}$
SFM0026	1	$3.85 \cdot 10^{-6}$	$3.33 \cdot 10^{-6}$		$2.72 \cdot 10^{-6}$	$2.70 \cdot 10^{-6}$
SFM0027	1	$3.68 \cdot 10^{-7}$	$3.03 \cdot 10^{-7}$		$9.44 \cdot 10^{-8}$	$7.94 \cdot 10^{-8}$
SFM0028	1	$1.34 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$		$2.18 \cdot 10^{-5}$	$1.76 \cdot 10^{-5}$
SFM0029	1	$2.31 \cdot 10^{-5}$	$2.13 \cdot 10^{-5}$	1	$2.76 \cdot 10^{-5}$	$1.90 \cdot 10^{-5}$
	2	$2.74 \cdot 10^{-5}$	$2.31 \cdot 10^{-5}$	2	$1.82 \cdot 10^{-5}$	$1.52 \cdot 10^{-5}$
SFM0030	1	$4.34 \cdot 10^{-7}$	$3.41 \cdot 10^{-7}$			
SFM0031	1	$5.80 \cdot 10^{-7}$	$4.43 \cdot 10^{-7}$	1	$3.07 \cdot 10^{-7}$	$2.33 \cdot 10^{-7}$
SFM0032	1	$6.20 \cdot 10^{-5}$	$4.86 \cdot 10^{-5}$	1	$4.01 \cdot 10^{-4}$	$3.20 \cdot 10^{-4}$
SFM0033	1	$8.41 \cdot 10^{-4}$	$6.59 \cdot 10^{-4}$	1	$6.13 \cdot 10^{-4}$	$5.18 \cdot 10^{-4}$
SFM0034	1	$3.59 \cdot 10^{-7}$	$2.52 \cdot 10^{-7}$	1	$5.88 \cdot 10^{-7}$	$6.79 \cdot 10^{-7}$
SFM0035	1	$1.09 \cdot 10^{-8}$	$8.10 \cdot 10^{-9}$	1	$2.90 \cdot 10^{-8}$	$2.15 \cdot 10^{-8}$
SFM0036	1	$2.07 \cdot 10^{-5}$	$1.76 \cdot 10^{-5}$	1	$2.40 \cdot 10^{-5}$	$1.85 \cdot 10^{-5}$
SFM0037	1	$7.74 \cdot 10^{-6}$	$5.63 \cdot 10^{-6}$	1	$9.67 \cdot 10^{-6}$	$6.96 \cdot 10^{-6}$
SFM0049	1	$2.93 \cdot 10^{-5}$	$2.65 \cdot 10^{-5}$	1	$3.52 \cdot 10^{-5}$	$3.53 \cdot 10^{-5}$

6.4 Discussion of results

All of the groundwater monitoring wells was evaluated according to Cooper et al /7/, Hvorslev /11/, and Bouwer & Rice /12/.

For most wells a good to acceptable fit was obtained for the Cooper et al method applying a fixed α (corresponding to $S = 10^{-5}$). For some wells a somewhat better fit was obtained by varying α. For some wells it was not possible to obtain an acceptable fit. There could be several reasons for this. The most common problem in evaluation of slug tests is skin effects due to incomplete well-development. The tested wells had only been developed by pumping. Some of the wells gave very little water and therefore the well development was not very effective. Development by water injection was not performed since the wells should also be used for water sampling. 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, radical flow etc. that can explain the difficulties to fit measured values to the type curves(see /7/, /8/ and /9/ for a more thorough discussion of restrictions on the applicability of the method).

For the reporting to the SICADA database, the values obtained with the fixed $S = 10^{-5}$ were used. The selection of the T-value to be reported was also based on which of the falling- or rising-head tests that gave the best fit to the type curves and to what extent the obtained and calculated initial displacement agreed.

For some wells a concave-upward shape curve was obtained in the semi-logarithmic plots used for the evaluation according to Hvorslev and Bouwer & Rice. Theoretically, a straight lined should be obtained. Possible explanations to this are the same as for the difficulties to fit measured data to the types curves of the Cooper et al method.

The T-values obtained from the Cooper et al method which were reported to the SICADA database varied between $5.62 \cdot 10^{-8}$ and $5.50 \cdot 10^{-4}$ m^2/s. The geometric mean of all wells was $1.18 \cdot 10^{-5}$ m^2/s and the standard deviation was $1.26 \cdot 10^{-4}$. The uncertainty in the estimation of S is large. However, the results did not reject the assumption that S is in the order of 10^{-5}.

The T-values obtained from the Hvorslev and Bouwer & Rice methods varied between $8.10 \cdot 10^{-9}$ and $8.41 \cdot 10^{-4}$ m^2/s. The geometric means were somewhat lower than for the Cooper et al evaluation; from $5.05 \cdot 10^{-6}$ m^2/s for the rising head evaluations according to Bouwer & Rice up to $6.56 \cdot 10^{-6}$ m^2/s for the falling head evaluation according to Hvorslev. The standard deviations were very similar to those obtained from the evaluation by the Cooper et al method.

7 References

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Appendix 1

List of generated raw data files and primary data files

Table A1-1. 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** **Parameters:** **Pressure and temperature**	**Data processing files:** ***.xls**	**Primary data files**	
			Cooper et al. method: ***.xls** **Parameters:** **Transmissivity and storativity**	**Hvorslev and Bouwer & Rice methods:** ***.mdb** **Parameter:** **Hydraulic conductivity**
SFM0001	SFM_0001_slugtest	SFM0001_bearbetningsfil	SFM0001_slugtest_***_Slug_Cooper_Greene SFM0001_bailtest_***_Slug_Cooper_Greene	SFM0001
SFM0002	SFM_0002_slugtest	SFM0002_bearbetningsfil	SFM0002_slugtest_***_Slug_Cooper_Greene SFM0002_bailtest_***_Slug_Cooper_Greene	SFM0002
SFM0003	SFM_0003_slugtest	SFM0003_bearbetningsfil	SFM0003_slugtest_***_Slug_Cooper_Greene	SFM0003
SFM0004	SFM_0004_slugtest_steg1 SFM_0004_slugtest_steg2 SFM_0004_slugtest_steg3	SFM0004_bearbetningsfil	SFM0004_slugtest_***_Slug_Cooper_Greene SFM0004_bailtest_***_Slug_Cooper_Greene	SFM0004
SFM0005	SFM_0005_slugtest	SFM0005_bearbetningsfil	SFM0005_slugtest__***_Slug_Cooper_Greene SFM0005_bailtest__***_Slug_Cooper_Greene	SFM0005
SFM0006	SFM_0006_slugtest_steg1 SFM_0006_slugtest_steg2 SFM_0006_slugtest_steg3	SFM0006_bearbetningsfil	SFM0006_slugtest__***_Slug_Cooper_Greene SFM0006_bailtest__***_Slug_Cooper_Greene	SFM0006

Table A1-1. Continued.

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
SFM0008	SFM_0008_slugtest	SFM0008_bearbetningsfil	SFM0008_slugtest_***_Slug_Cooper_Greene SFM0008_bailtest_***_Slug_Cooper_Greene	SFM0008
SFM0009	SFM_0009_slugtest_test1 SFM_0009_slugtest_test2	SFM0009_bearbetningsfil	SFM0009_slugtest_1_***_Slug_Cooper_Greene SFM0009_bailtest_1_***_Slug_Cooper_Greene SFM0009_slugtest_2_***_Slug_Cooper_Greene SFM0009_bailtest_2_***_Slug_Cooper_Greene	SFM0009
SFM0010	SFM_0010_slugtest	SFM0010_bearbetningsfil	SFM0010_slugtest_***_Slug_Cooper_Greene SFM0010_bailtest_***_Slug_Cooper_Greene	SFM0010
SFM0011	SFM_0011_slugtest	SFM0011_bearbetningsfil	SFM0011_slugtest_***_Slug_Cooper_Greene SFM0011_bailtest_***_Slug_Cooper_Greene	SFM0011
SFM0012	SFM_0012_slugtest	SFM0012_bearbetningsfil	SFM0012_slugtest_***_Slug_Cooper_Greene SFM0012_bailtest_***_Slug_Cooper_Greene	SFM0012
SFM0013	SFM_0013_slugtest1 SFM_0013_slugtest2	SFM0013_bearbetningsfil	SFM0013_slugtest_***_Slug_Cooper_Greene SFM0013_bailtest_***_Slug_Cooper_Greene	SFM0013
SFM0014	SFM_0014_slugtest	SFM0014_bearbetningsfil	SFM0014_slugtest_***_Slug_Cooper_Greene SFM0014_bailtest_***_Slug_Cooper_Greene	SFM0014
SFM0015	SFM_0015_slugtest_steg1 SFM_0015_slugtest_steg2 SFM_0015_slugtest_steg3	SFM0015_bearbetningsfil	SFM0015_slugtest_***_Slug_Cooper_Greene SFM0015_bailtest_***_Slug_Cooper_Greene	SFM0015

Table A1-1. Continued.

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
SFM0016	SFM_0016_slugtest	SFM0016_bearbetningsfil	SFM0016_slugtest_***_Slug_Cooper_Greene SFM0016_bailtest_***_Slug_Cooper_Greene	SFM0016
SFM0017	SFM_0017_slugtest	SFM0017_bearbetningsfil	SFM0017_slugtest_***_Slug_Cooper_Greene SFM0017_bailtest_***_Slug_Cooper_Greene	SFM0017
SFM0018	SFM_0018_slugtest	SFM0018_bearbetningsfil	SFM0018_slugtest_Slug_Cooper_Greene SFM0018_bailtest_Slug_Cooper_Greene	SFM0018
SFM0019	SFM_0019_slugtest	SFM0019_bearbetningsfil	SFM0019_slugtest_***_Slug_Cooper_Greene SFM0019_bailtest_***_Slug_Cooper_Greene	SFM0019
SFM0020	SFM_0020_slugtest	SFM0020_bearbetningsfil	SFM0020_slugtest_1_***_Slug_Cooper_Greene SFM0020_bailtest_1_***_Slug_Cooper_Greene SFM0020_slugtest_2_***_Slug_Cooper_Greene SFM0020_bailtest_2_***_Slug_Cooper_Greene	SFM0020
SFM0021	SFM_0021_slugtest	SFM0021_bearbetningsfil	SFM0021_slugtest_***_Slug_Cooper_Greene SFM0021_bailtest_***_Slug_Cooper_Greene	SFM0021
SFM0023	SFM_0023_slugtest1 SFM_0023_slugtest2 SFM_0023_slugtest3	SFM0023_bearbetningsfil	SFM0023_slugtest_***_Slug_Cooper_Greene SFM0023_bailtest_***_Slug_Cooper_Greene	SFM0023

Table A1-1. Continued.

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
SFM0024	SFM_0024_slugtest	SFM0024_bearbetningsfil	SFM0024_slugtest_1_***_Slug_Cooper_Greene SFM0024_bailtest_1_***_Slug_Cooper_Greene SFM0024_slugtest_2_***_Slug_Cooper_Greene	SFM0024
SFM0025	SFM_0025_slugtest	SFM0025_bearbetningsfil	SFM0025_slugtest_***_Slug_Cooper_Greene SFM0025_bailtest_***_Slug_Cooper_Greene	SFM0025
SFM0026	SFM_0026_slugtest	SFM0026_bearbetningsfil	SFM0026_slugtest_***_Slug_Cooper_Greene SFM0026_bailtest_***_Slug_Cooper_Greene	SFM0026
SFM0027	SFM_0027_slugtest1 SFM_0027_slugtest2 SFM_0027_slugtest3	SFM0027_bearbetningsfil	SFM0027_slugtest_***_Slug_Cooper_Greene SFM0027_bailtest_***_Slug_Cooper_Greene	SFM0027
SFM0028	SFM_0028_slugtest	SFM0028_bearbetningsfil	SFM0028_slugtest_***_Slug_Cooper_Greene SFM0028_bailtest_***_Slug_Cooper_Greene	SFM0028
SFM0029	SFM_0029_slugtest_test1 SFM_0029_slugtest_test2	SFM0029_bearbetningsfil	SFM0029_slugtest_1_***_Slug_Cooper_Greene SFM0029_bailtest_1_***_Slug_Cooper_Greene SFM0029_slugtest_2_***_Slug_Cooper_Greene SFM0029_bailtest_2_***_Slug_Cooper_Greene	SFM0029
SFM0030	SFM_0030_slugtest_steg1 SFM_0030_slugtest_steg2 SFM_0030_slugtest_steg3	SFM0030_bearbetningsfil	SFM0030_slugtest_***_Slug_Cooper_Greene	SFM0030

Table A1-1. Continued.

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
SFM0031	SFM_0031_slugtest_steg1 SFM_0031_slugtest_steg2 SFM_0031_slugtest_steg3	SFM0031_bearbetningsfil	SFM0031_slugtest_***_Slug_Cooper_Greene SFM0031_bailtest_***_Slug_Cooper_Greene	SFM0031
SFM0032	SFM_0032_slugtest	SFM0032_bearbetningsfil	SFM0032_slugtest_***_Slug_Cooper_Greene SFM0032_bailtest_***_Slug_Cooper_Greene	SFM0032
SFM0033	SFM_0033_slugtest	SFM0033_bearbetningsfil	SFM0033_slugtest_***_Slug_Cooper_Greene SFM0033_bailtest_***_Slug_Cooper_Greene	SFM0033
SFM0034	SFM_0034_slugtest_steg1 SFM_0034_slugtest_steg2 SFM_0034_slugtest_steg3	SFM0034_bearbetningsfil	SFM0034_slugtest_***_Slug_Cooper_Greene SFM0034_bailtest_***_Slug_Cooper_Greene	SFM0034
SFM0035	SFM_0035_slugtest_steg1 SFM_0035_slugtest_steg2	SFM0035_bearbetningsfil	SFM0035_slugtest_***_Slug_Cooper_Greene SFM0035_bailtest_***_Slug_Cooper_Greene	SFM0035
SFM0036	SFM_0036_slugtest	SFM0036_bearbetningsfil	SFM0036_slugtest_***_Slug_Cooper_Greene SFM0036_bailtest_***_Slug_Cooper_Greene	SFM0036
SFM0037	SFM_0037_slugtest	SFM0037_bearbetningsfil	SFM0037_slugtest_***_Slug_Cooper_Greene SFM0037_bailtest_***_Slug_Cooper_Greene	SFM0037
SFM0049	SFM_0049_slugtest	SFM0049_bearbetningsfil	SFM0049_slugtest_***_Slug_Cooper_Greene SFM0049_bailtest_***_Slug_Cooper_Greene	SFM0038

Appendix 2

Diagrammes

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

Figures A2-1 to A2-40 show semi-log plots of the normalized displacement versus time (the scale for the time is logarithmic). Further, the displacement data is fitted to type curves according to the Cooper et al. method, whereby the estimates of T and S, (presented in Section 6.3.1) are obtained. The results of the curve-fitting are shown for the estimated storativity $S = 10^{-5}$ (see Section 6.3.1). Hence, the results on Figures A2-1 to A2-40 do not consider an adjustment of S. Note that in these 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

Figures A2-41 to A2-77 show semi-log plots of the normalized displacement versus time (the scale for the normalized displacement is logarithmic). Further, the displacement data is used to estimate the hydraulic conductivity K (presented in Section 6.3.2). Note that in the diagrammes on Figures A2-41 to A2-77, the nomenclature for the normalized displacement is as follows:

h/h0 = dh_p/dh0_p for falling head test
h/h0 = abs(dh_F/dh0_F) for rising head test

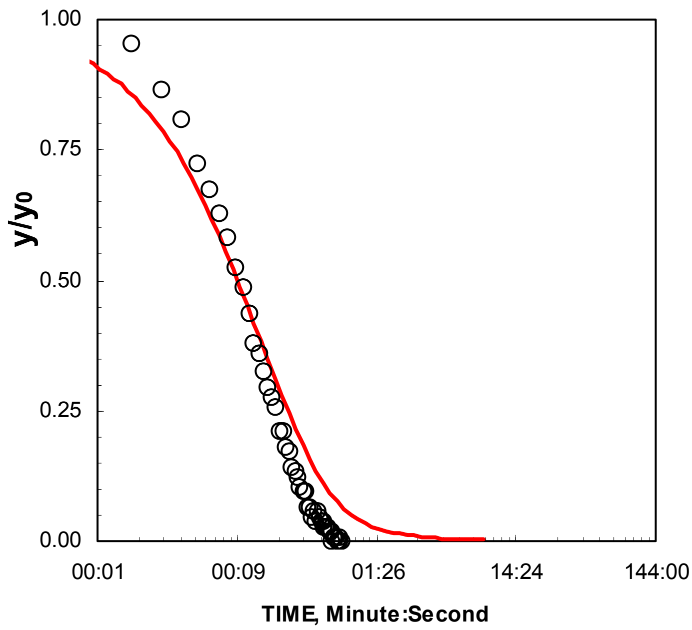

Fig A2-1. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0001.

