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Comparison of Constant-Rate Pumping Test and Slug Interference Test Results at the Hanford Site B Pond Multilevel Test Facility

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Summary

Slug interference testing provides a method for determining aquifer hydrologic properties without extracting large volumes of groundwater. This report compares the results of slug interference tests and a conventional constant-rate pumping test conducted at a multiwell facility on the Hanford Site. Of particular importance for characterization investigations was that one of the wells was configured with a system that allowed simultaneous pressure monitoring of four separate depth intervals.

The slug interference test is conducted by instantaneously changing the water-level in a well and monitoring the response at one or more observation wells. The technique used to analyze slug-interference responses in unconfined aquifers is based on the fact that type curves designed for constant-rate pumping tests with pumping-well storage can be mathematically converted to equivalent slug-interference curves. The reverse situation is also true, slug-interference response can be mathematically converted to an equivalent constant-rate pumping test response. Diagnostic log-log plots of the equivalent response and its derivative can then be examined to determine test and formation characteristics, as is commonly done for constant-rate pumping tests.

Hydrologic property values obtained from analysis of the constant-rate pumping test and slug interference tests were nearly identical. The close correspondence in hydrologic property values suggests that slug interference testing can provide representative aquifer characterization results, under favorable test conditions (e.g., observation well distances $\leq$ 30 m). Slug interference testing may be particularly useful for characterizing hydraulic properties of aquifer sites where disposal of contaminated groundwater makes pumping tests undesirable. The quality and extent of test data obtained also indicates the usefulness of multilevel test facilities for three-dimensional hydrologic characterization.

Acknowledgments

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(a) MOSDAX is a trademark of Westbay Instruments Inc., North Vancouver, British Columbia.

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1.0 Introduction

Pacific Northwest Laboratory[a] (PNL), as part of the Hanford Site Ground-Water Surveillance Project, is responsible for monitoring the movement and fate of contamination within the unconfined aquifer to ensure that public health and the environment are protected. To support the monitoring and assessment of contamination migration on the Hanford Site, a sitewide 3-dimensional groundwater flow model is being developed. Providing quantitative hydrologic property data is instrumental in development of the 3-dimensional model. Multilevel monitoring facilities have been installed to provide detailed, vertically distributed hydrologic characterization information for the Hanford Site unconfined aquifer. In previous reports, vertically distributed water-level and hydrochemical data obtained over time from these multi-level monitoring facilities have been evaluated and reported (e.g., Gilmore et al. 1991).

This report describes the B pond facility in Section 2.0. It also provides analysis results for a constant-rate pumping test (Section 3.0) and slug interference test (Section 4.0) that were conducted at a multilevel test facility located near B Pond (see Figure 1.1) in the central part of the Hanford Site. A hydraulic test summary (Section 5.0) that focuses on the comparison of hydraulic property estimates obtained using the two test methods is also presented. Reference materials are listed in Section 6.0.

(a) Pacific Northwest Laboratory, operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

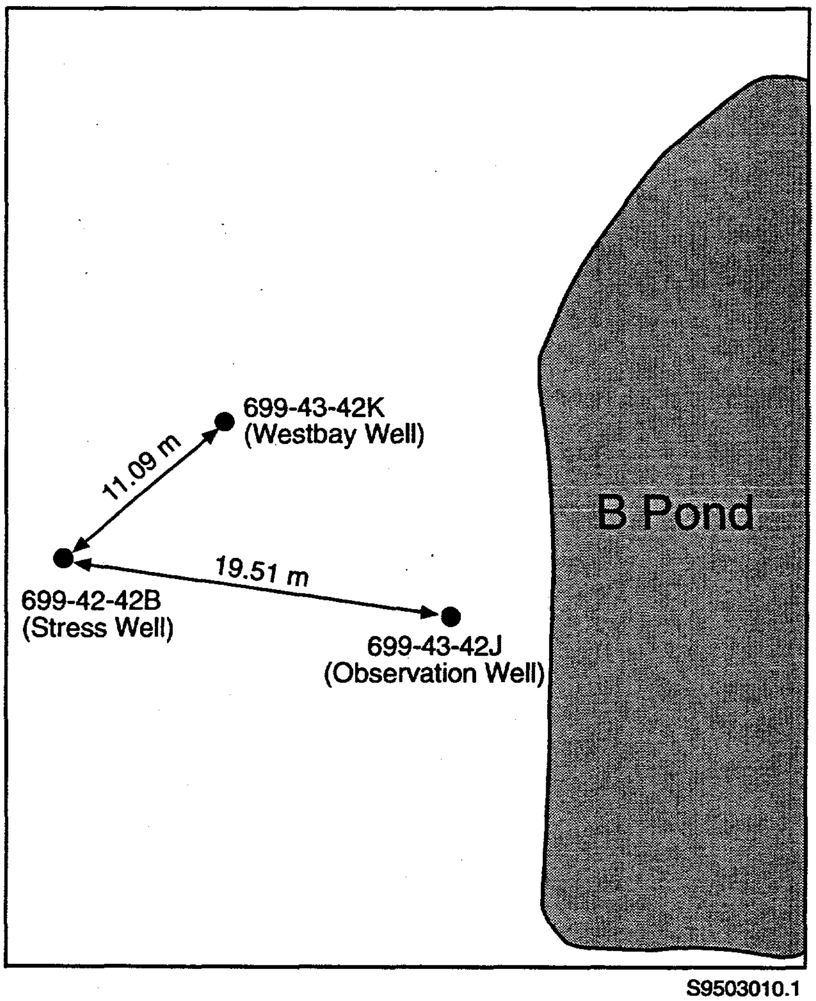

Figure 1.1. B Pond Multilevel Test Facility Location

2.0 B Pond Test Facility Description

The B pond test facility, referred to in this report, consists of three wells (699-42-42B, 699-43-42K, and 699-43-42J) completed at different depths within the unconfined aquifer. During testing, hydrologic responses were monitored at each of the wells. Well 699-42-42B served as the stress well during both the pumping and slug interference tests. This well was open to a depth interval from 7.02 to 12.8 m below the water table. The as-built configuration of the wells is shown in Figure 2.1, together with a generalized description of the aquifer geology. Pertinent well information is listed in Table 2.1. Observation well 699-43-42J, located 19.5 m from the stress well (see Figure 1.1), was open to a 4.7 m interval immediately below the water table. At observation well 699-43-42K, access to four separate depth intervals was provided by a Westbay Instruments Multiport (MP^{TM}) system. The separate monitoring intervals were isolated by bentonite grout placed in the annular area outside the well. A Westbay Modular Subsurface Data Acquisition System (MOSDAX^{TM}) was used to measure and record hydraulic pressure simultaneously in all of the monitored intervals. Although the MP system at well 699-43-42K had a total of eight monitoring intervals, damage that occurred previously during the installation of the MP system (Gilmore et al. 1991) eliminated the possibility of monitoring responses in the lower four zones. A more detailed description of the test facility is presented in Gilmore (1989), Gilmore et al. (1991), and Thorne et al. (1993).

Static water-level depths of 49.4 m below ground surface (bgs) existed at the site during the time encompassed by hydrologic testing. The unconfined aquifer at the test facility is composed of fluvial sediments that vary from muddy gravel to sandy mud. A low permeability mud layer that occurs at a depth of approximately 12.8 m below the water table (62.2 m bgs) represents the bottom of the unconfined aquifer at this location. Sediments encountered from approximately the water table to 6.9 m below the water table are described as gravelly sandy mud and sediments from 6.9 to 12.8 m below the water table are described as muddy sands and gravels. The subsurface geologic description suggests that the lower half of the aquifer may be more permeable than the upper half.

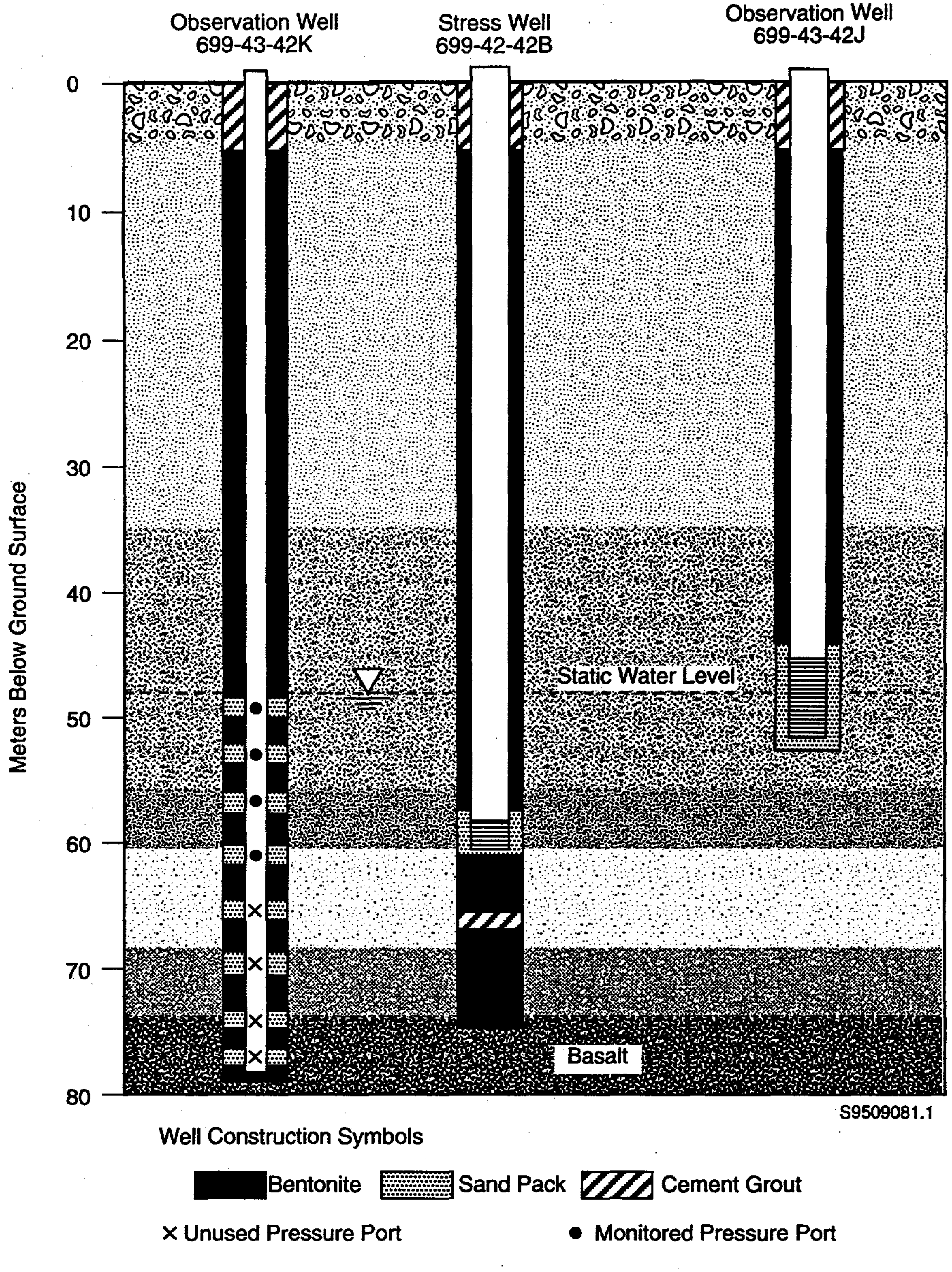

Figure 2.1. Schematic Showing As-Built Well Completion Relationships for the B Pond Test Facility (adapted from Thorne et al. 1993)