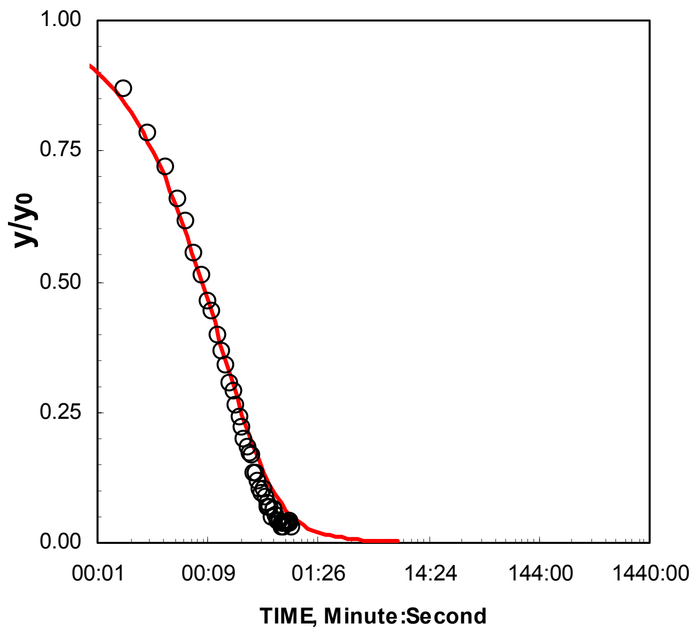

Fig A2-2. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0001.

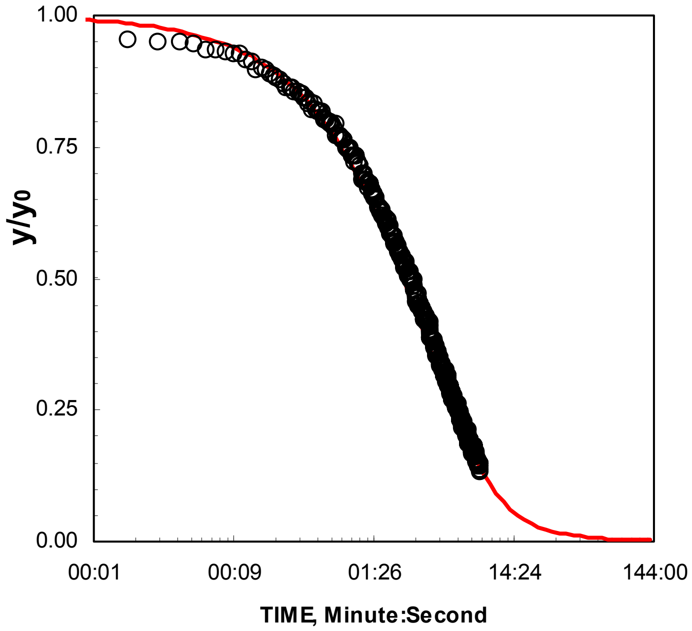

Fig A2-3. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0002.

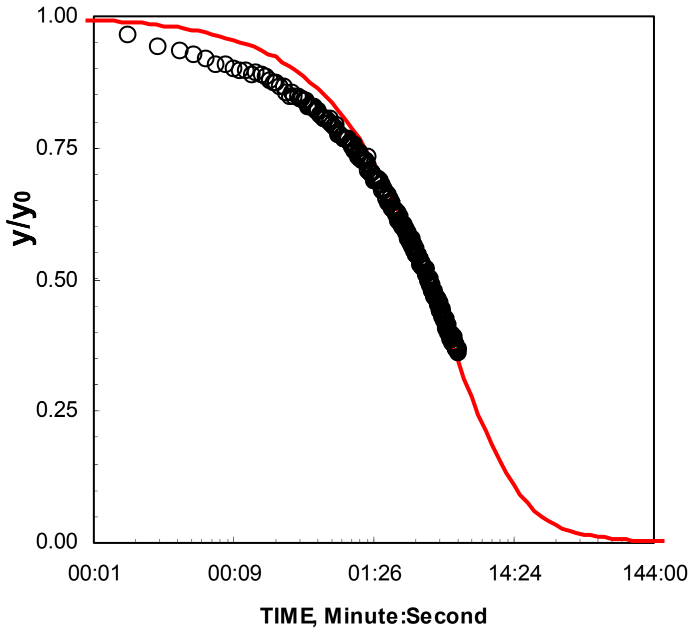

Fig A2-4. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0002.

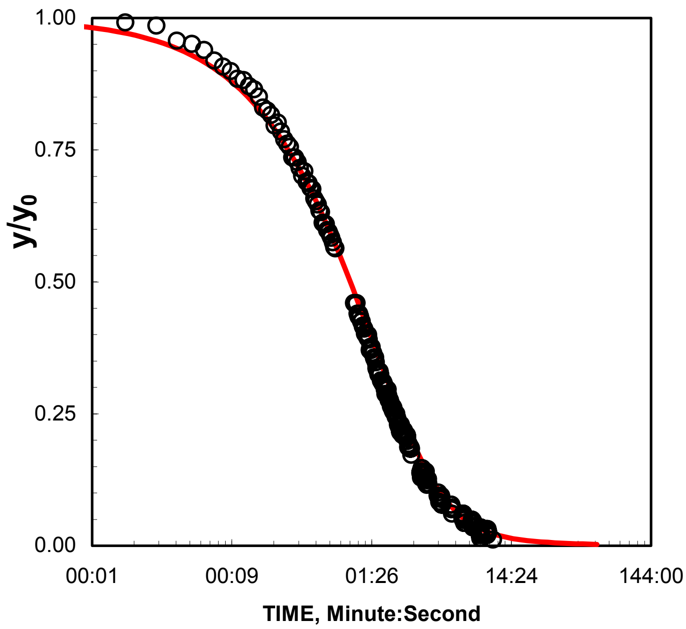

Fig A2-5. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0003.

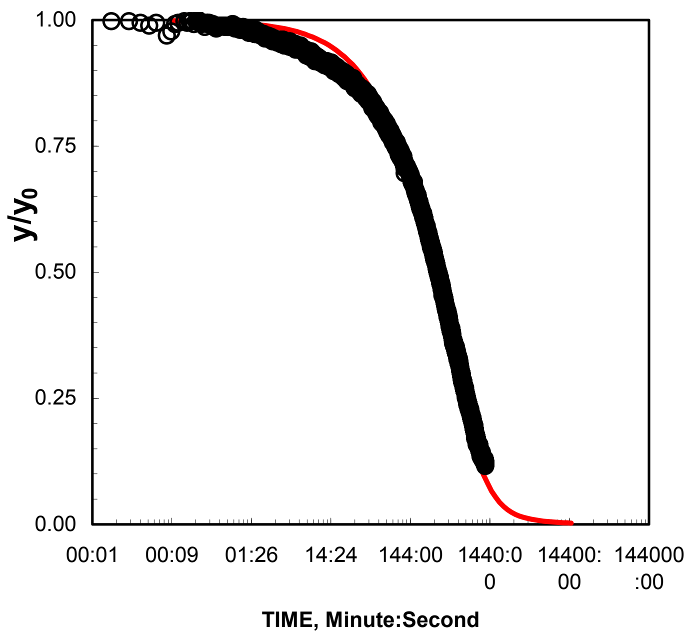

Fig A2-6. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0004.

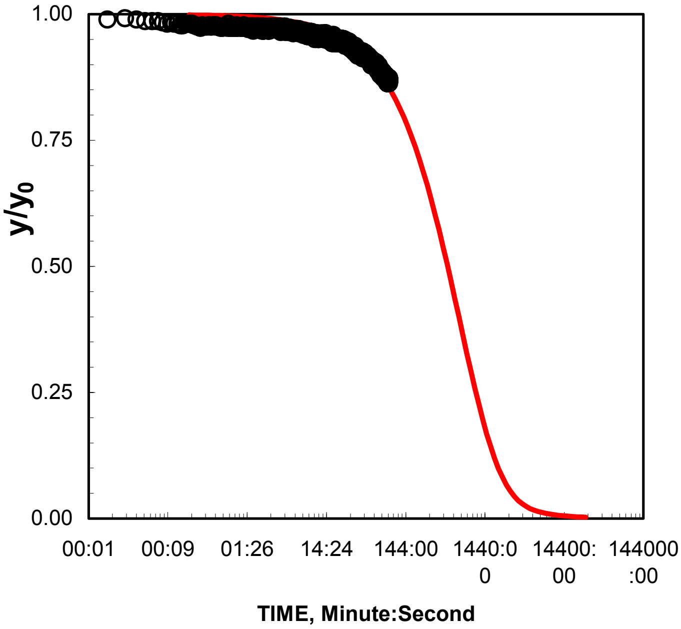

Fig A2-7. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the rising-head test in SFM0004.*

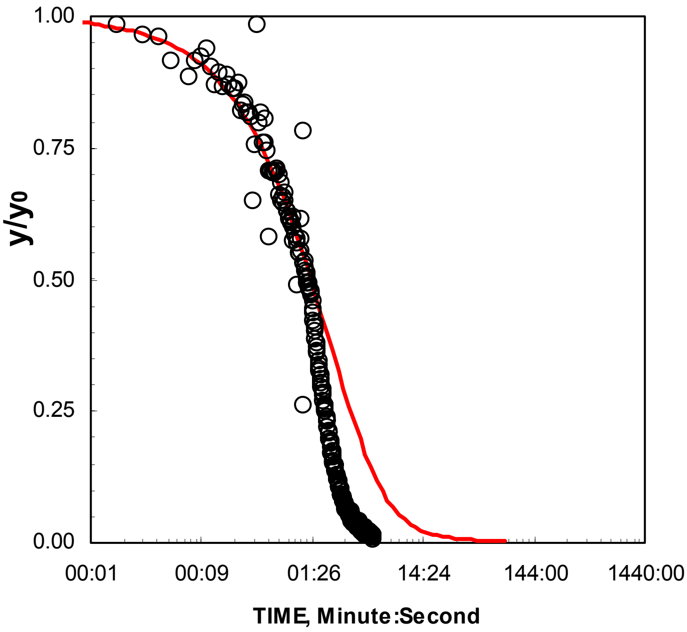

Fig A2-8. *Log-linear plot of the normalized displacement* y/y_0 *versus time for the falling-head test in SFM0005.*

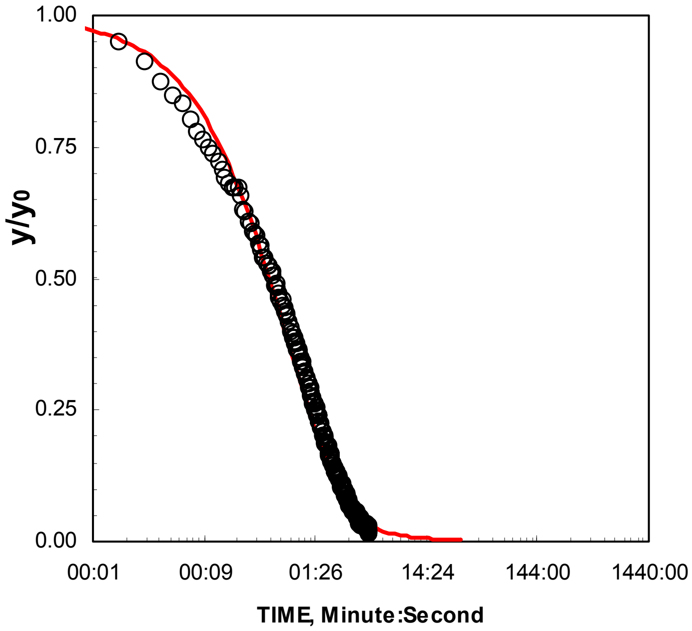

Fig A2-9. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0005.

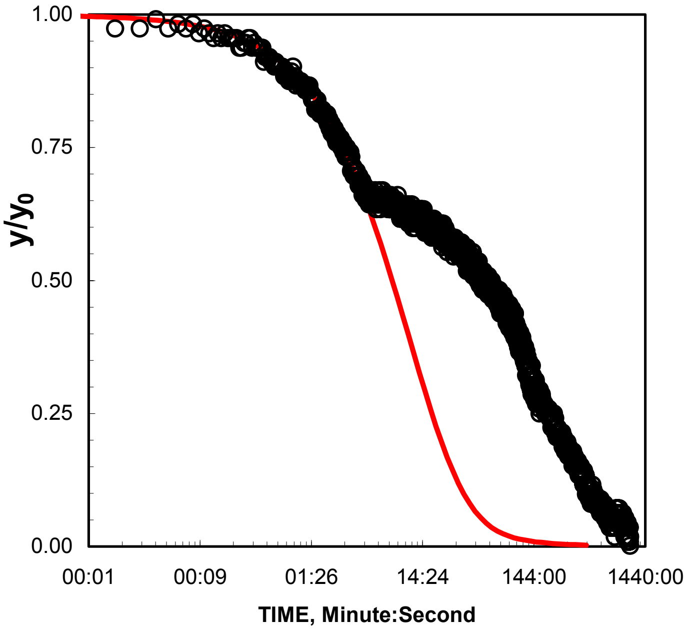

Fig A2-10. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0006.

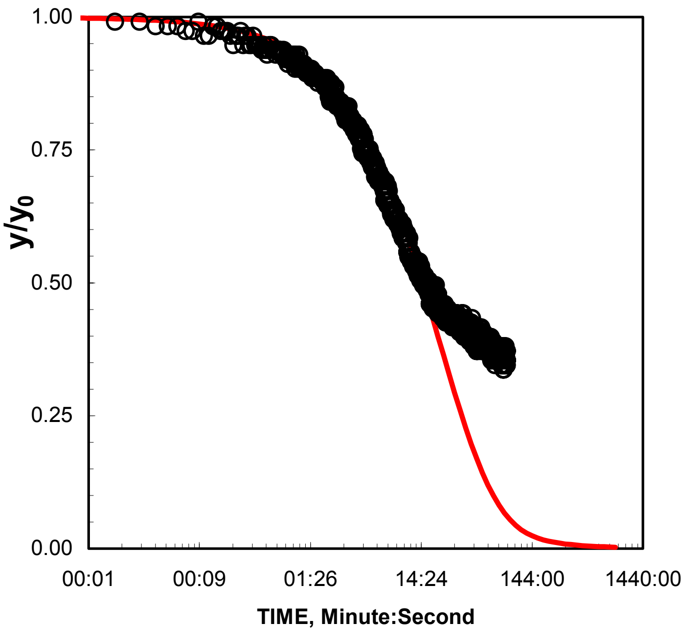

Fig A2-11. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0006.