Table 2.1. Pertinent Well Completion/Distance Relationships and Test Information (modified from Thorne et al. 1993)

Well Completion/Distance Relationships				
Well/Test Site	**Top of Screen, m[(a)]**	**Distance Bottom of Screen, m[(a)]**	**Well From Pumping Well, m**	**Radius, m**
699-43-42K				
Zone 4	10.97	12.80	11.09	0.051
Zone 3	6.71	8.83	11.09	0.051
Zone 2	0.74	4.88	11.09	0.051
Zone 1	0.0	0.91	11.09	0.051
699-43-42J	0.0	4.70	19.51	0.051
699-42-42B[(b)]	7.02	12.80	-	0.051

(a) Screen depths calculated as distance below the water table (water table = 49.4 m bgs).
(b) Pumping well.

3.0 Constant-Rate Pumping Test Analysis

A 24-hr constant-rate pumping test was conducted at the test site between June 1 and 2, 1993. During the test, well 699-42-42B was utilized as the stress well, with associated test responses recorded at the multilevel monitoring well 699-43-42K and observation well 699-43-42J. The average discharge rate during the test was 18.5 L/min. Preliminary results of the constant-rate pumping test were previously reported in Thorne et al. (1993). In their report, detailed analysis of pumping test data was performed only for early-time drawdown responses (i.e., only the first 30 min of the test) observed for Monitor Zones 3 and 4 at well 699-43-42K. Results from this preliminary analysis indicated the following ranges for transmissivity (18 m^2/d to 23.5 m^2/d), storativity (0.0001), and vertical anisotropy (0.039 to 0.059) for monitor zones 3 and 4, respectively.

A re-examination of the preliminary analysis presented in Thorne et al. (1993) indicates a number of deficiencies. Identified weaknesses include:

1. The previous analysis was limited to early-time data (the first 30 min), and only to data for the drawdown phase, which were subject to discharge fluctuations.

2. The Neuman Type A curve and derivative plot pairs used in the analysis did not match the observed early-time drawdown responses well, suggesting that incorrect values for vertical anisotropy (i.e., beta curve values) were used in the previous analysis.

Quantitative analyses were not reported in Thorne et al. (1993) for Monitor Zones 1 and 2 at well 699-43-42K, because of the extremely small test response observed (i.e., < 0.06 m for Zone 1 and < 0.15 m for Zone 2) and the masking effects of extraneous responses imposed by barometric pressure fluctuations and instrument noise. A qualitative analysis of the small responses (< 0.13 m) recorded at well 699-43-42J was attempted by Thorne et al. (1993). However, because of the wide differences in the exhibited drawdown and recovery responses, Thorne et al. (1993) considered the preliminary analysis results to be highly qualitative. For these same reasons, no additional quantitative analysis were attempted for well 699-43-42J or Monitor Zones 1 and 2 at well 699-43-42K in this report.

Review of the preliminary results presented in Thorne et al. (1993) indicates that improved hydraulic property estimates can be obtained by using a more comprehensive analysis procedure. The analysis procedure utilized in this report includes the complete test data analysis of the drawdown and recovery phases. In addition, analysis of data from stress well 699-42-42B is also included.

The quantitative analysis procedure applied for each monitoring location included a diagnostic derivative analysis of drawdown or recovery data, and type-curve matching of the observed drawdown or recovery response. The derivative of each test response was calculated using the DERIV program described in Spane and Wurstner (1993). The derivative plots were then examined to diagnose the type of test behavior (i.e., presence of wellbore storage, delayed-yield response). Results of the diagnostic analysis indicated that elastic and delayed-yield, unconfined aquifer responses were exhibited at all the test sites analyzed. In addition, wellbore storage effects of the pumping well were also evident within early-time test response at the observation wells. Additional information pertaining to the use of data derivative analysis for diagnosing hydraulic test behavior is presented in Spane and Wurstner (1993).

Unconfined aquifer type curves that account for the effects of wellbore storage at the pumping well were generated using a computer program (Model Number 15) presented in Dawson and Istok (1991), which is based on the method described by Boulton and Streltsova (1976). The program accounts for the effects of partial penetration, aquifer anisotropy, and pumping well wellbore storage on the Type A type curves presented by Neuman (1975). Because of the closed installation utilized for monitoring zones at well 699-43-42K, no observation-well wellbore storage effects were expected. Complete unconfined aquifer type curves were developed by combining the calculated Type A curve, including wellbore storage effects, with the appropriate (i.e., same beta value) Type B curve generated using the WTAQ1 program described in Moench (1993). The development of complete unconfined aquifer type curves was similar to the graphical procedure described in Prickett (1965) and Neuman (1975) for combining Type A and Type B curves. In this instance, however, the generated Type A curves include the effects of pumping wellbore storage.

The preceding discussion on type-curve generation is valid for the analysis of drawdown pumping test data. However, recovery data obtained following termination of pumping can also be analyzed using drawdown type curves, provided that the recovery buildup pressure (i.e., the observed formation pressure during recovery, minus the observed formation pressure at the termination of testing) are plotted versus the equivalent time function described in Agarwal (1980). The Agarwal equivalent time function accounts for the duration of the discharge period, thereby permitting the use of drawdown type curves for the analysis of recovery data. The equivalent time function (t_e) is defined in Agarwal (1980) as

$$t_e = (t \times t')/(t + t') \qquad (1)$$

where t is duration of the discharge period [T], and t' is time since discharge terminated [T]. A more detailed discussion of the development of unconfined aquifer type curves for the analysis of drawdown and recovery pumping test data is presented in Spane (1993a,b) and Spane and Wurstner (1993).

3.1 Well 699-42-42B

Combined test data and data derivative plots are powerful diagnostic tools in identifying operative flow conditions and factors influencing drawdown during constant discharge pumping tests (e.g., Bourdet et al. 1983, 1989, Spane 1993a). Figure 3.1 shows the combined data and data derivative plots for drawdown and recovery phases for pumping well 699-42-42B. The data derivatives were calculated using the DERIV program described in Spane and Wurstner (1993). Based on a diagnostic analysis of the patterns exhibited in the figures, the following test conditions were interpreted:

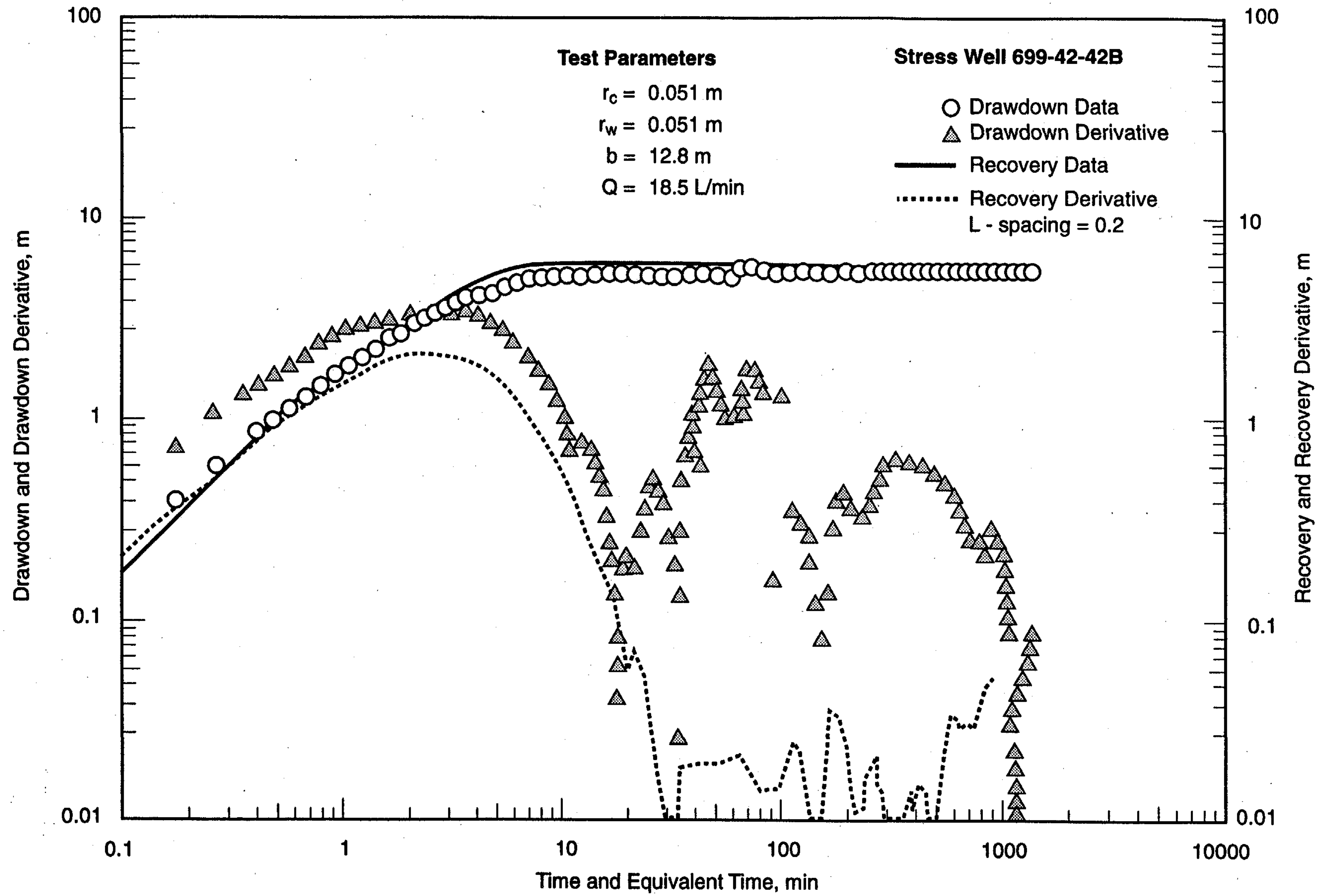

Figure 3.1. Combined Diagnostic Log-Log Data and Data Derivative Plot of Drawdown and Recovery for Pumping Well 699-42-42B

- significant discharge flow variations occurred during the drawdown phase, especially during the early stages of the test (i.e., between 0 and 1 min) and at approximately 35 min and 65 min into the test

- wellbore storage effects were dominant during the initial 4 min of the test

- delayed-yield response characteristics were exhibited over most the test period (i.e., after ≈ 10 min).