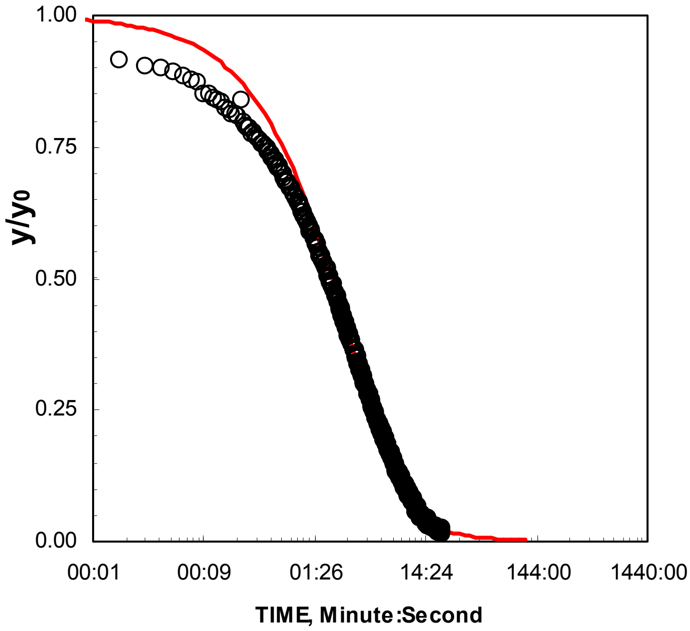

Fig A2-12. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0008.

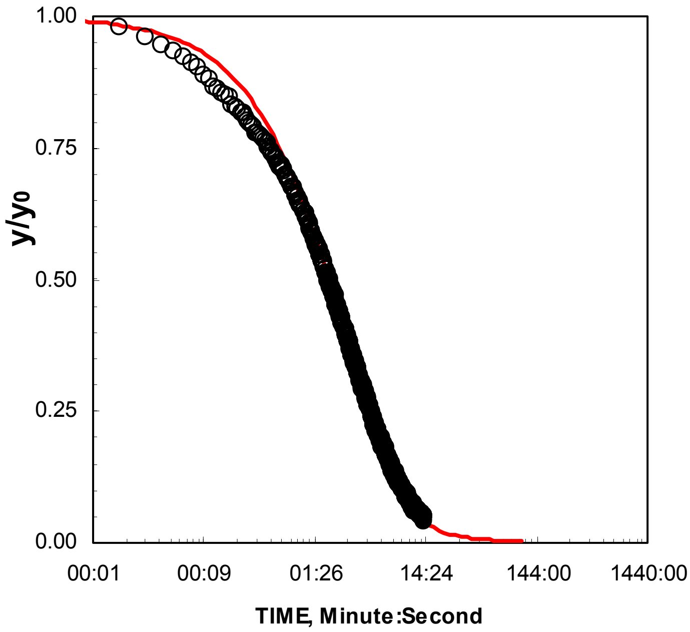

Fig A2-13. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0008.

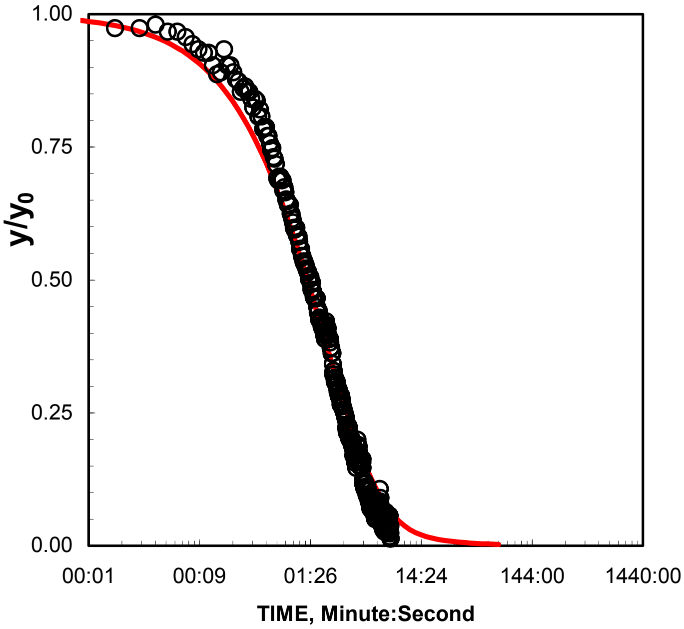

Fig A2-14. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 1 in SFM0009.

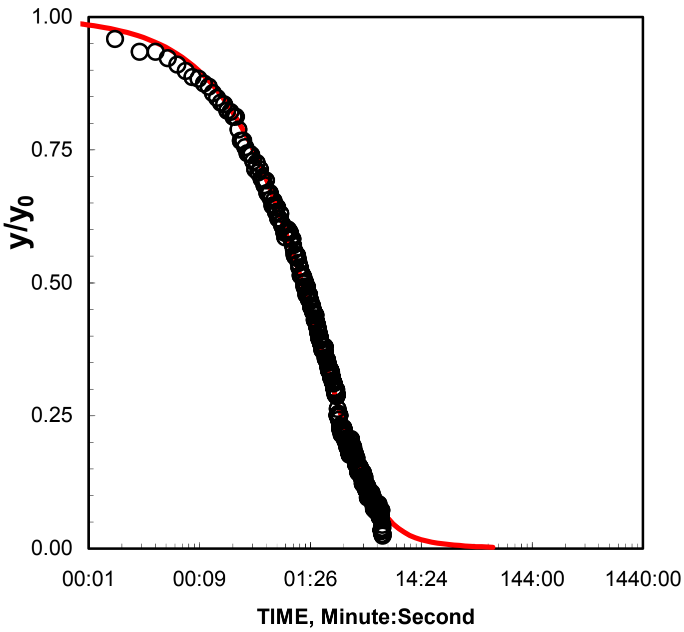

Fig A2-15. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 1 in SFM0009.

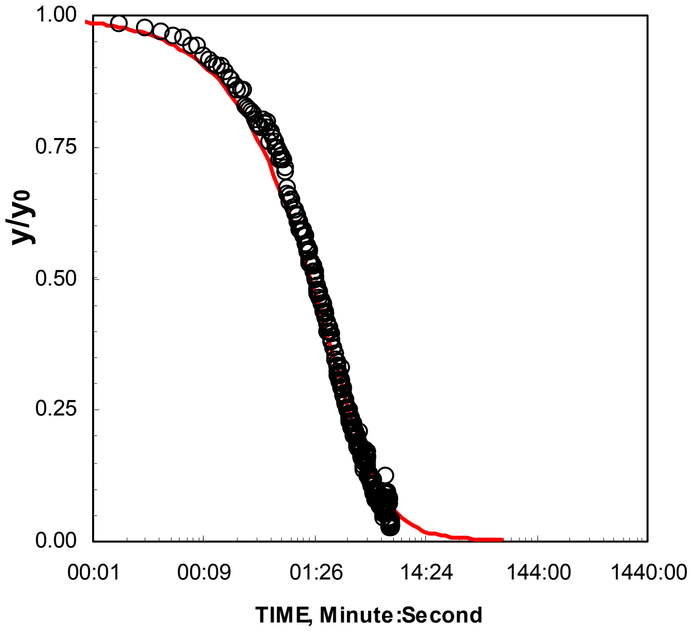

Fig A2-16. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 2 in SFM0009.

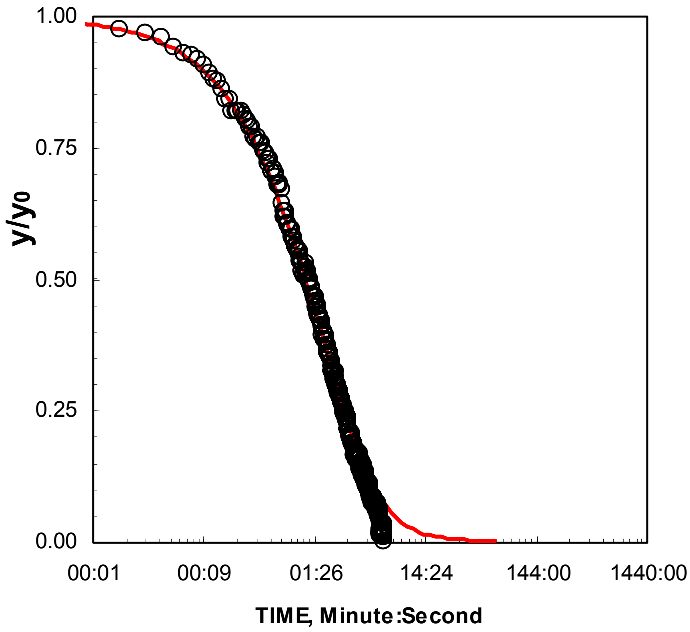

Fig A2-17. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 2 in SFM0009.

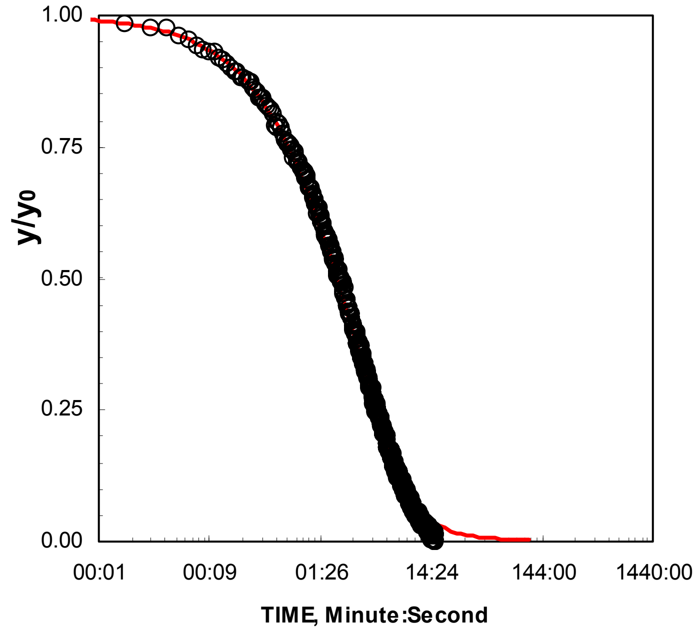

Fig A2-18. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0010.

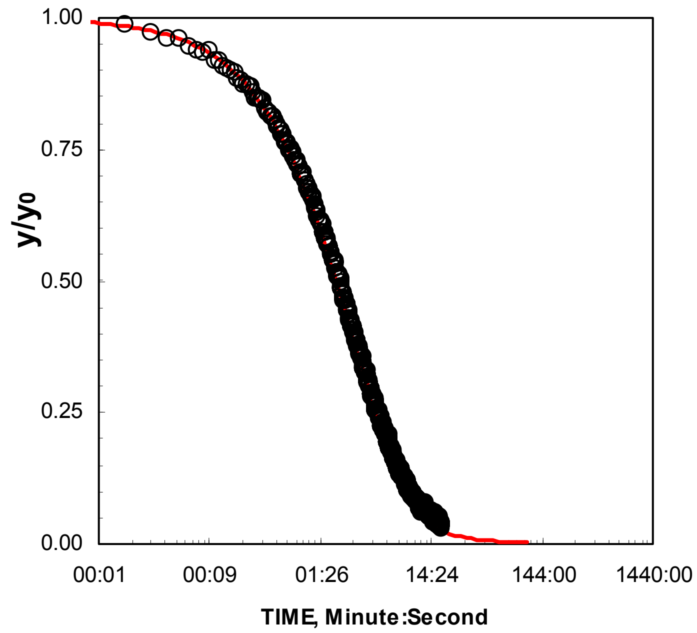

Fig A2-19. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0010.

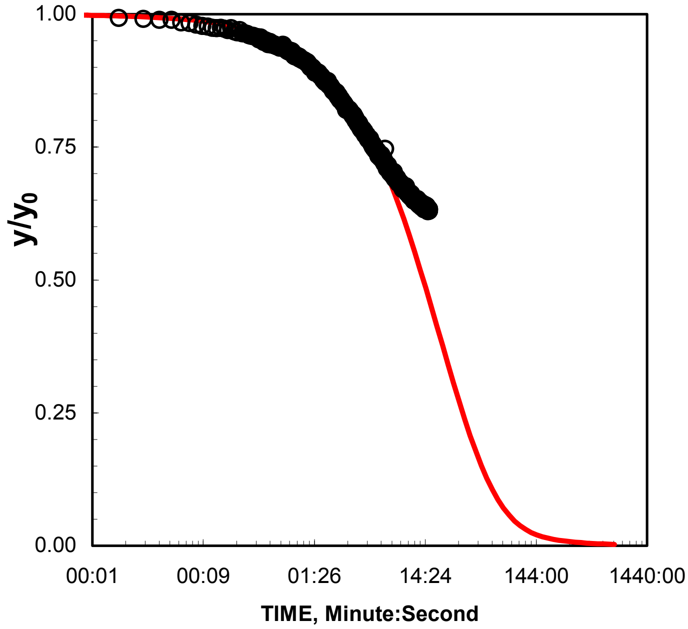

Fig A2-20. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0011.

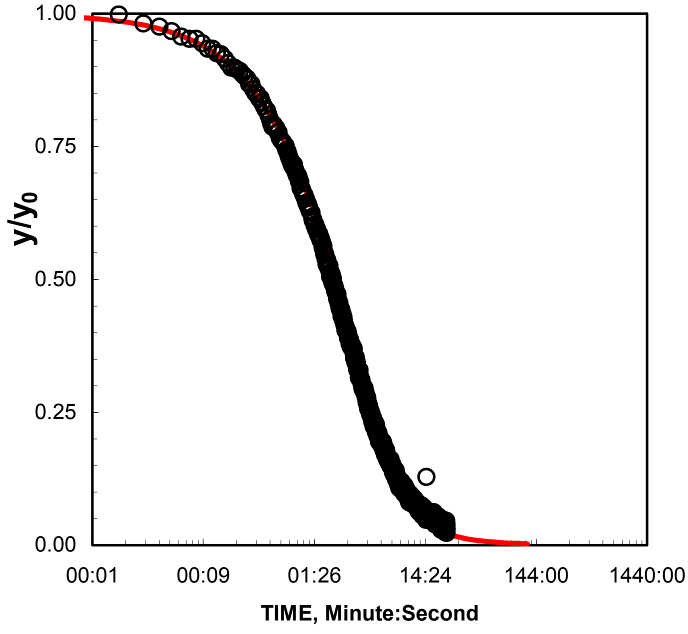

Fig A2-21. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0011.

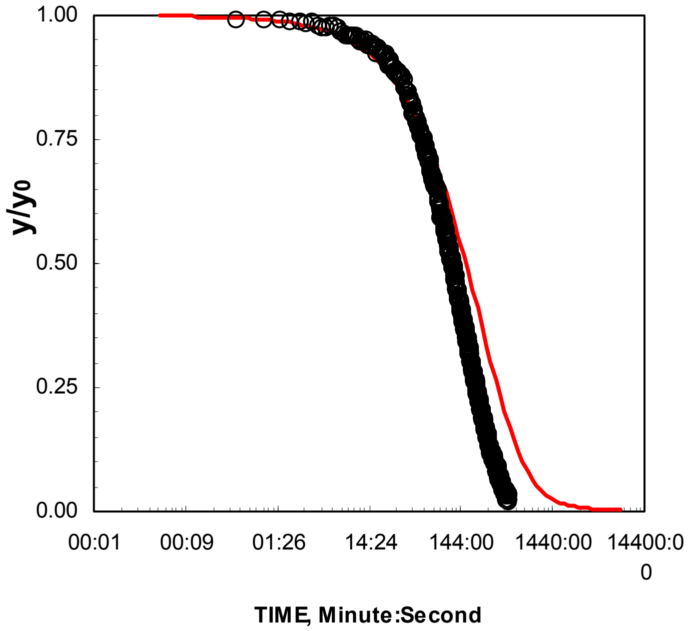

Fig A2-22. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0012.

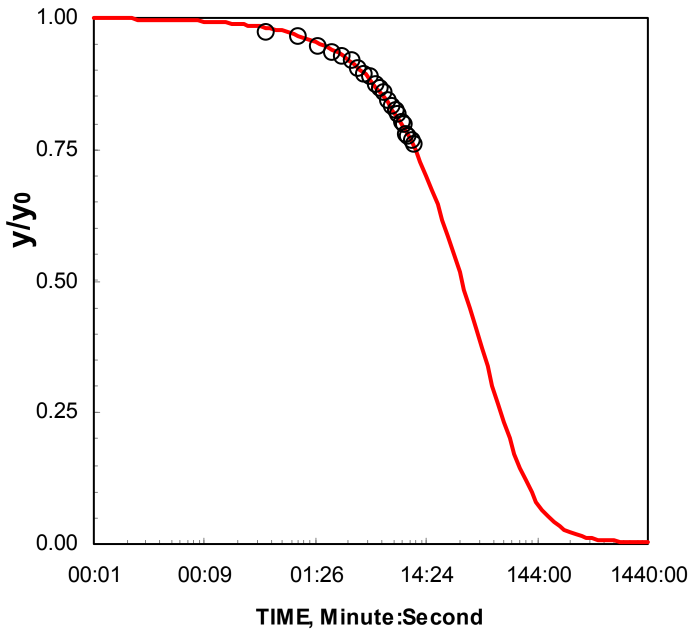

Fig A2-23. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0012.

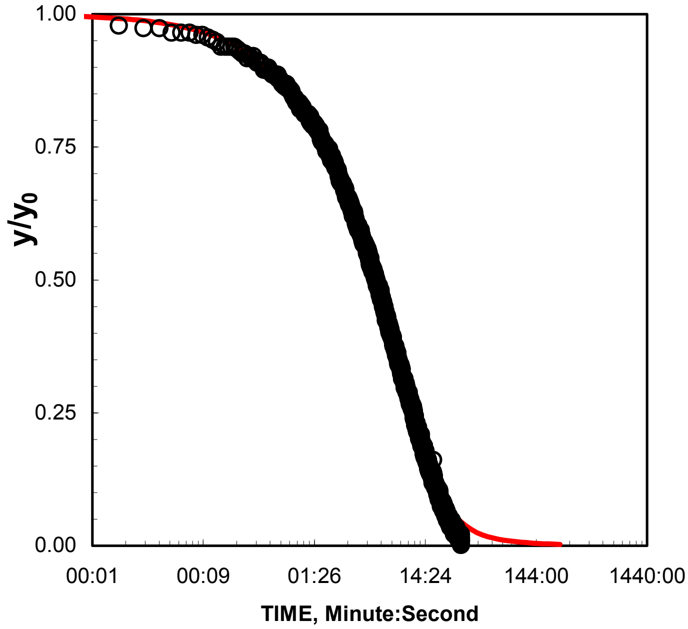

Fig A2-24. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0013.

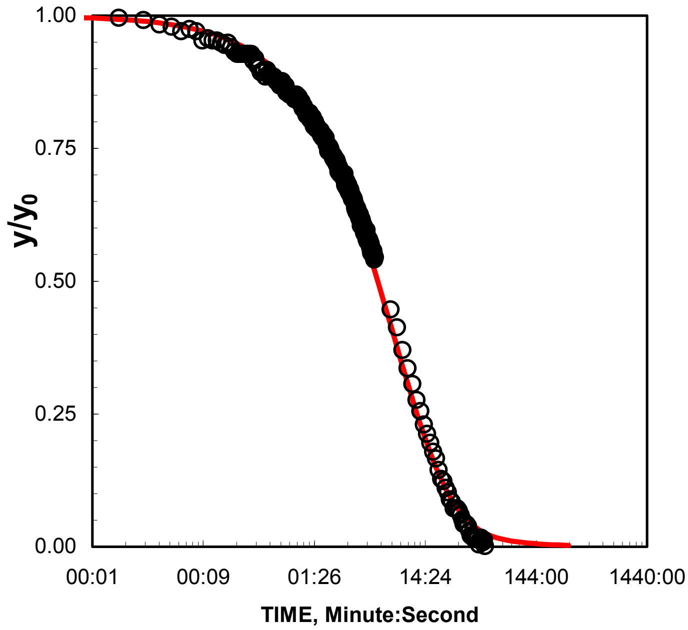

Fig A2-25. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0013.

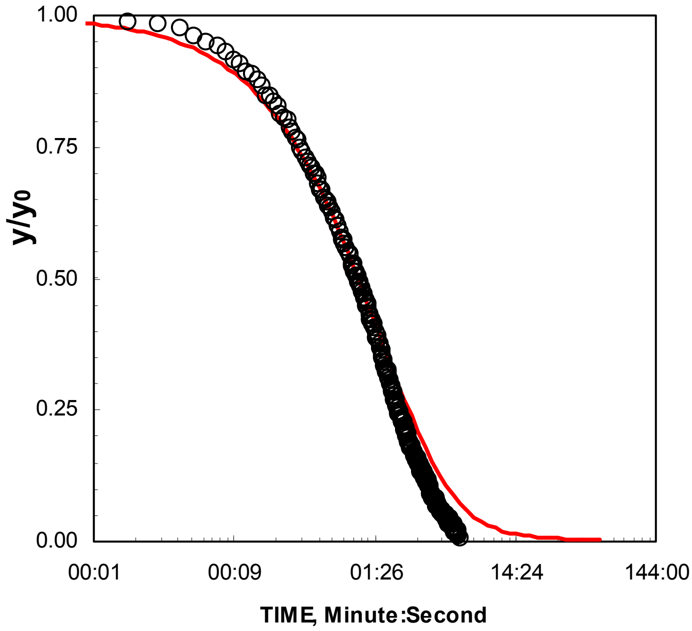

Fig A2-26. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0014.

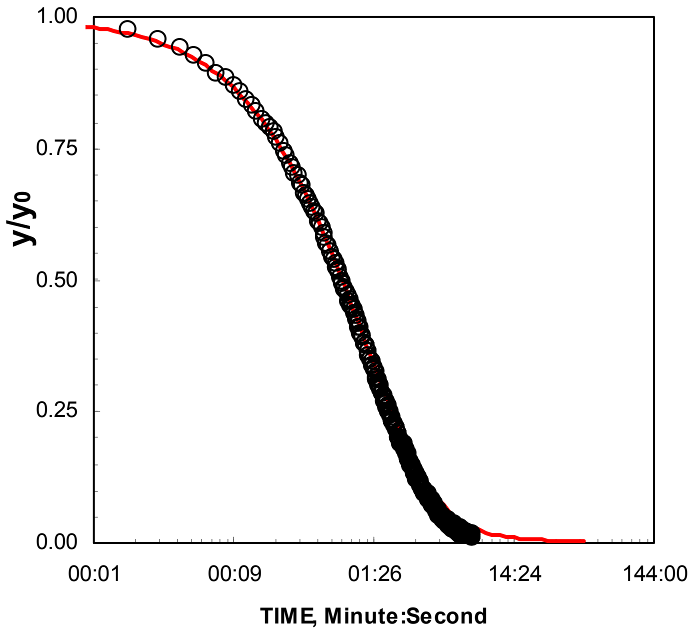

Fig A2-27. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0014.

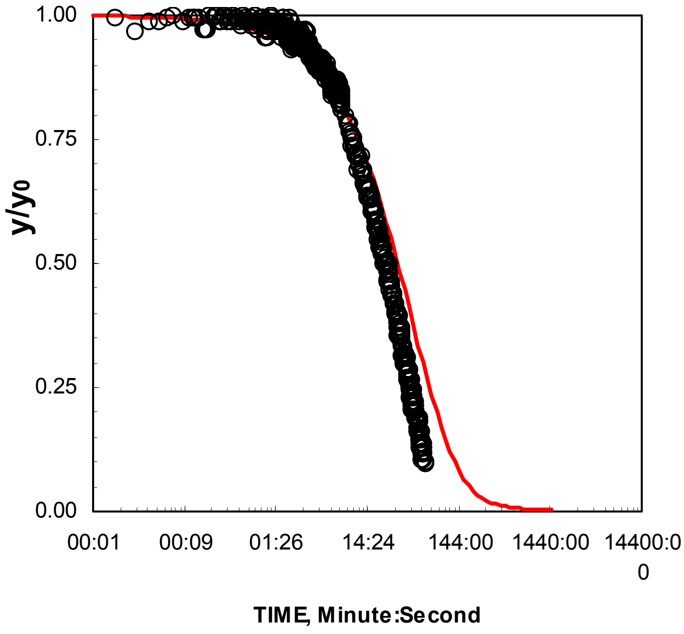

Fig A2-28. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0015.

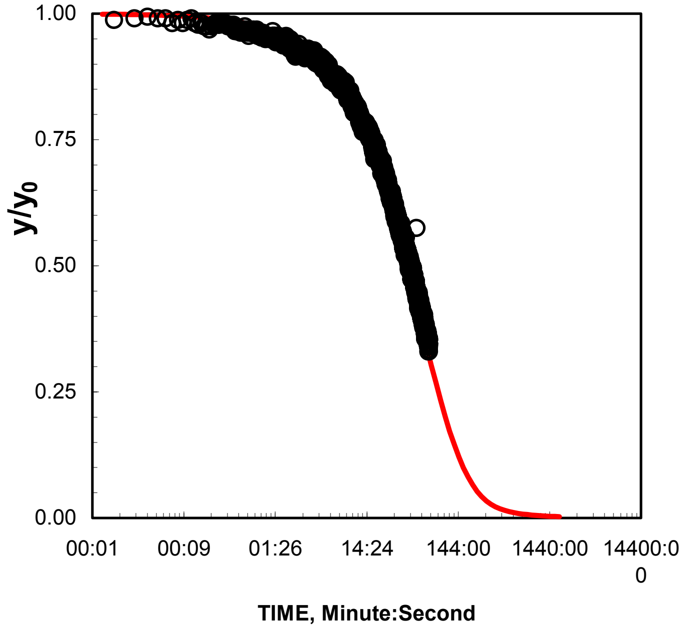

Fig A2-29. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0015.

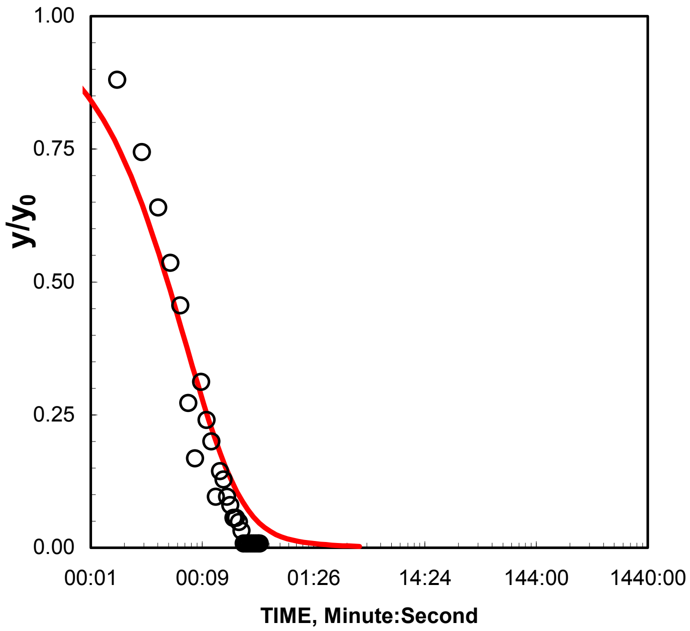

Fig A2-30. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0016.

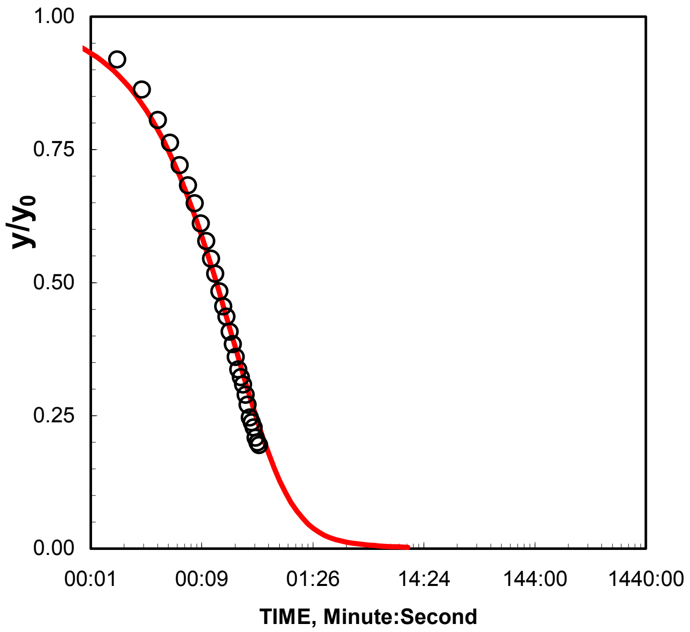

Fig A2-31. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0016.

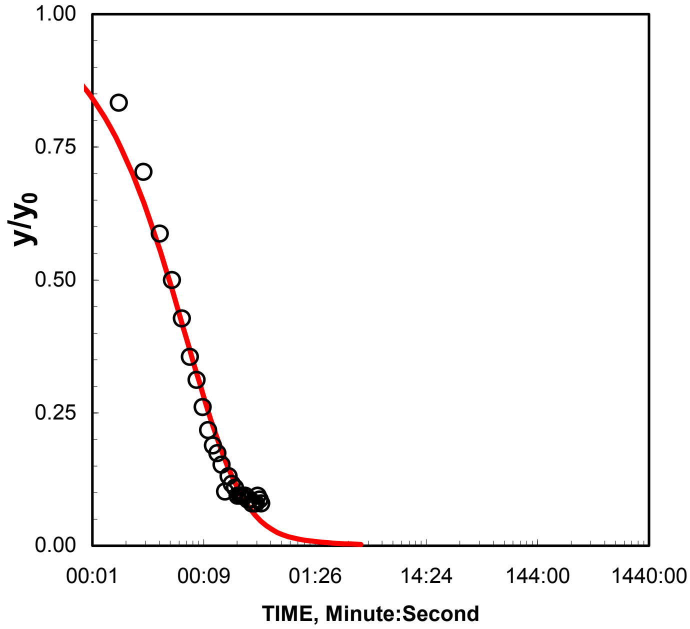

Fig A2-32. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0017.

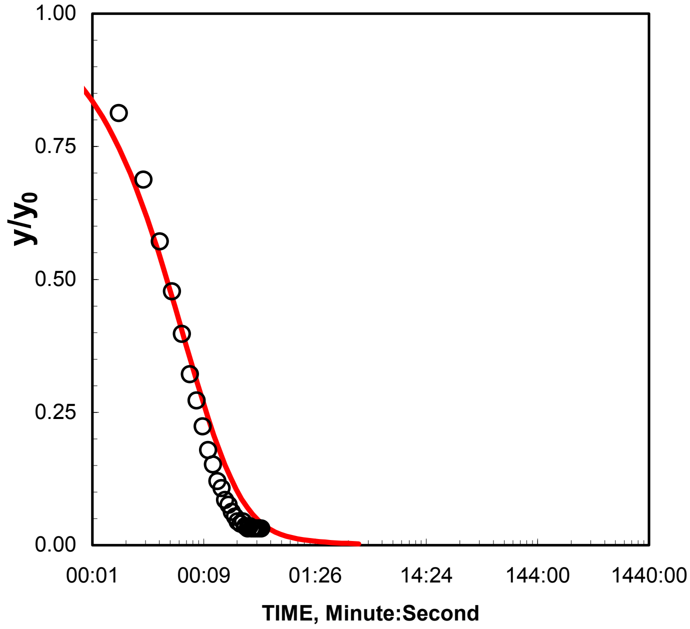

Fig A2-33. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0017.