An initial estimate of hydraulic properties was provided by type-curve analysis of the recovery data *and* data derivative using the procedure described in Spane (1993a). Recovery data were analyzed instead of drawdown data, because of discharge flow variations that occurred during the discharge phase. The variation in discharge was confirmed previously in Thorne et al. (1993).

In ground-water hydrology, type-curve matching analysis methods are not normally used for the quantitative analysis of data from the pumped well because part of the water-level response within the stress well is associated with well/formation inefficiencies or damage induced by the construction of the well. In the petroleum industry, the effects of well/formation inefficiencies or damage are lumped together and referred to as the skin effect (Earlougher 1977). If the skin effect is not known, a qualitative estimate for transmissivity can be obtained by assuming the skin effect is equal to zero.

Figure 3.2 shows the results of the composite type-curve match of the recovery data and recovery derivative. The analysis type curves and type-curve derivatives were calculated following the procedure outlined in Section 3.0. As indicated, a transmissivity (T) of 8.5 m^2/d was determined from the type-curve match. Test response within partially penetrating pumping wells is rather insensitive to aquifer storativity (S) and vertical anisotropy (K_D). For the composite type-curve and derivative plot match shown in Figure 3.3, a storativity value of 0.0001 and a storativity/specific yield (S/Sy) ratio value of 0.001 were assumed. A vertical anisotropy value, K_D, of 0.45 was also assumed in the analysis, to be consistent with analysis results obtained from multilevel monitoring well 699-43-42K.

3.2 Well 699-43-42K - Monitor Zone 4

Figure 3.3 shows the combined diagnostic plots for drawdown and recovery phases for Monitor Zone 4 at well 699-43-42K. Based on an analysis of the patterns exhibited in the figures, the following test conditions were interpreted:

- a close similarity in drawdown and recovery test response was exhibited

- discharge flow variations occurring during the pumping test were evident within the drawdown data (especially at approximately 65 min into the test)

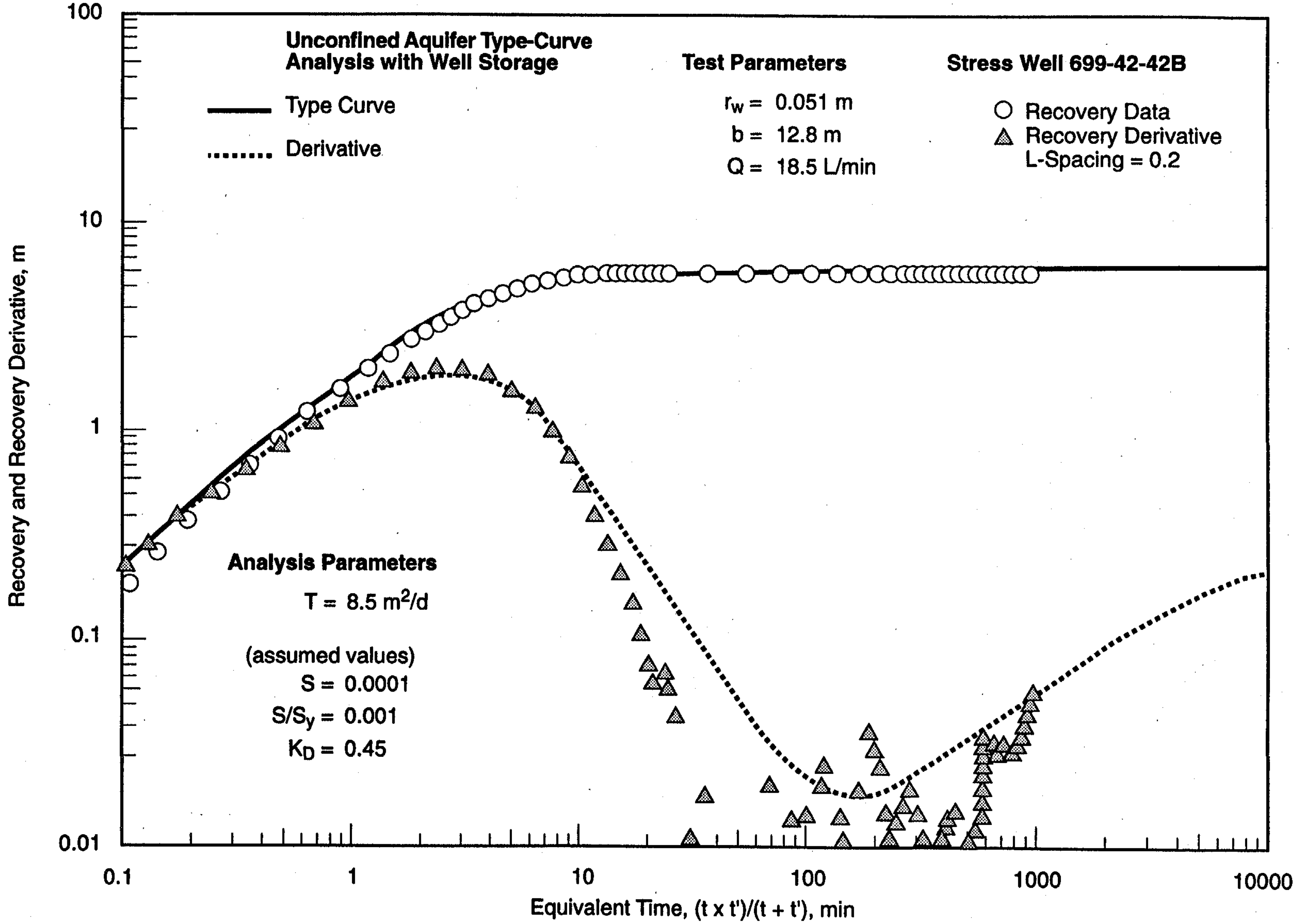

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Figure 3.2. Composite Type Curve and Derivative Plot Analysis of Recovery Test Data for Pumping Well 699-42-42B

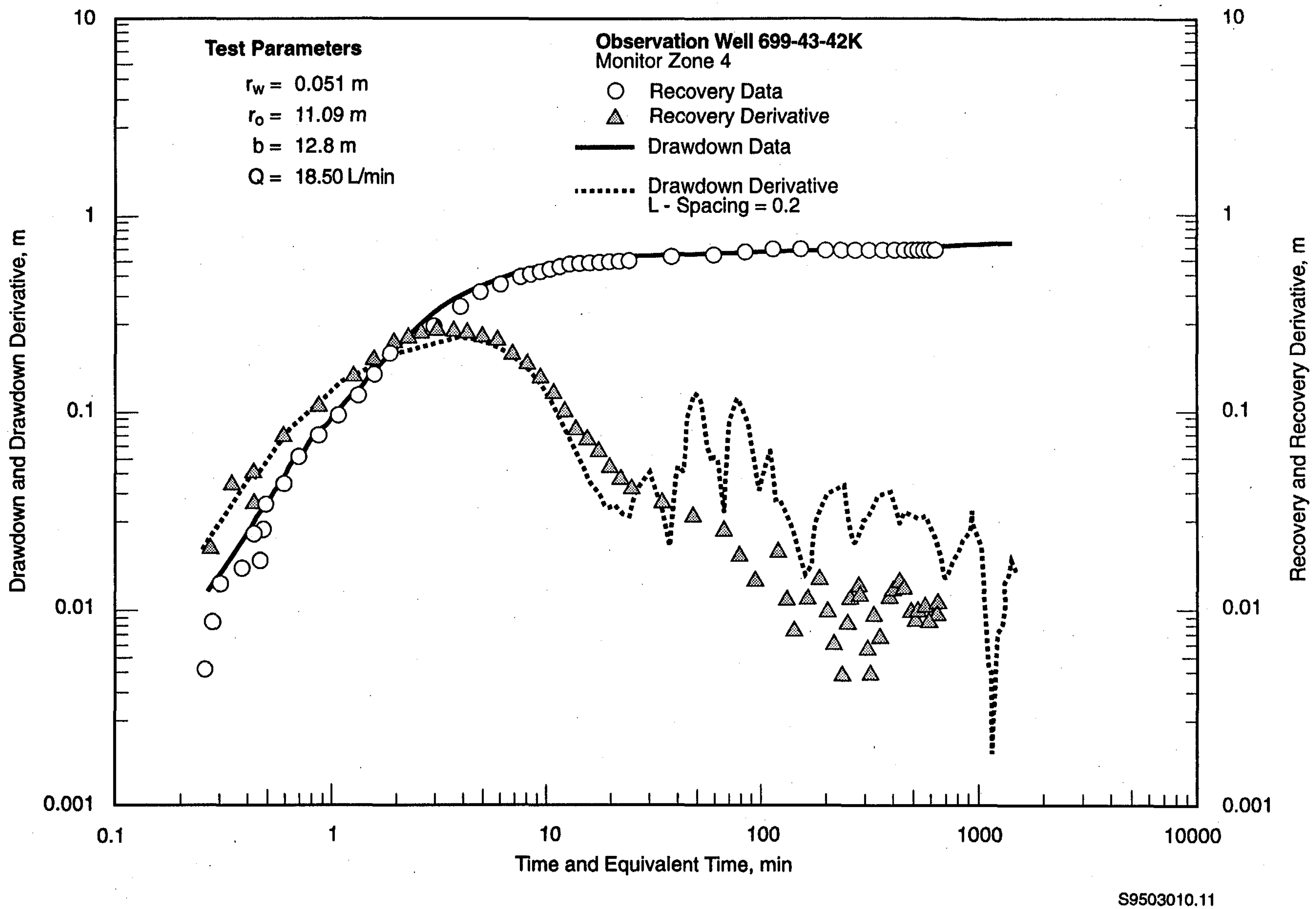

Figure 3.3. Combined Diagnostic Log-Log Data and Data Derivative Plot of Drawdown and Recovery for Observation Well 699-43-42K - Monitor Zone 4

- pumping well wellbore storage effects were exhibited during the initial 10 min of the test
- delayed-yield response characteristics were exhibited over most of the test period (i.e., after ≈ 15 min).

Recovery data were analyzed by type-curve matching of the combined data and data derivative plots using the procedure described in Spane (1993a). Recovery data were analyzed instead of drawdown data, because of the variation in pumping rate that occurred during the drawdown phase. However, because of the overall close similarity in drawdown and recovery responses, similar analysis results would be expected for the drawdown phase.