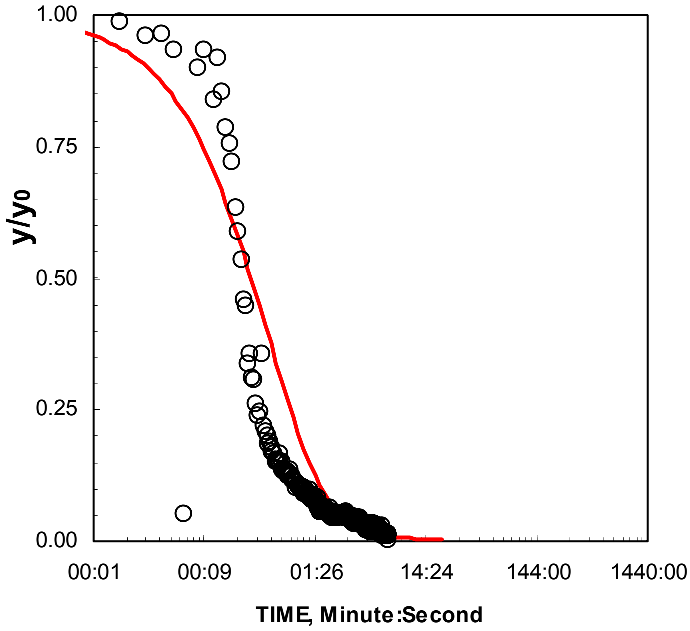

Fig A2-34. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0018.

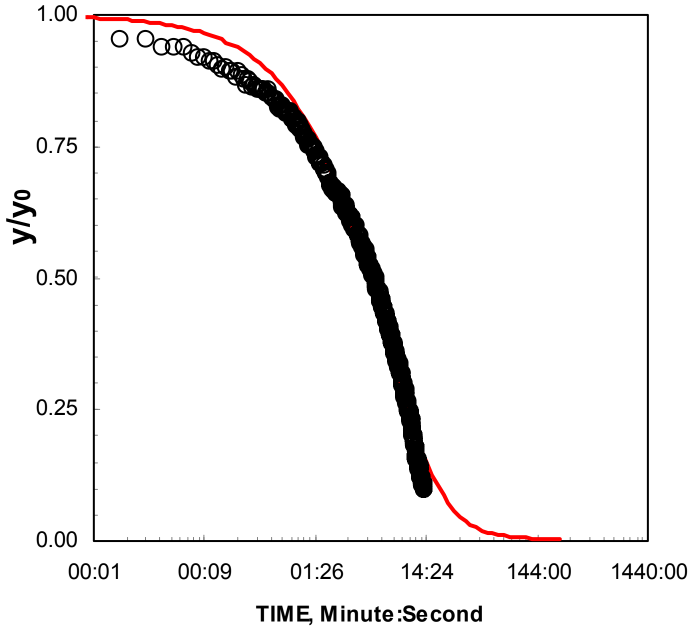

Fig A2-35. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0018.

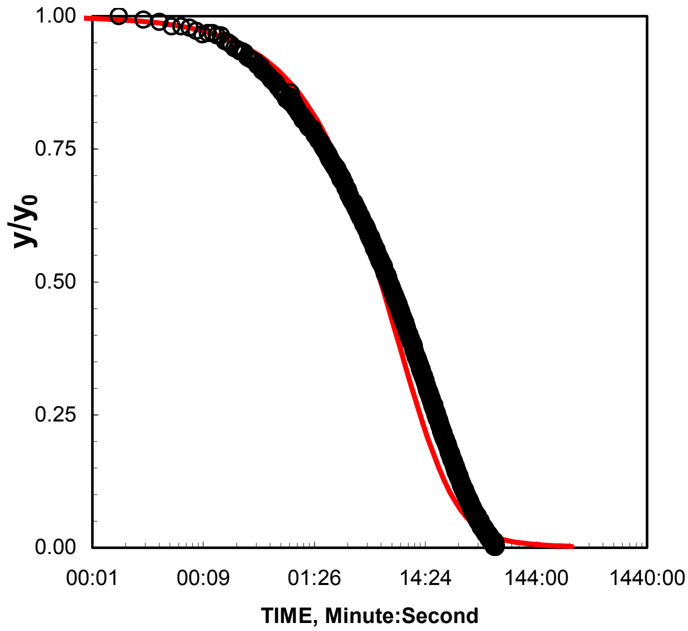

Fig A2-36. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0019.

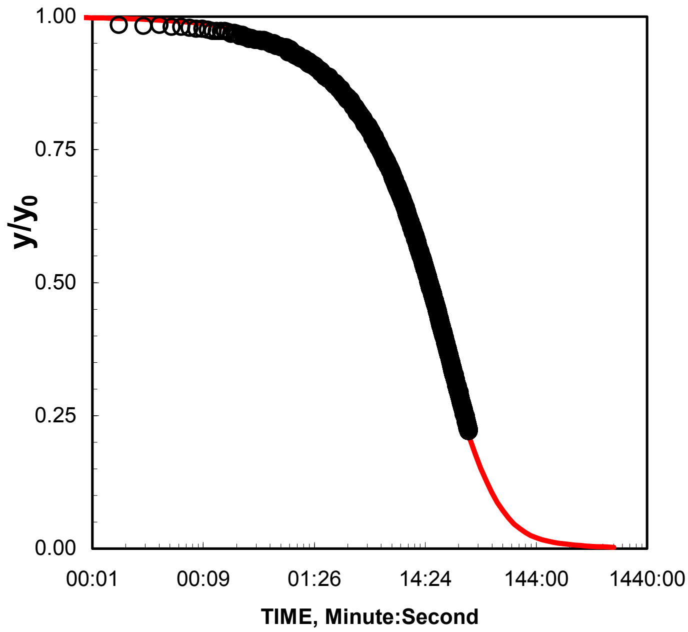

Fig A2-37. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0019.

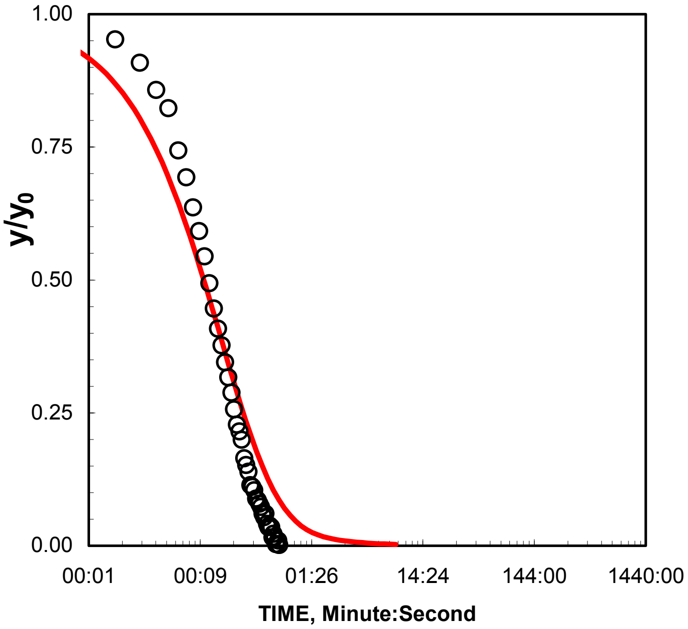

Fig A2-38. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 1 in SFM0020.

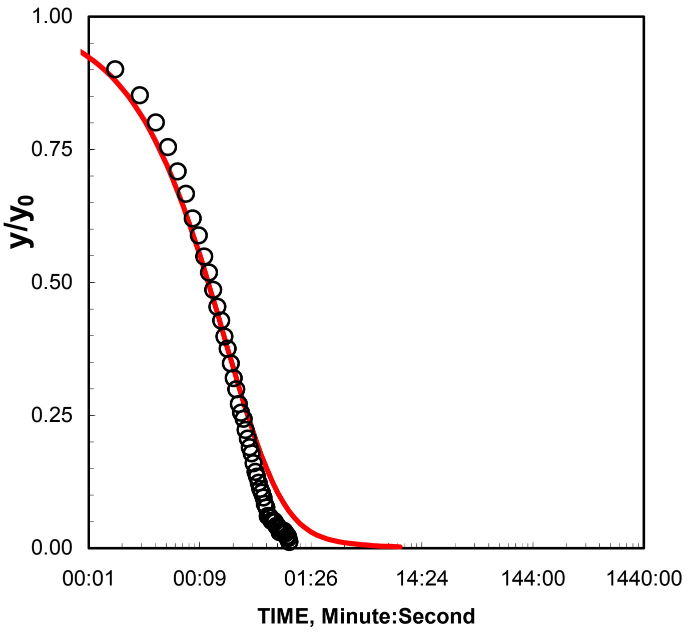

Fig A2-39. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 1 in SFM0020.

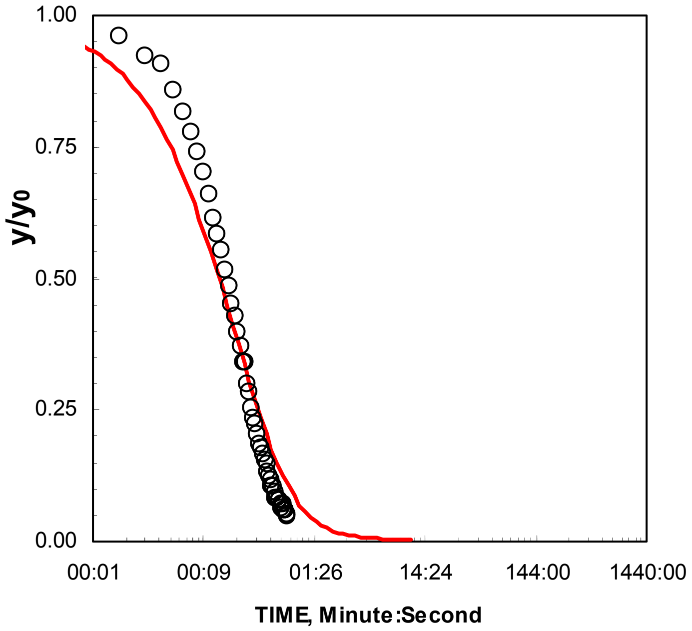

Fig A2-40. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 2 in SFM0020.

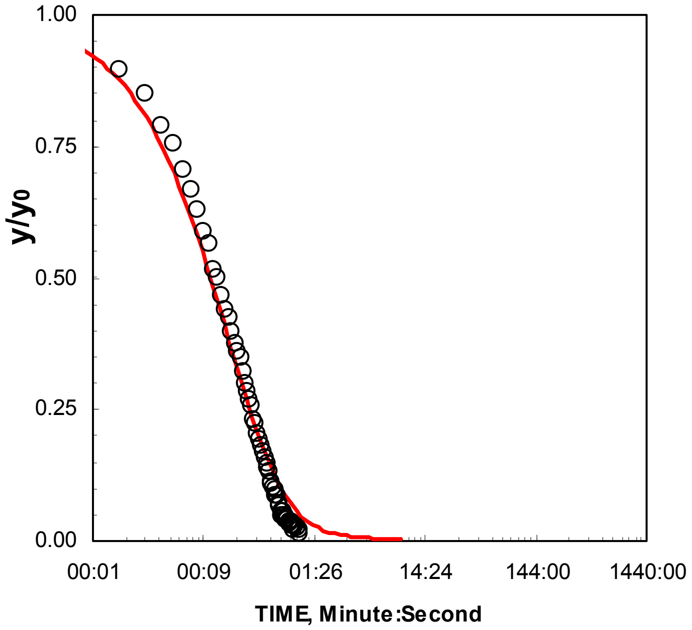

Fig A2-41. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 2 in SFM0020.

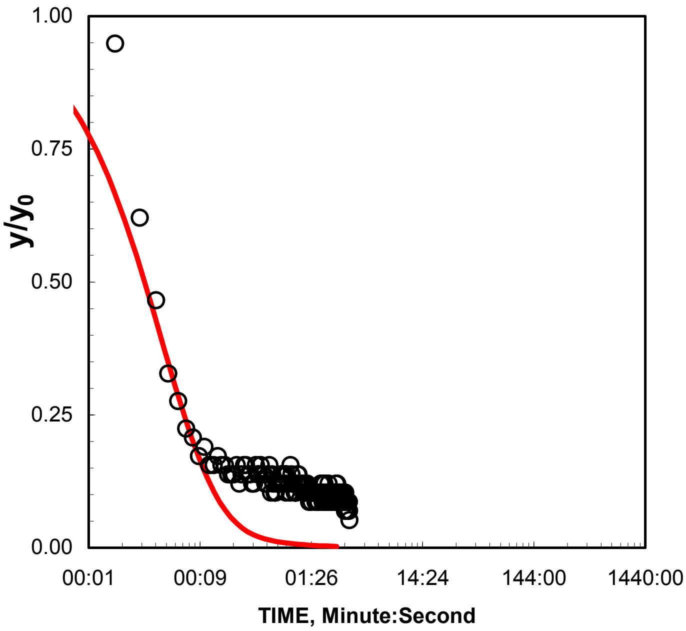

Fig A2-42. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0021.

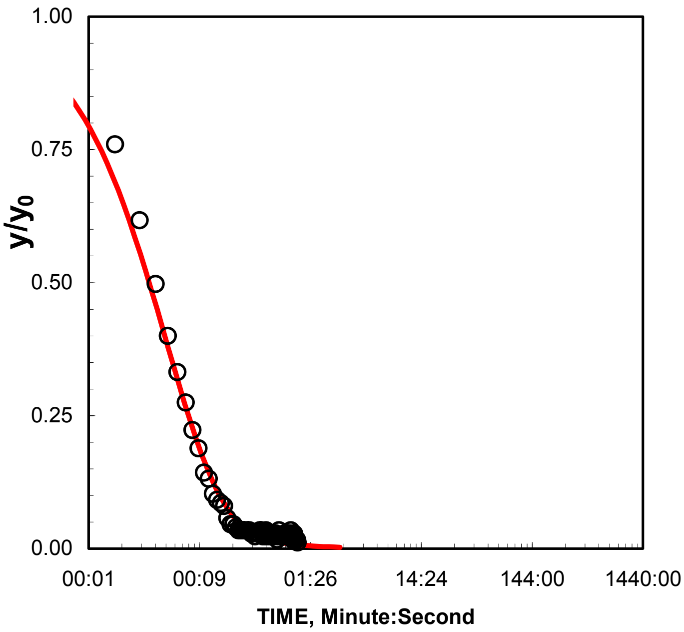

Fig A2-43. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0021.

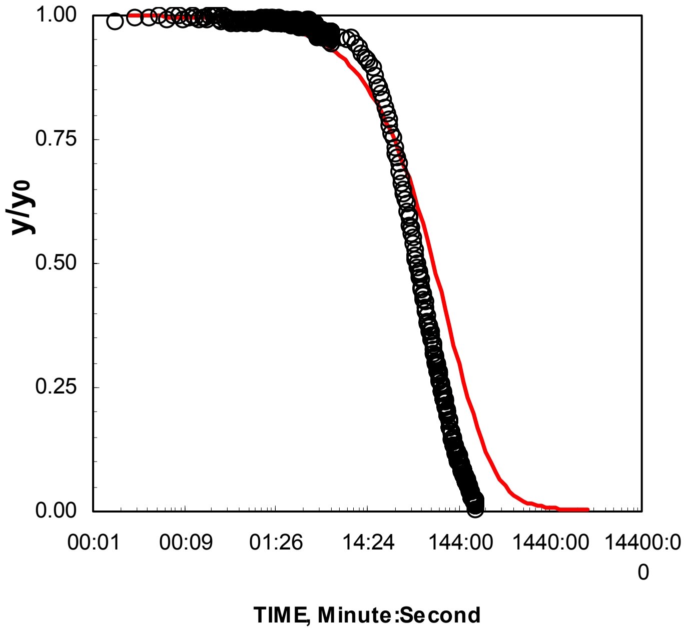

Fig A2-44. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0023.

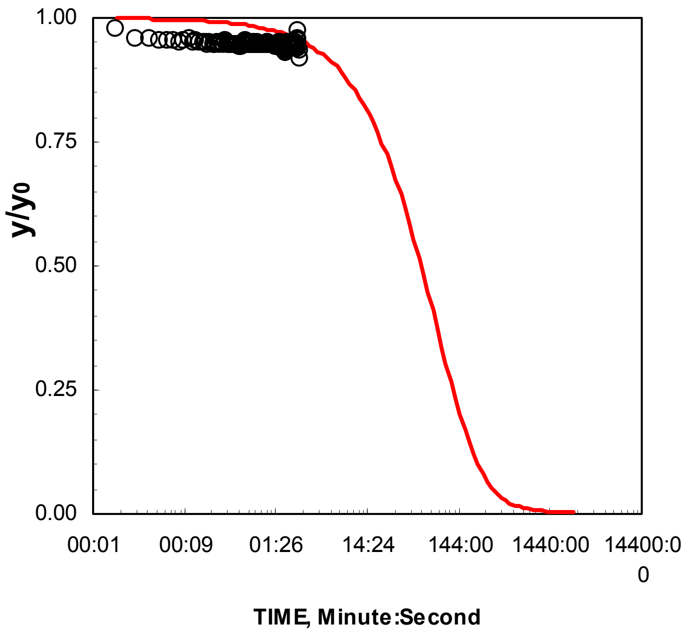

Fig A2-45. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0023.

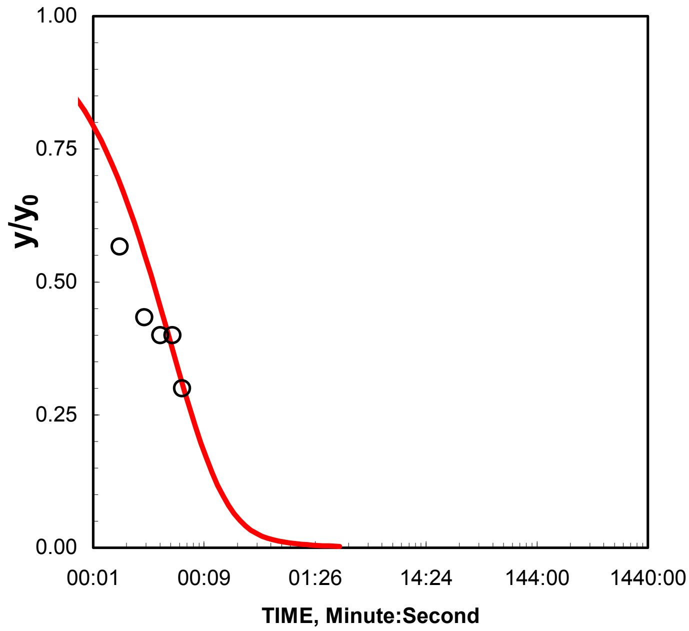

Fig A2-46. Log-linear plot of the normalized displacement y/y$_0$ versus time for falling-head test no. 1 in SFM0024.

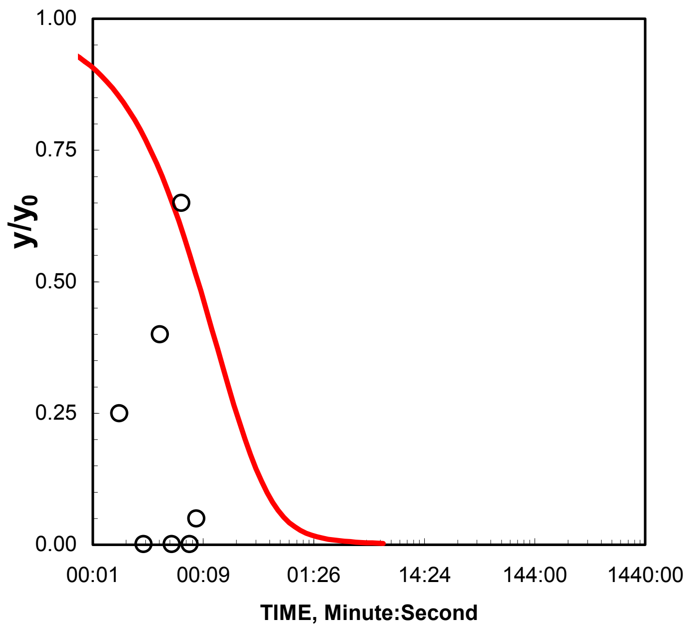

Fig A2-47. Log-linear plot of the normalized displacement y/y$_0$ versus time for the rising-head test in SFM0024.

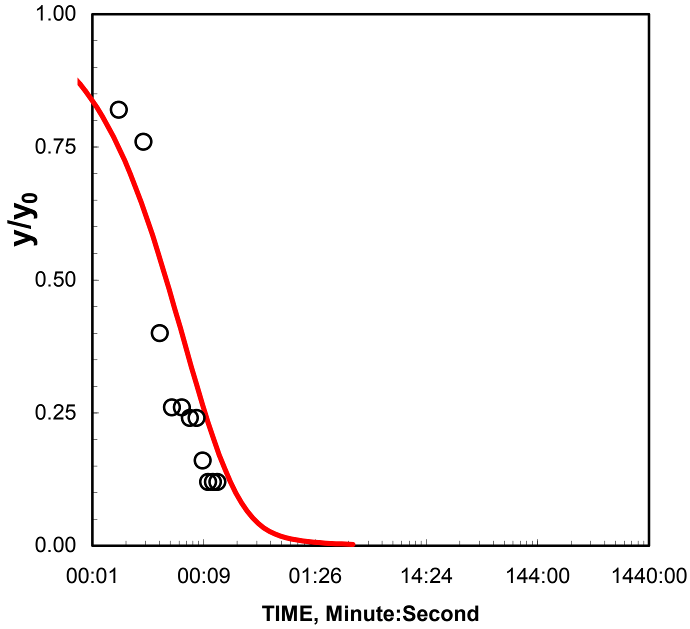

Fig A2-48. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 2 in SFM0024.

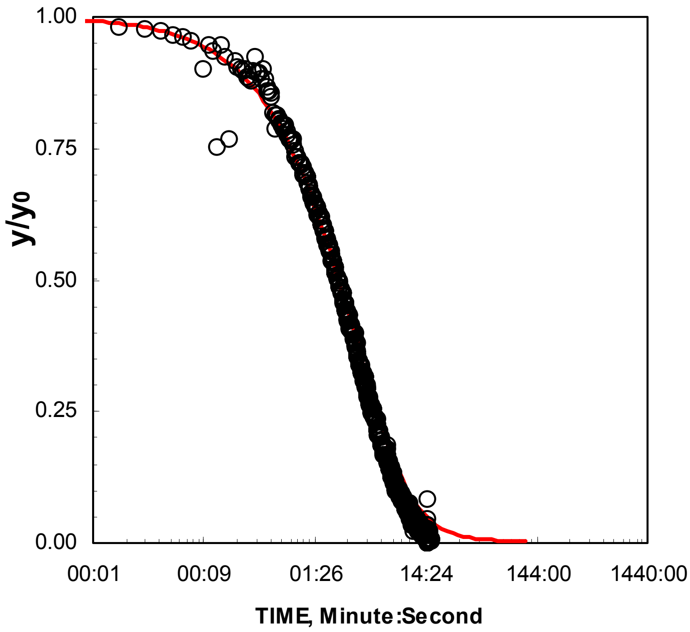

Fig A2-49. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0025.

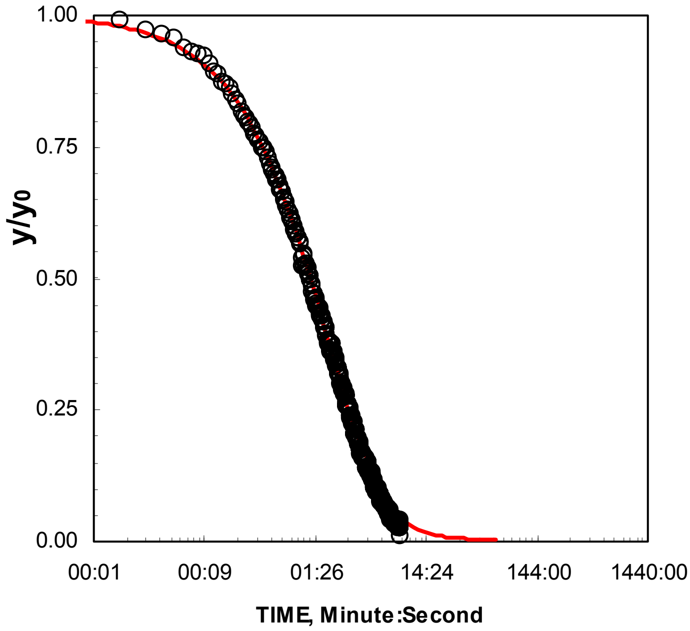

Fig A2-50. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0025.

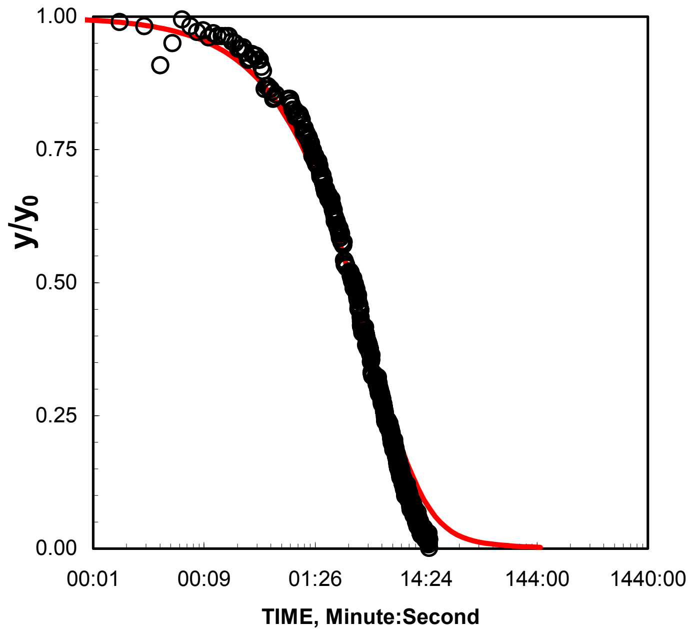

Fig A2-51. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0026.

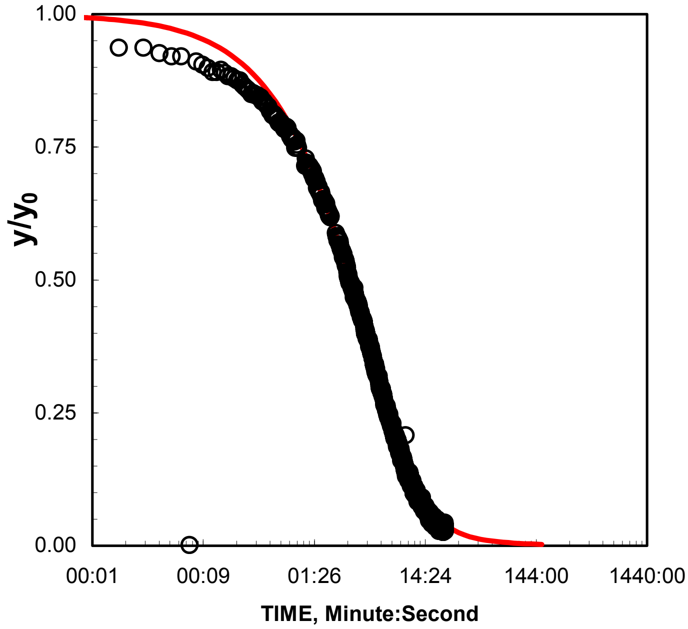

Fig A2-52. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0026.

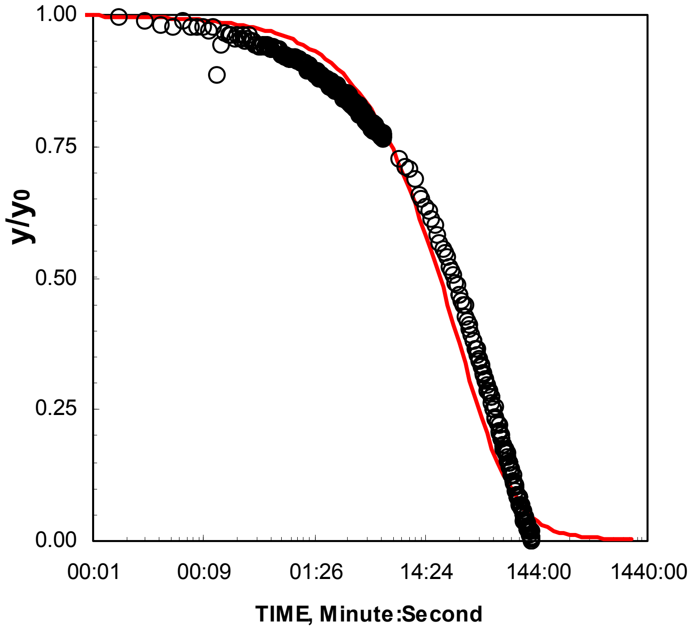

Fig A2-53. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0027.

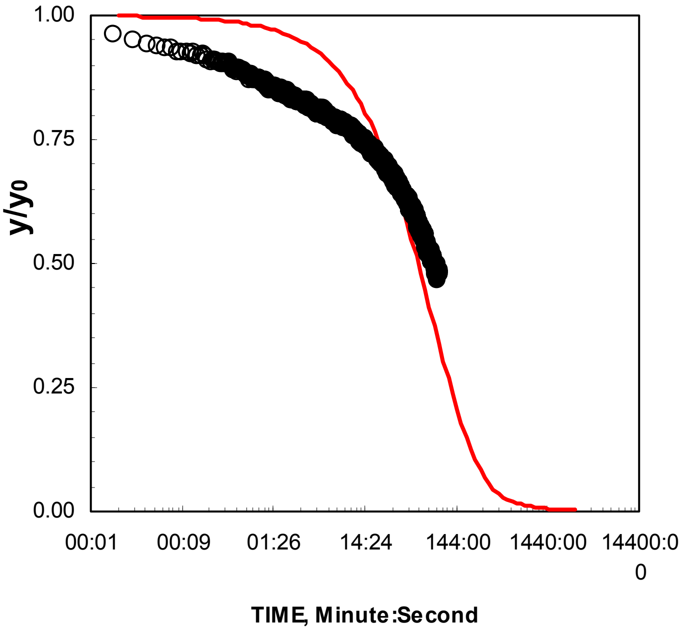

Fig A2-54. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0027.

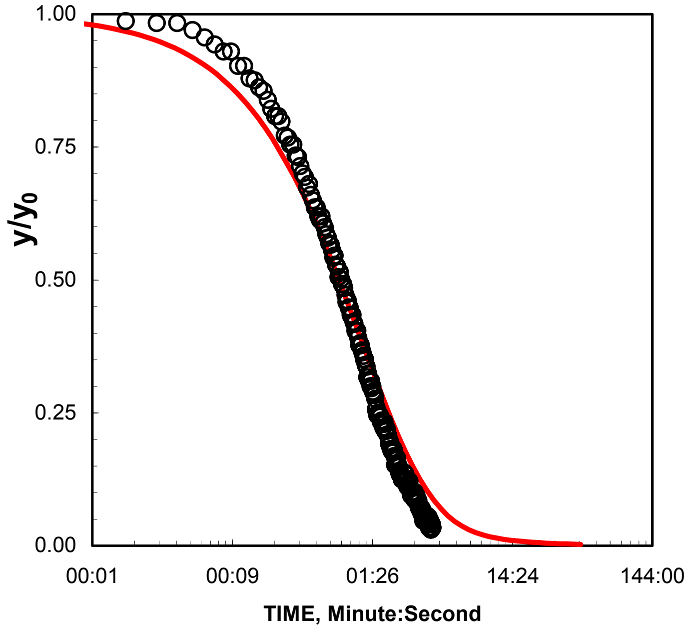

Fig A2-55. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0028.