Figure 3.4 shows the results of the composite type-curve match of the recovery data and data derivative. The analysis type curves and derivatives were calculated following the procedure outlined in Section 3.0. As indicated, a transmissivity of 5.8 m^2/d and a storativity of 0.000023 were determined from the type-curve match. An estimated value for vertical anisotropy (K_D) of 0.45, based on the beta curve value (0.338), observation well distance (11.09 m), and aquifer thickness (12.8 m) relationship, is also indicated. Because of the short duration of the test (i.e., 1440 min), a quantitative estimate for specific yield could not be obtained. However based on the S/S_y ratio parameter of 0.0002 used in the test analysis, a specific yield value of ≥ 0.10 is suggested.

3.3 Well 699-43-42K - Monitor Zone 3

Figure 3.5 shows the combined diagnostic plots for drawdown and recovery phases for Monitor Zone 3 at well 699-43-42K. Based on a diagnostic analysis, the following test conditions were interpreted:

- a divergence in early-time (≤ 6 min) drawdown and recovery test response was exhibited
- discharge flow variations occurring during the pumping test were evident within the drawdown data (especially at approximately 65 min into the test)
- wellbore storage effects at the pumping well were exhibited during the initial 10 min of the test
- delayed-yield response characteristics were exhibited over most of the test period (i.e., after ≈ 15 min).

Because of the divergence exhibited during early test times, drawdown and recovery test phase data were analyzed separately. Similar analysis results for transmissivity were expected for both test drawdown and recovery phases because of the similarity in intermediate- and late-time drawdown and recovery responses. The divergence in early-time data was, however, expected to yield different estimates for storativity. The test data were analyzed using the same procedure as described previously for Monitor Zone 4.

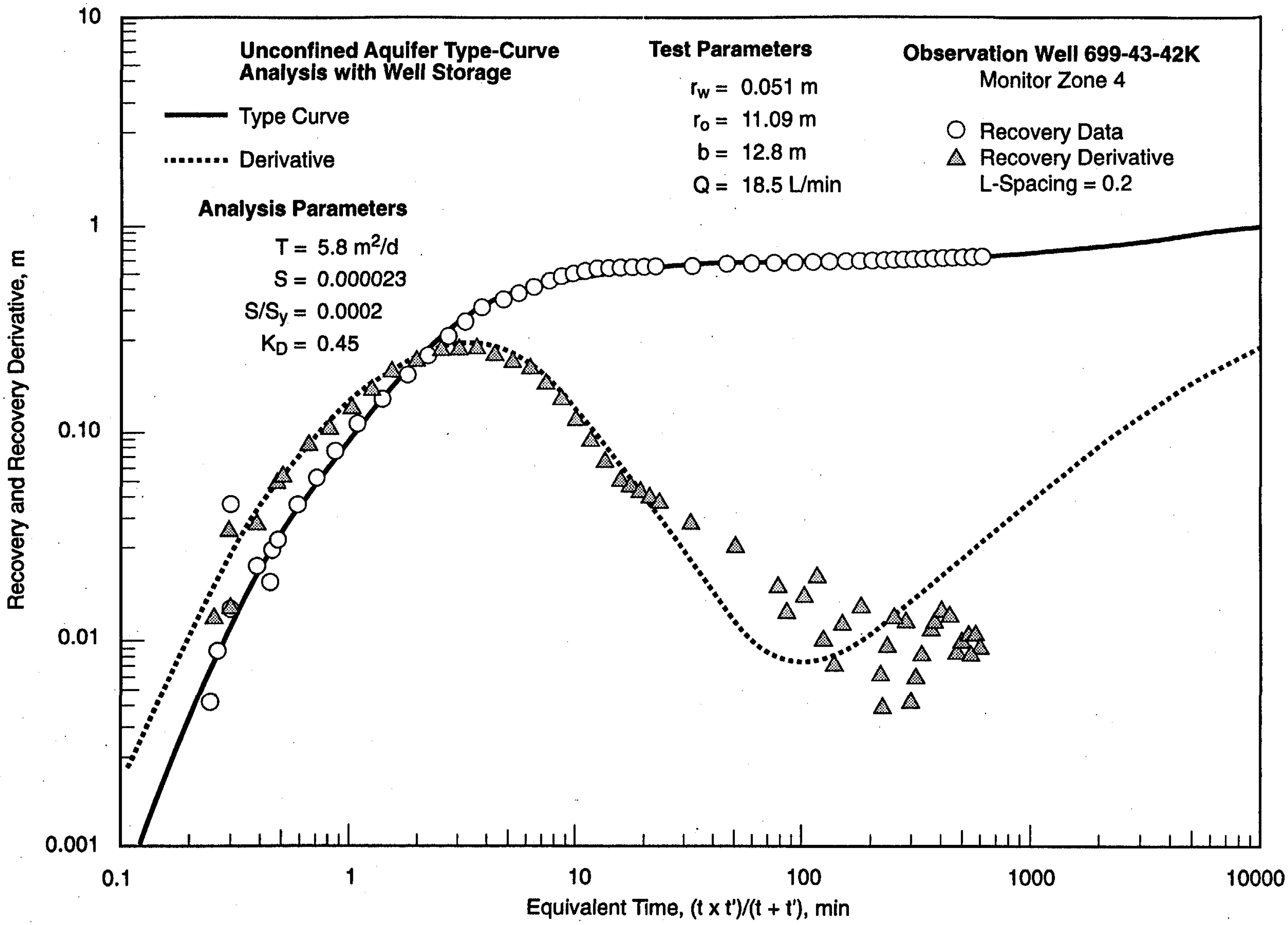

Figure 3.4. Composite Type Curve and Derivative Plot Analysis of Recovery Test Data for Observation Well 699-43-42K - Monitor Zone 4

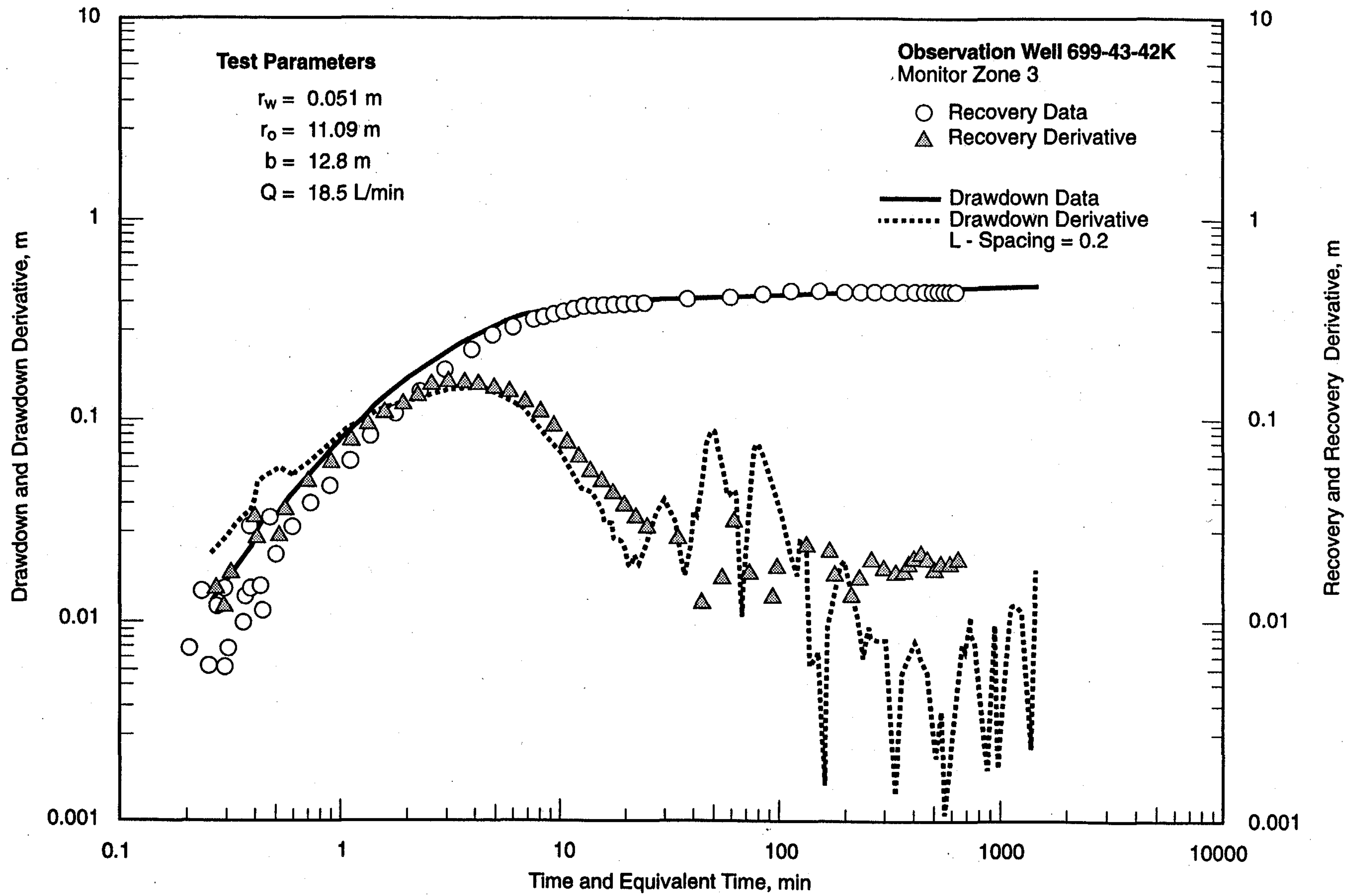

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Figure 3.5. Combined Diagnostic Log-Log Data and Data Derivative Plot of Drawdown and Recovery for Observation Well 699-43-42K - Monitor Zone 3

Figure 3.6 shows the results of the composite type-curve match of recovery and the recovery derivative. The analysis type curves and derivatives were calculated following the procedure outlined in Section 3.0. Efforts to match the entire early-time recovery (i.e., $\leq$ 3 min) were not successful. Close examination of the early-time recovery response indicates an initial rapid recovery from 0 to 0.7 min, followed by a slower recovery period from 0.7 min to 1.2 min, and then a final more rapid recovery phase after 1.2 min. The cause for this composite-type formation response is not fully understood. However, this type of response can occur when a zone of higher permeability occurs in the immediate vicinity of the well facility. This zone of higher permeability can be a natural *in situ* characteristic of the formation (i.e., local aquifer heterogeneity) or be associated with well construction/installation processes (e.g., high permeability sand/gravel well pack). Because this type of response was not observed for well 699-42-42B or for Monitor Zone 4 (well 699-443-42K), the apparent cause of the composite response would appear to be in proximity of Monitor Zone 3.