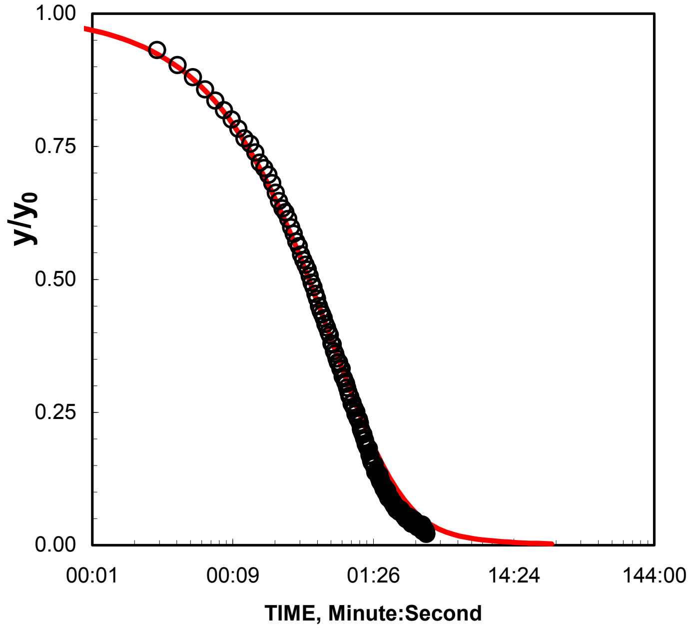

Fig A2-56. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0028.

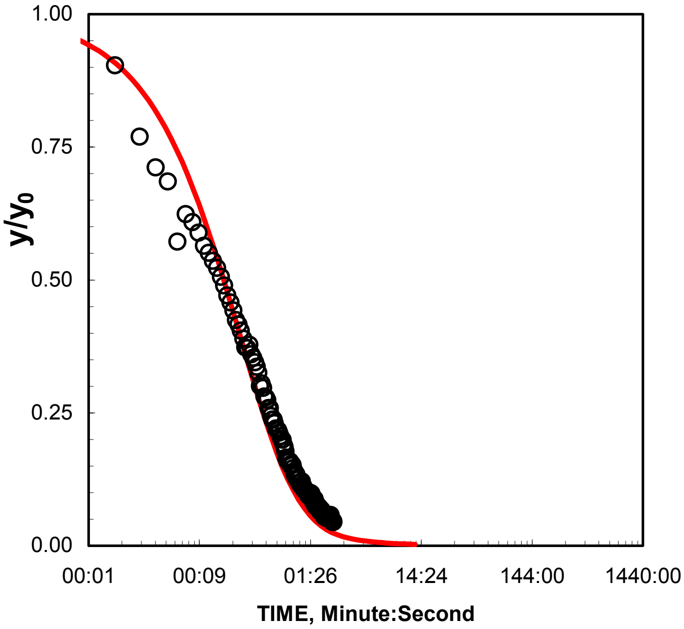

Fig A2-57. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 1 in SFM0029.

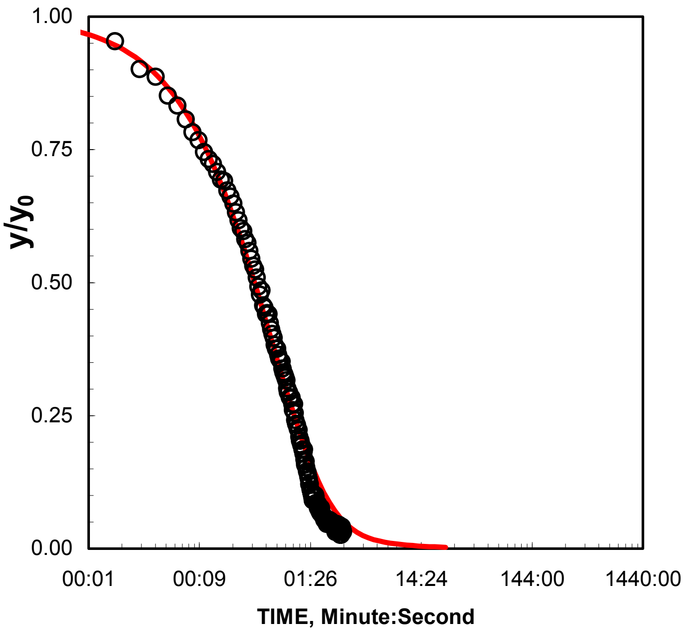

Fig A2-58. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 1 in SFM0029.

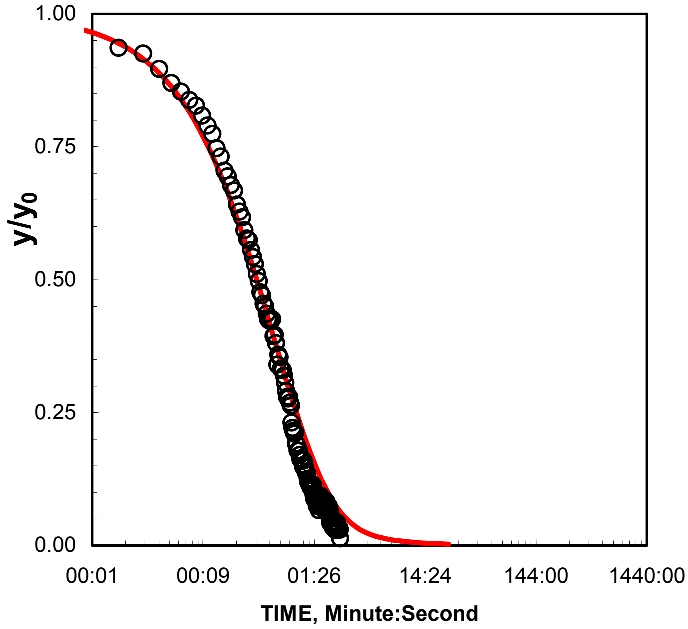

Fig A2-59. Log-linear plot of the normalized displacement y/y_0 versus time for falling-head test no. 2 in SFM0029.

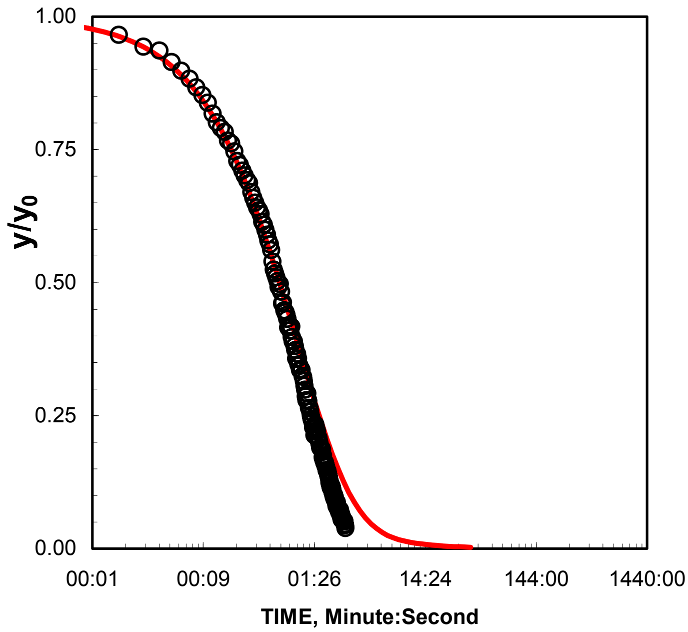

Fig A2-60. Log-linear plot of the normalized displacement y/y_0 versus time for rising-head test no. 2 in SFM0029.

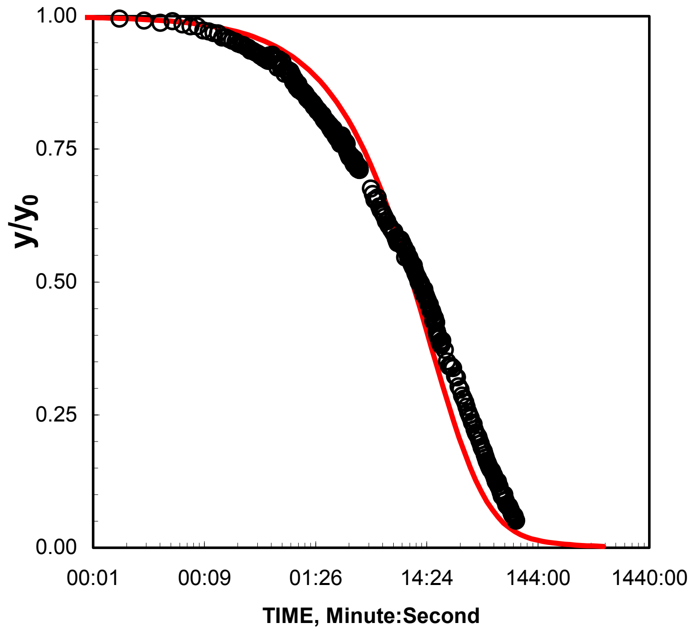

Fig A2-61. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0030.

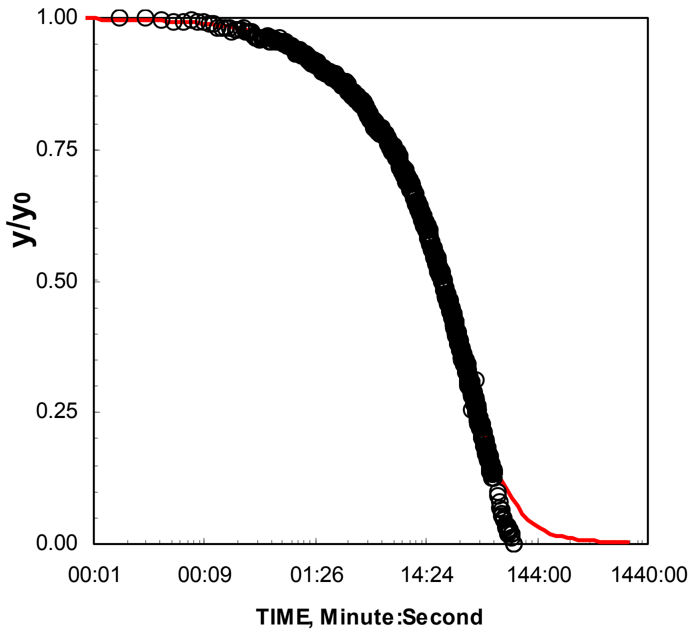

Fig A2-62. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0031.

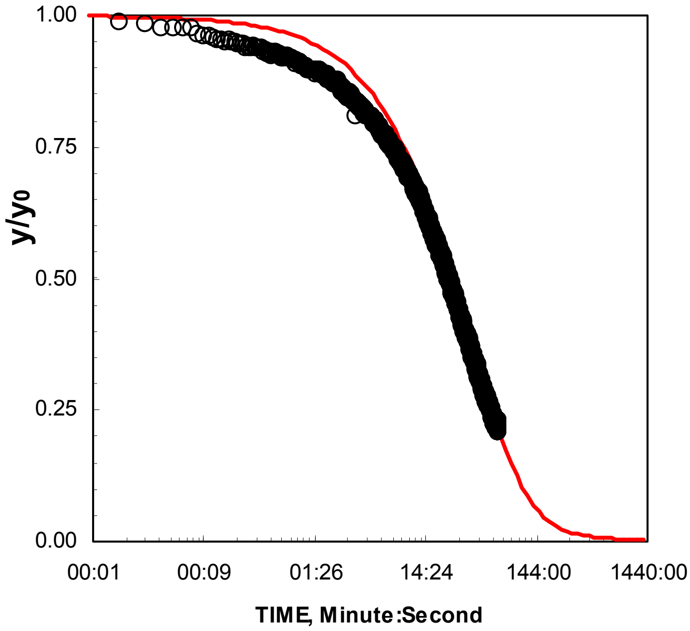

Fig A2-63. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0031.

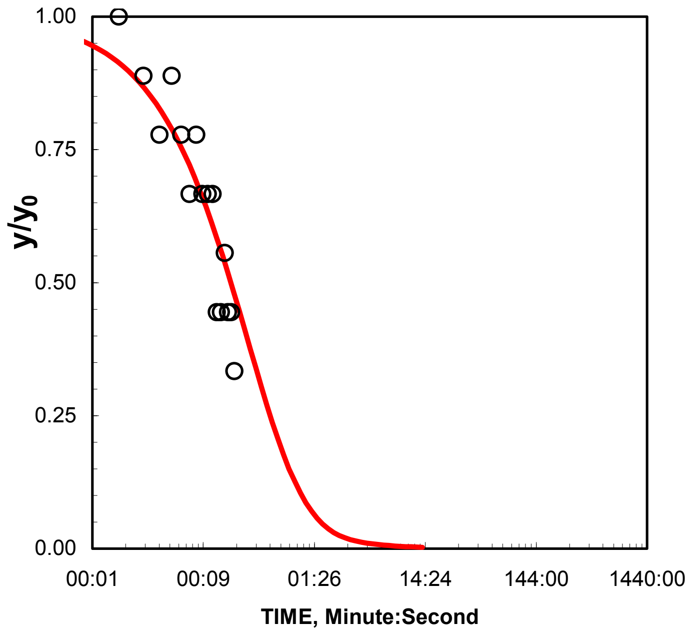

Fig A2-64. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0032.

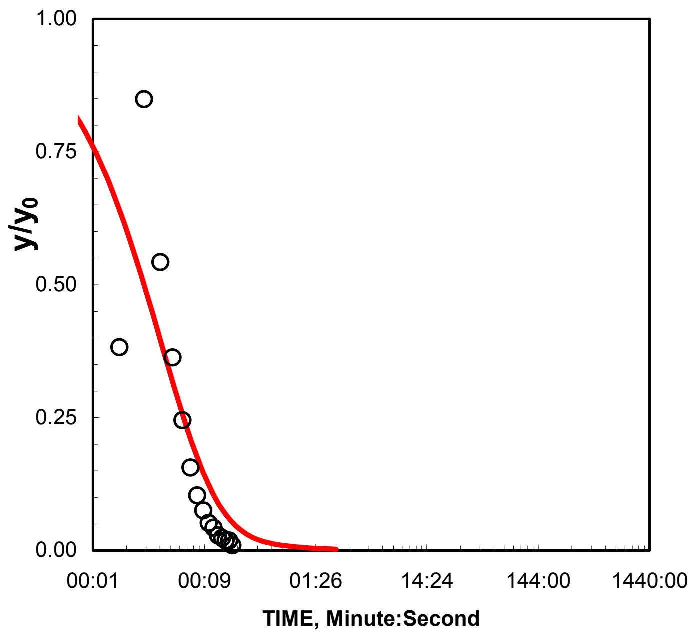

Fig A2-65. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0032.

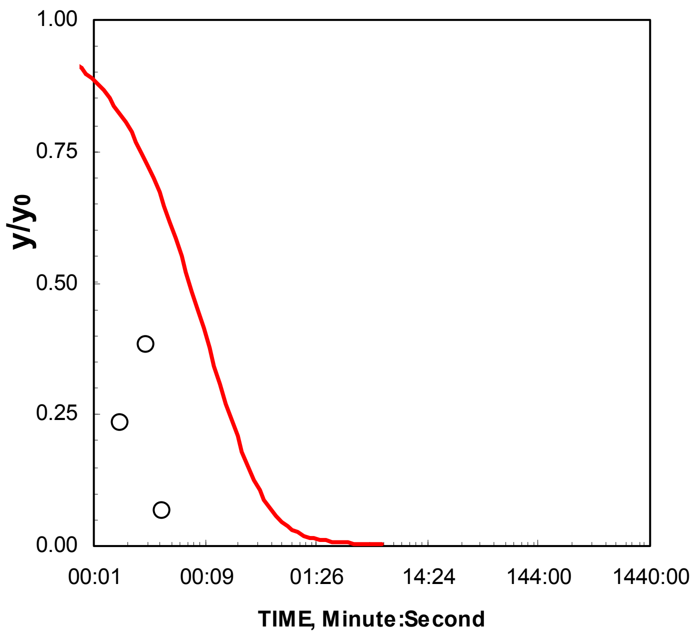

Fig A2-66. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0033.