Recovery analysis for Monitor Zone 3 focused on analyzing data for equivalent recovery times $\geq$ 1.2 min. This rationale assumes that data for equivalent recovery times $\leq$ 1.2 are more reflective of localized heterogeneities in the immediate vicinity of Monitor Zone 3, and are not representative of larger-scale formational behavior. Figure 3.6 shows the final composite type-curve match for recovery and derivative data in the analyzed range. As indicated, a transmissivity of 7.8 m^2/d and a storativity of 0.00005 were determined from the type-curve match. An estimated value for vertical anisotropy (K_D) of 0.45, based on the beta curve value (0.338), observation well distance (11.09 m), and aquifer thickness (12.8 m) relationship, is also indicated. Because of the short duration of the test (i.e., 1440 min), a quantitative estimate for specific yield could not be obtained. However, based on the S/S_y ratio parameter (i.e., 0.0007) used in the test analysis, a specific yield value of $\geq$ 0.07 is suggested.

Figure 3.7 shows the results of the composite type-curve match of drawdown data and drawdown derivative. As noted for the recovery analysis, efforts to match the entire early-time drawdown period were not successful. The cause for this lack of complete early-time match is attributed to the same response phenomena noted for the recovery test data analysis. The composite-type formation response, however, is not as readily observable in the drawdown data, because of fluctuations in discharge rate.

Drawdown analysis for Monitor Zone 3 focused on analyzing drawdown data for test times $\geq$ 1 min. Drawdown data for time periods that were obviously affected by discharge rate fluctuations (e.g., $\geq$ 65 min) were also weighted less heavily in the analysis procedure. Figure 3.7 shows the final composite type-curve match for drawdown data and derivative after 1 min. As indicated, a transmissivity of 7.5 m^2/d and a storativity of 0.00002 were determined from the type-curve match. An estimated value for vertical anisotropy (K_D) of 0.45, based on the beta curve value (0.338), observation well distance (11.1 m), and aquifer thickness (12.8 m) relationship, is also indicated. Because of the short duration of the test (i.e., 1440 min), a quantitative estimate for specific yield could not be obtained. However based on the S/S_y ratio parameter used in the test analysis (i.e., 0.0001), a specific yield value of $\geq$ 0.20 is suggested. The effects of discharge variation during the later stages of the test, however, make this qualitative estimate for specific yield highly suspect.

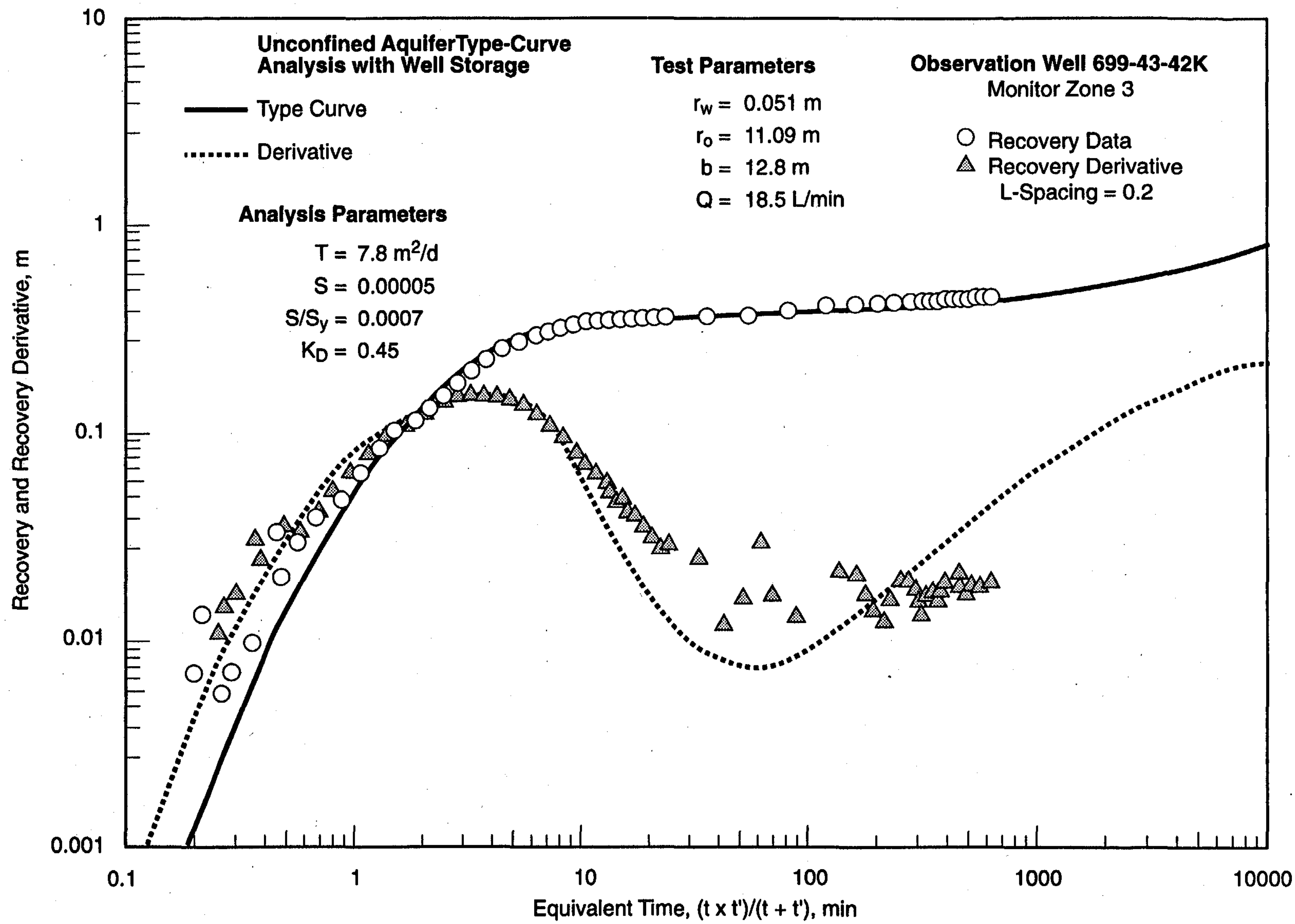

Figure 3.6. Composite Type Curve and Derivative Plot Analysis of Recovery Test Data for Observation Well 699-43-42K - Monitor Zone 3

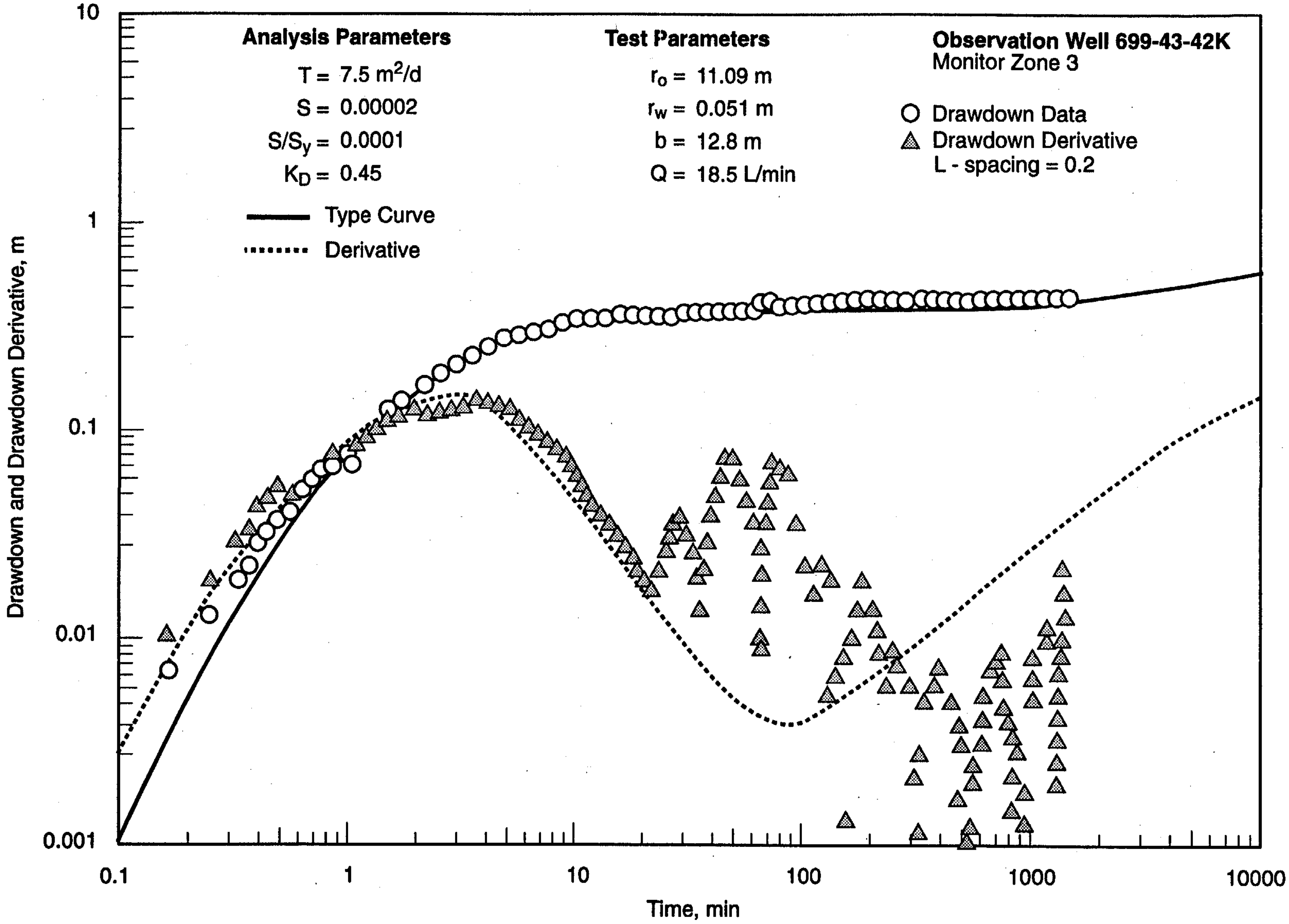

Figure 3.7. Composite Type Curve and Derivative Plot Analysis of Drawdown Test Data for Observation Well 699-43-42K - Monitor Zone 3

3.4 Composite Test Recovery Analysis

Weeks (1978) and Moench (1994) have demonstrated the usefulness of simultaneously analyzing the responses from multiple wells for a single test event. This composite test response analysis facilitates the determination of more areally representative aquifer hydraulic properties. Spane (1993a) also reports the advantage of this analysis method for assessing the homogeneity of the aquifer, which is commonly assumed in analysis of individual test well responses.