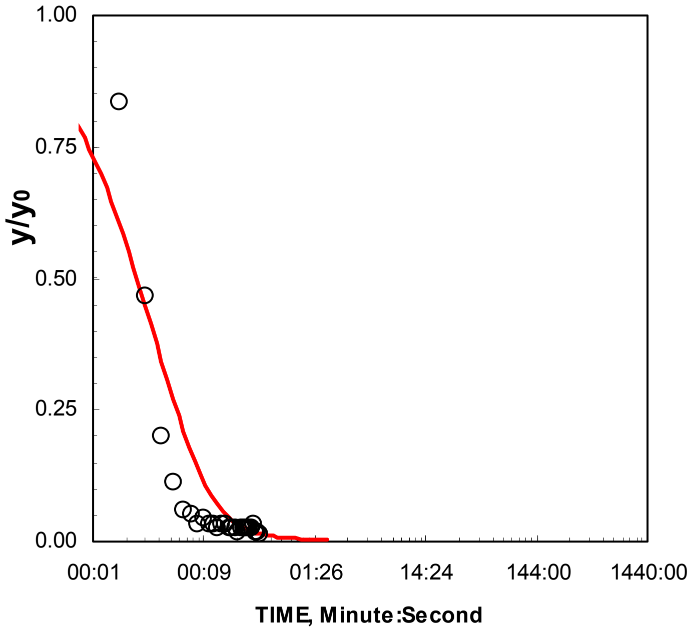

Fig A2-67. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0033.

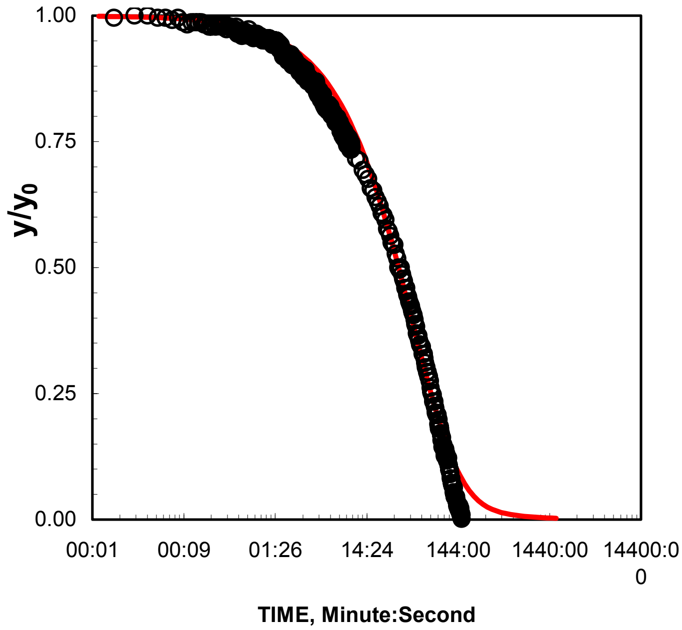

Fig A2-68. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0034.

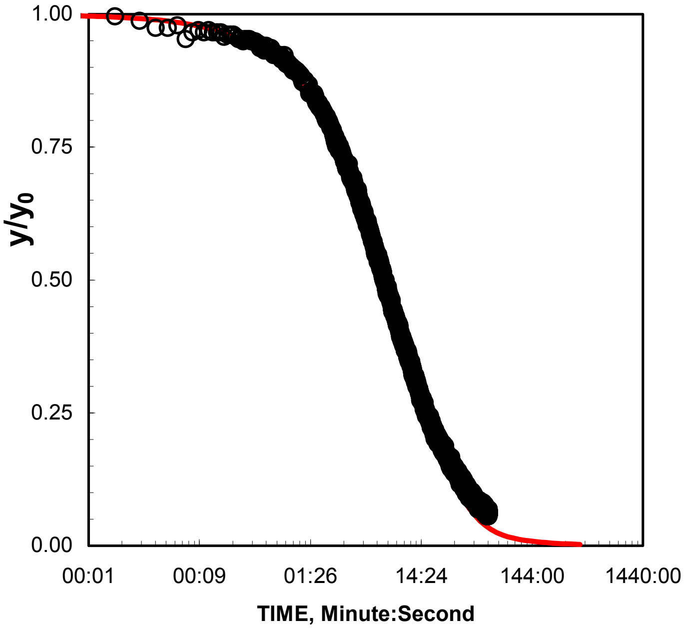

Fig A2-69. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0034.

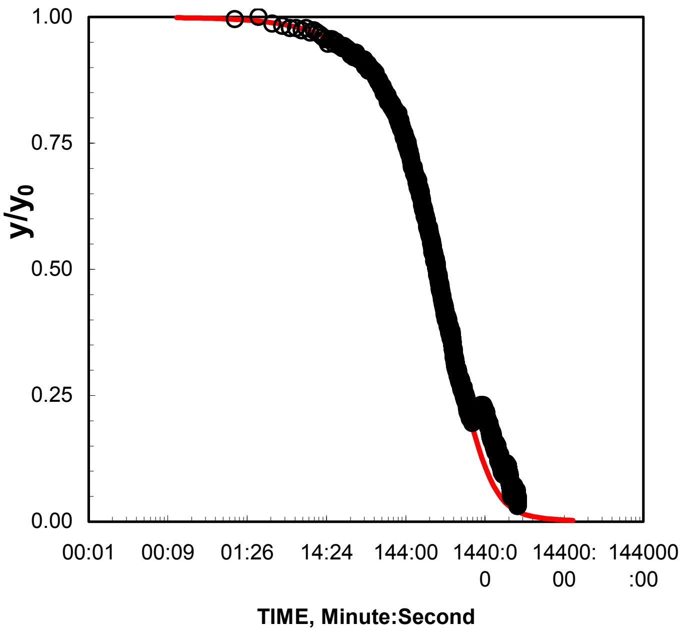

Fig A2-70. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0035.

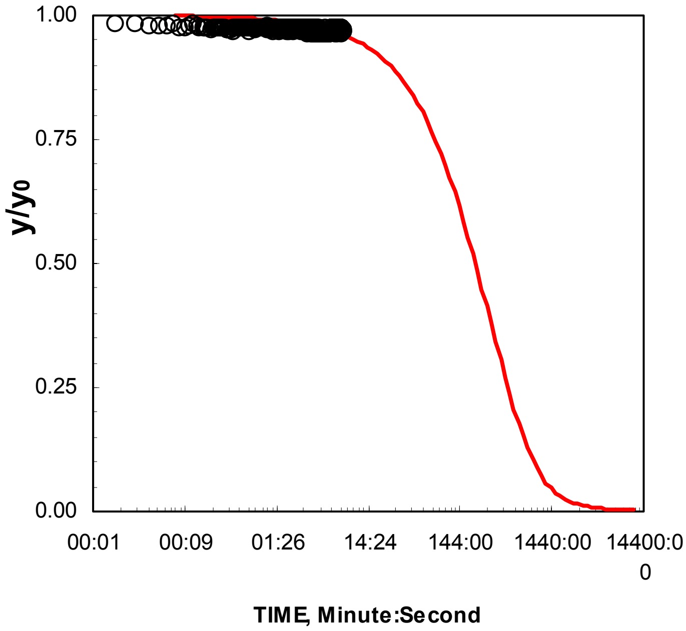

Fig A2-71. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0035.

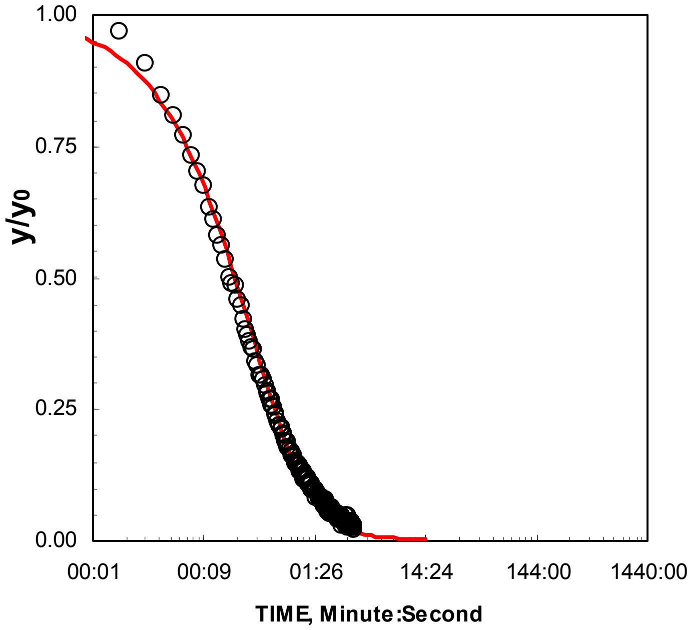

Fig A2-72. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0036.

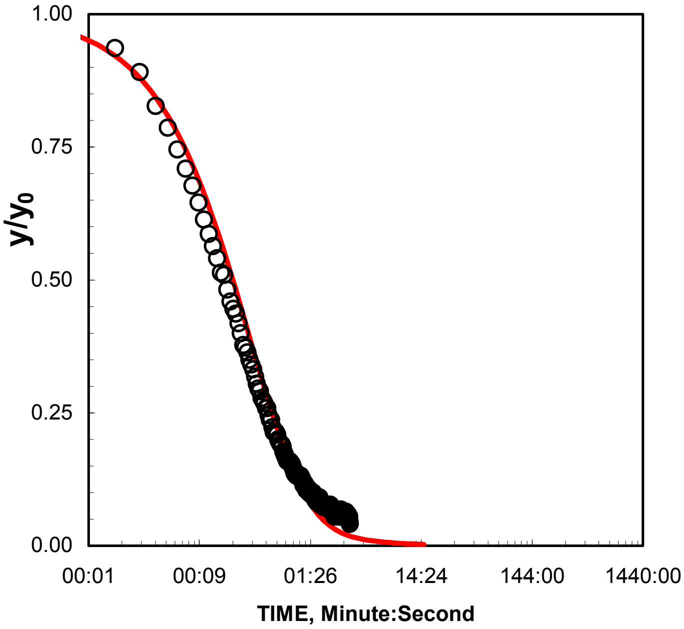

Fig A2-73. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0036.

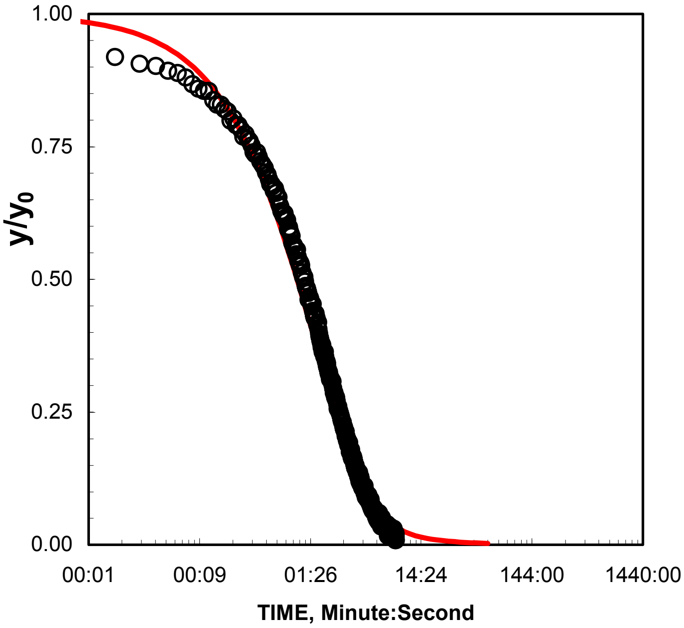

Fig A2-74. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0037.

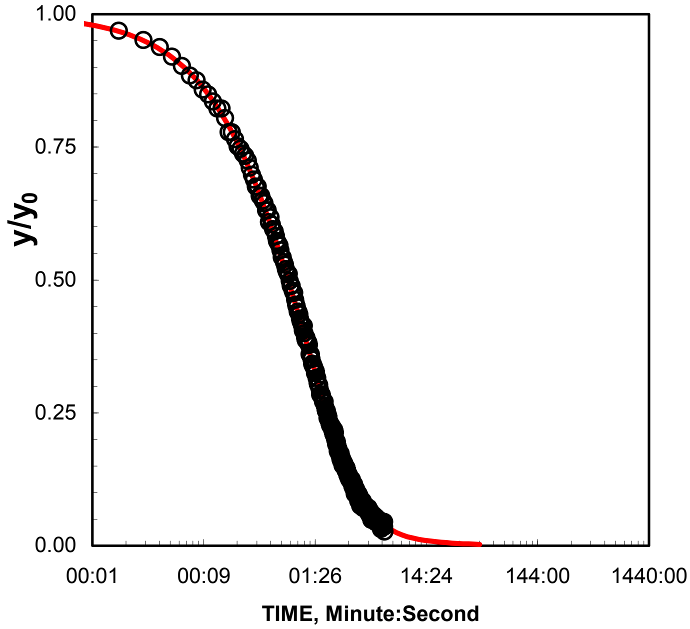

Fig A2-75. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0037.

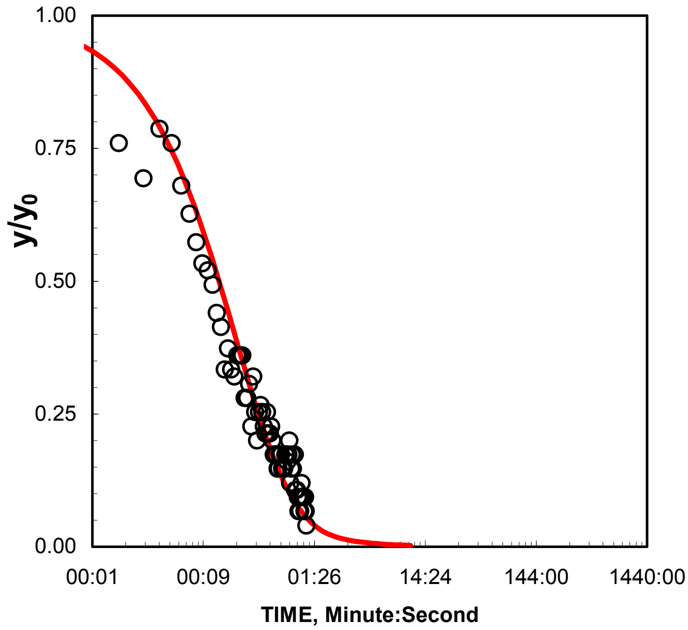

Fig A2-76. Log-linear plot of the normalized displacement y/y_0 versus time for the falling-head test in SFM0049.

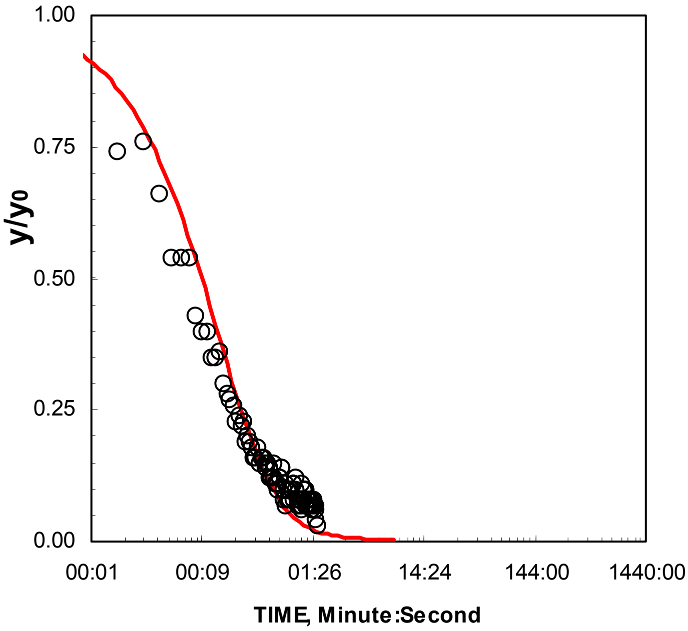

Fig A2-77. Log-linear plot of the normalized displacement y/y_0 versus time for the rising-head test in SFM0049.