Figure 3.8 shows the composite recovery response for Monitor Zones 3 and 4 at well 699-43-42K and pumping well 699-42-42B. Predicted test responses, based on the hydraulic properties indicated, are also shown. Observed and predicted test responses for observation well 699-43-42J were also included for comparison purposes. For direct comparison with well 699-43-42K monitor zone responses, observed and predicted responses for wells 699-43-42J and 699-42-42B were normalized by multiplying time by the square of the quotient of the well distances (19.51 m /11.09 m^2). The predicted test responses shown in Figure 3.8 were based on the approximate average for hydraulic property values determined from individual pumping test analyses. These values are: transmissivity = 7.5 m^2/d, storativity = 0.00003, specific yield = 0.075, and vertical anisotropy = 0.45. The predicted Theis curve response (with respect to the specific yield) for well 699-43-42K shown in the figure, indicates the pumping test would have to be extended for at least 7 days in order to reach late-time Theisian behavior. The indicated time for merging predicted test zone and late-time Theisian responses also denotes the time after which partial penetration effects are no longer significant.

The correspondence of observed and predicted test responses for the stress well and Zones 3 and 4 at well 699-43-42K suggests that the aquifer can be adequately characterized with a homogeneous porous media model, having the aforementioned average hydraulic properties in the vicinity of the wells. Deviation of the observed response at observation well 699-43-42J probably reflects heterogeneity within the aquifer in the vicinity of this well.

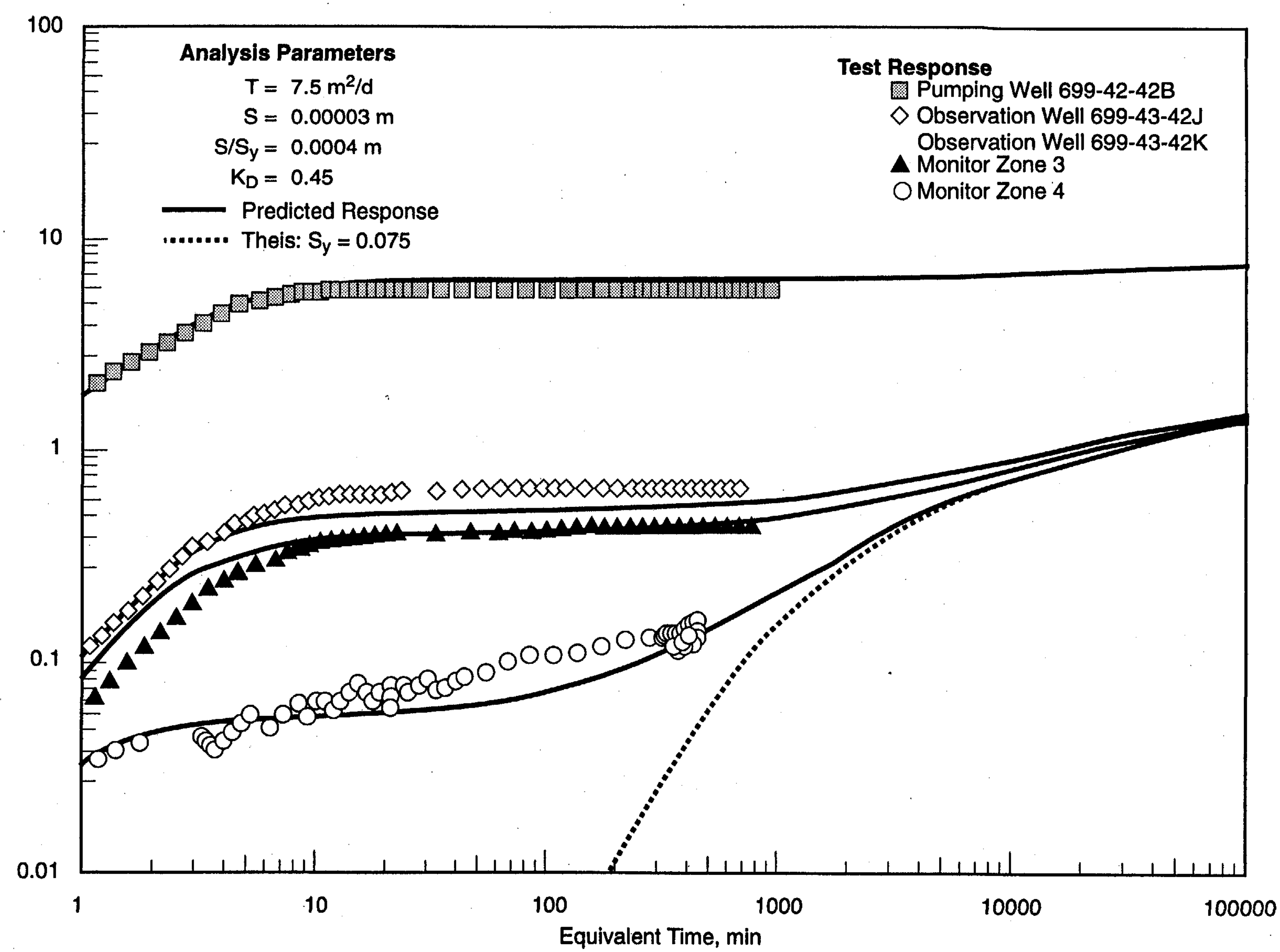

Figure 3.8. Composite Test Recovery Response Analysis

4.0 Slug Interference Test Analysis

Between May 26 and 27, 1993, three slug interference tests were conducted at the test site. During these tests, well 699-42-42B was utilized as the stress well. Associated test responses were recorded at the multilevel monitoring well 699-43-42K and observation well 699-43-42J. Figure 4.1 shows a schematic drawing of the stress well configuration and test equipment used during slug interference testing. As-built diagrams and other information on well completions are provided in Figure 2.1 and Table 2.1. Test equipment specifications are discussed in detail in Thorne et al. (1993).

The well-head assembly shown in Figure 4.1 was designed to make the well casing relatively airtight, while providing an airline connection, ball valves for quickly releasing gas pressure, and access for a pressure transducer placed below the minimum water level. Prior to initiating each slug test, the fluid level within the stress well (699-42-42B) was depressed approximately 8 m by pressurizing the well casing with compressed nitrogen gas supplied from bottles located near the well head. The depressed water level in the stress well was maintained until downhole pressures at the observation wells had stabilized. As expected, the measured pressures were affected by the injection of water at the stress well. When pressures reflected static formation conditions, the slug interference test was initiated by abruptly releasing the gas pressure within the well casing at the stress well. The pressure was released rapidly ($\approx$ 1 sec) by simultaneously opening the four, 4-in. ball valves on the well head assembly. The release of gas pressure allowed ground water within the test interval to flow back inside the well casing, thus creating a slug withdrawal at the stress well.

Only results from slug interference test 3 are presented in this report. Results from previous slug interference tests were not analyzed due to lower data recording rates (i.e., every 5 sec) used during the initial stages of the test. The lack of a higher recording rate severely restricts the ability to precisely determine the time of test initiation. This restriction creates additional uncertainties in determining the imposed slug stress level and distorts the early-time slug interference response observed within adjacent monitor zones.

Slug interference results analyzed in this report include responses observed for Monitor Zones 3 and 4 at well 699-43-42K and slug test results for stress well 699-42-42B. Test results for Monitor Zones 1 and 2 at well 699-43-42K were not analyzed due to the extremely low interference response amplitudes. These response amplitudes were similar to the instrument noise levels. No response was observed at well 699-43-42J. This is attributed, in part, to the greater observation well distance and lower sensitivity in the pressure monitoring system used for this well.

4.1 Analysis Procedure

One of the first descriptions of an analysis method for single-well slug tests was presented by Ferris and Knowles (1954). The Ferris and Knowles method is based on the Theis (1935) nonequilibrium equation for fully penetrating wells in confined aquifers. The solution represents the stress well as a

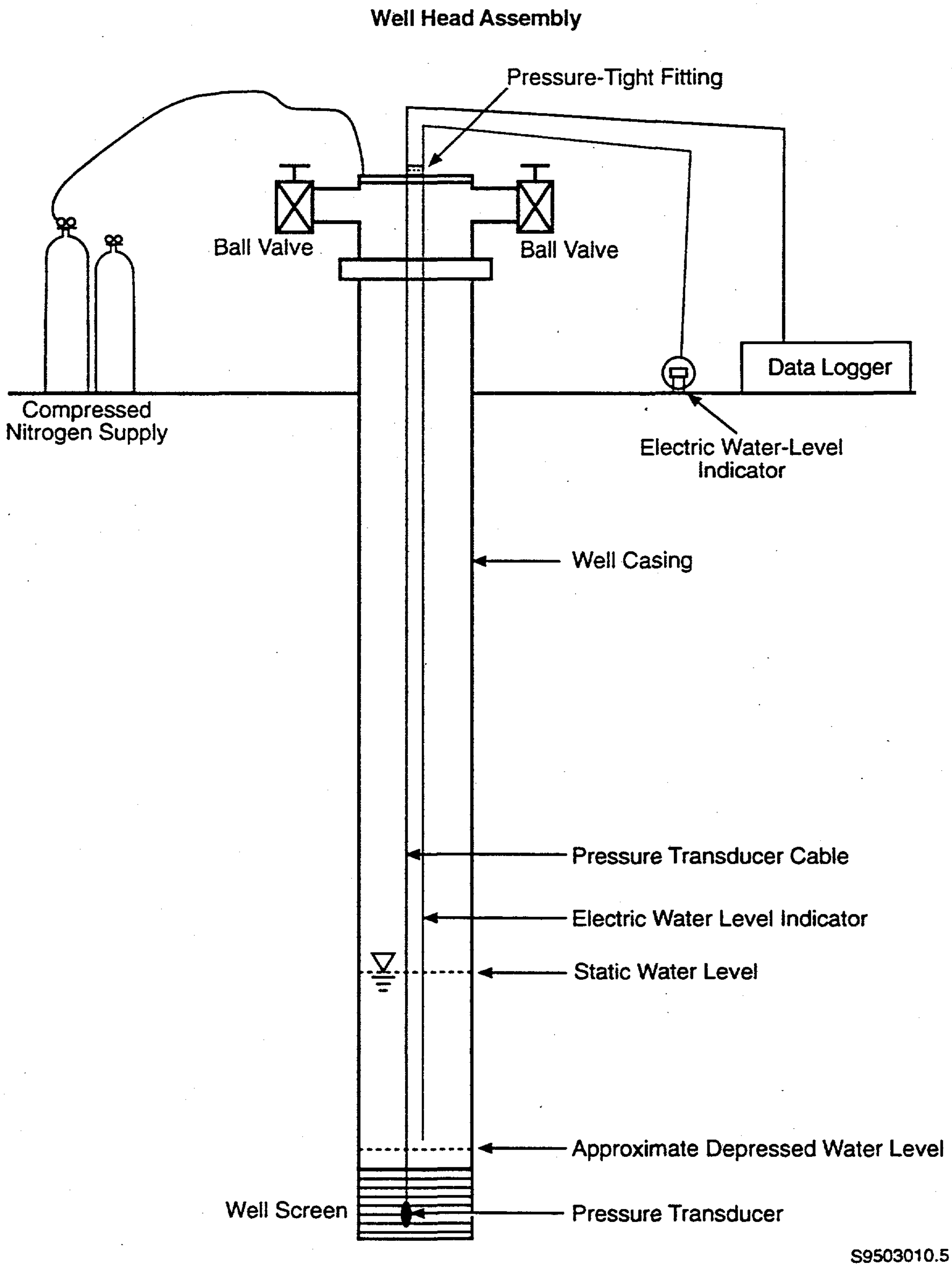

Figure 4.1. Well Configuration and Test Equipment Used in the Stress Well During Slug Interference Testing

line-source. Water injected or withdrawn from the well instantaneously enters or is removed from the aquifer with no wellbore storage effects. Cooper et al. (1967) provided an exact solution, based on a well of finite diameter, and showed the line-source solution proposed by Ferris and Knowles (1954) is valid only at extremely late times during the test (i.e., for test times representative of the last 0.25 percent of the imposed slug stress level).

Both the line-source and finite-well diameter solutions have been used to predict the interference response caused by the slug test at a distance from the stress well. As is the case for single-well slug tests, analysis of slug interference tests based on the line-source solution can lead to significant errors in hydraulic property determination. Therefore, analysis of slug interference responses should be based on finite-well diameter solutions. Analysis methods for fully penetrating wells in isotropic confined aquifers are presented by Ramey et al. (1975), Sageev (1986), Karasaki et al. (1988), and Novakowski (1989).

More recently, analytical methods have been developed that allow the extension of slug interference test analysis to a variety of test conditions, including unconfined aquifers, partially penetrating wells, and anisotropic conditions. The analysis extension is based on discussions presented in Novakowski (1989), Peres (1989), and Peres et al. (1989) that demonstrate that slug tests can be represented as a specialized form of constant-rate pumping tests. A detailed description of the derivation of the relationship between slug and constant-rate analytical solutions is not presented in this report. These references should be consulted for a detailed analytical justification. Briefly stated, the general relationship between the slug test (H_D) and constant-rate pumping test (p_D) solutions is shown by Peres (1989) and Peres et al. (1989) to be:

$$H_D(t_D,r_D,C_D) = C_D \frac{\partial p_D}{\partial t_D}(t_D,r_D,C_D) \tag{1}$$

where the dimensionless parameters for head (H_D), time (t_D), pressure (p_D), distance (r_D), and wellbore storage constant (C_D) are defined below as:

$$H_D = \frac{H}{H_o} \tag{2}$$

$$t_D = \frac{Tt}{r_o^2 S} \tag{3}$$

$$r_D = \frac{r_o}{r_w} \tag{4}$$

$$C_D = \frac{r_c^2}{2 r_w^2 S} \quad (5)$$

$$p_D = \frac{2\pi T}{Q} \Delta H \quad (6)$$

where H = observed head at time t, minus pretest static head level in well [L]

H_o = instantaneous head change applied to stress well at the start of the slug test [L]

T = transmissivity [L^2/T]

t = test time [T]

r_o = radial distance between stress and observation wells [L]

S = aquifer storativity [dimensionless]

Q = pumping discharge rate [L^3/T]

r_w = effective stress well radius [L]

r_c = stress well casing radius [L]

Equation (1) indicates the slug test solution, H_D, is equivalent to the time derivative of the constant-rate wellbore storage solution, p_D. Type curves for analysis of single-well slug tests and slug interference tests can, therefore, be obtained from type curves developed for constant-rate pumping tests. Although equation (1) was developed for conditions of fully penetrating wells in confined aquifers, Peres (1989) and Peres et al. (1989) show that through the use of Duhamel's principle, equation (1) is also valid for any aquifer and well configuration, and does not require radial flow conditions.

Slug interference test type curves for unconfined aquifers are derived from constant-rate pumping test type curves for the given test well configuration and aquifer conditions. Neuman (1975) provides type curves for constant-rate pumping tests in an anisotropic unconfined aquifer with partially penetrating wells. However, the type curves are based on the line-source solution presented in Neuman (1972, 1974) and do not include wellbore storage effects. To account for the effects of pumping wellbore storage, type curves based on the line-source solution are adjusted using the analytical method described by Boulton and Streltsova (1976) or Fenske (1977).

The dimensionless pressure derivative, p_D', with respect to the dimensionless time parameter group $[(t_D\, r_D^2)/C_D]$, was calculated for the constant-rate wellbore storage type curves using the derivative calculation method described in Spane and Wurstner (1993). The dimensionless slug interference response, H_D, for the specified aquifer/test conditions was then calculated directly by dividing the dimensionless pressure derivative by the dimensionless time parameter group, using the following relationship:

$$H_D = \frac{p_D'}{\frac{t_D r_D^2}{C_D}} \tag{7}$$

A detailed description of this conversion process is provided in Spane (1994).

The general procedure used to analyze slug interference tests conducted at the B Pond test facility consisted of two elements: an initial diagnostic comparison of the slug test and pumping test response, followed by quantitative type-curve analysis of the slug interference response. The initial diagnostic analysis procedure follows:

1. Convert the slug interference test data to an equivalent constant-rate pumping test, following the procedure presented in Peres et al. (1989). This conversion can be calculated directly using the DERIV program presented in Spane and Wurstner (1993).

2. To normalize the equivalent head response to the pumping test response, multiply by the ratio of the average pumping test discharge rate, Q_p, to the **instantaneous** slug test constant-rate discharge, Q_i. The parameter Q_i can be calculated directly from the slug test stress level, H_o, using the relationship presented by Cooper et al. (1967) and Novakowski (1989):

$$Q_i = \pi r_c^2 H_o \tag{8}$$

3. Construct a composite log-log plot of the equivalent head and equivalent head derivative versus time, and of the pumping test recovery and recovery derivative. Compare the test response results for the slug and pumping tests. If test/flow conditions are identical, the converted slug test results will overlay the early-time pumping test response. If this is the case, comparable hydraulic property estimates can be obtained from the slug interference and pumping test analyses.

For slug interference test type-curve analysis, the following steps are recommended as a general analysis procedure and were utilized for this report:

1. Calculate the dimensionless head response, H_D, from the test zone data by dividing the observed slug interference response by the calculated stress level, H_o, applied at the stress well [Equation 2].

2. Generate dimensionless head versus time slug interference type curves by converting unconfined aquifer pumping test type curves with wellbore storage effects, following the procedure outlined in Section 4.1.

3. Use trial and error curve-fitting procedures by varying T, S, S/S_y, and K_D until a match is obtained between the predicted and observed slug interference response. As a general guide, the slug interference amplitude and initial rising limb segments should be approximately matched first by adjusting the predicted aquifer S and T. The descending limb segment match can then be approximately matched by adjusting predicted values for K_D and S/S_y. Repetitive minor adjustments for the four hydrologic input parameters will then be required until a final match is obtained.

4.2 Well 699-42-42B Analysis

To evaluate characteristics of the slug test applied to the aquifer system and to provide an initial estimate of hydraulic properties, the slug test response at the stress well was examined. Figure 4.2 shows the downhole pressure history at well 699-42-42B during fluid column pressurization and subsequent slug initiation upon release of the fluid column gas pressure. As shown, the fluid column pressurization phase lasted approximately 32 min, with the last 20 min indicating re-establishment of near static pressure conditions (i.e., 20.32 m). The inequality between the pressure buildup peak amplitude during fluid column pressurization and the larger pressure drop associated with the release of the fluid column gas is attributed to limitations within the surface gas delivery system (i.e., gas cannot be immediately administered to the fluid column during the pressurization phase). For this reason, only the interference response associated with the release of fluid column gas pressure was quantitatively analyzed, using the slug interference procedure described in Section 4.1.

An important input parameter for slug interference analysis is the actual maximum stress level, H_o, applied to the system. For slug interference tests using compressed gas to depress the fluid column (i.e., pneumatic tests), H_o can be determined by measuring the fluid column gas pressure with an accurate pressure transducer. For situations where an accurate applied gas pressure is not attainable, the applied slug test stress level can be determined by back projection of downhole pressures to the time of slug test initiation. Figure 4.3 shows the calculated H_o value of 8.86 m based on the back projection procedure. It compares favorably with the calculated fluid column gas pressure change of 8.93 m observed at test initiation.

Figure 4.4 shows a comparison of the pumping test recovery with the slug test equivalent head response. The equivalent head response was normalized to the pumping test stress level using the procedure outlined in Section 4.1. For this test, the equivalent head values were normalized by multiplying by a value of 0.256 (i.e., Q_p/Q_i = 18.5 L/min/72.398 L/min). As shown in the figure, a close correspondence between the two tests is indicated over the slug test time duration of ≈ 30 min. This correspondence indicates that test conditions for the slug test were the same as those that existed during the early stages of the pumping test. Because of the illustrated similarity in test response, similar hydrologic property estimates from the respective test analyses are also expected.

To analyze the slug test response observed at stress well 699-42-42B, dimensionless head slug test type curves were developed from unconfined aquifer pumping test type curves following the procedure outlined in Section 4.1. To support the slug test analysis, slug test derivative plots were also generated

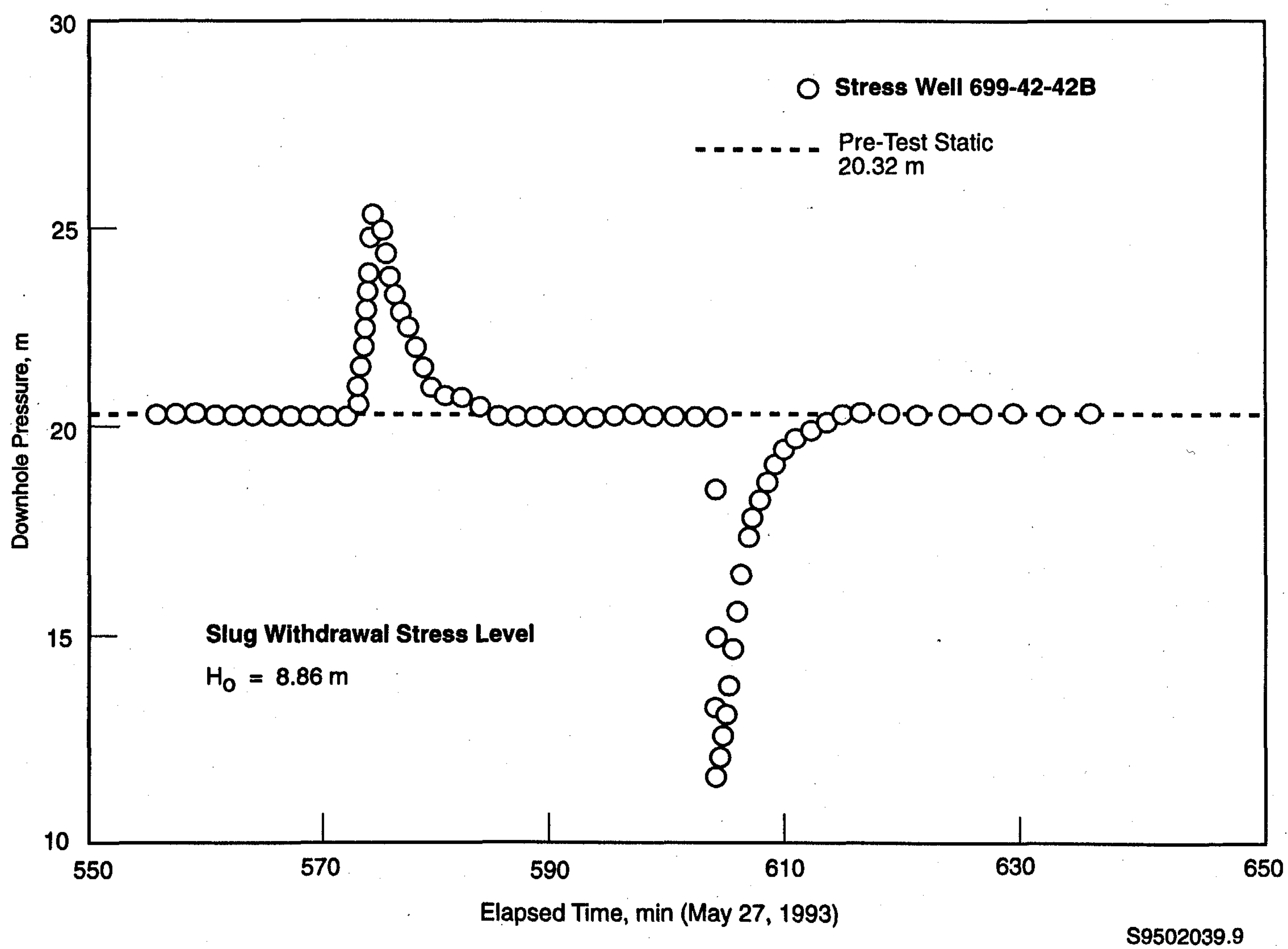

Figure 4.2. Downhole Pressure History Response at Stress Well 699-42-42B During Slug Interference Testing

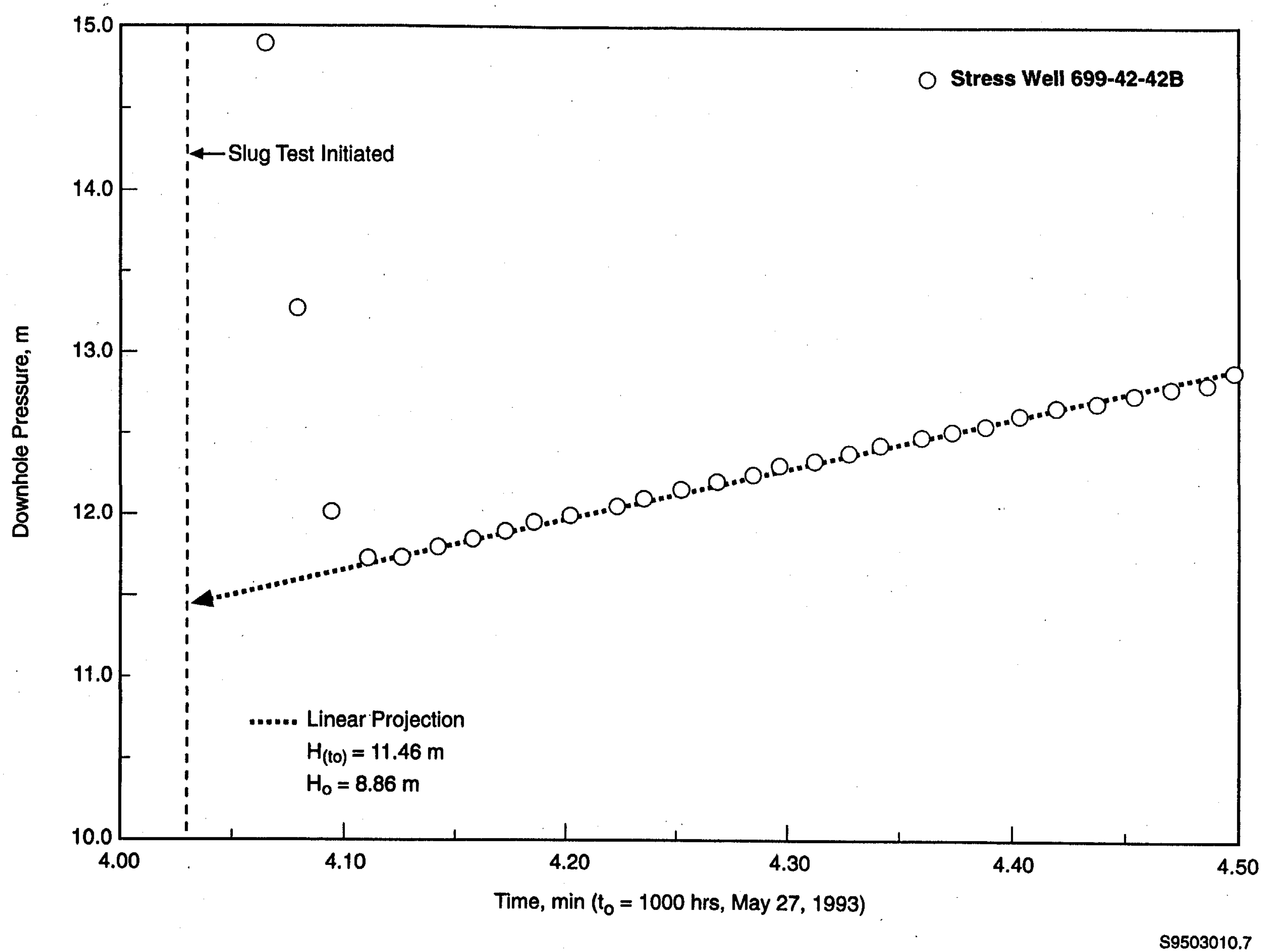

Figure 4.3. Projected Slug Stress Level at Stress Well 699-42-42B

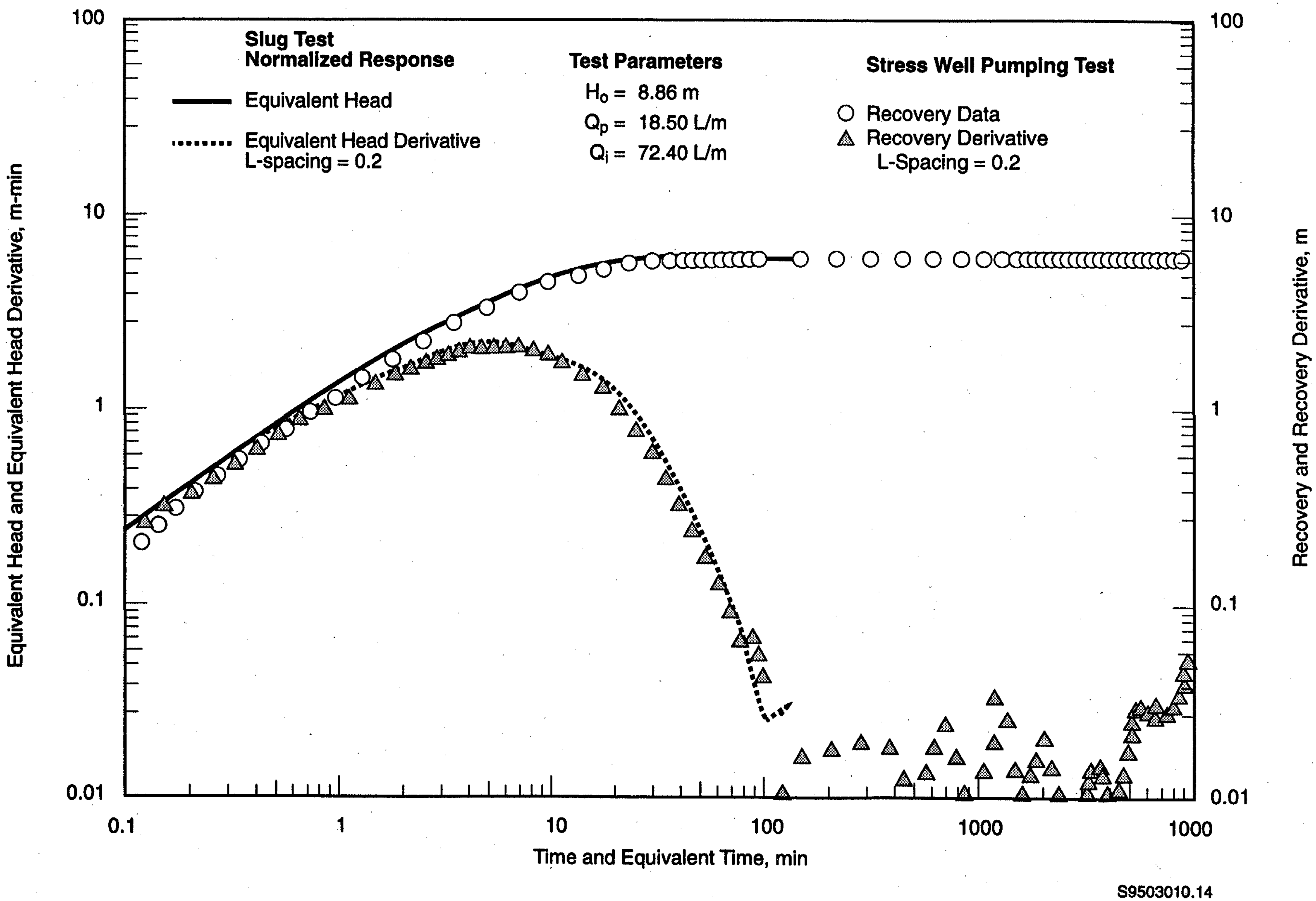

Figure 4.4. Comparison of Normalized Slug Equivalent Head Response and Pumping Test Recovery for Stress Well 699-42-42B

using the DERIV program presented in Spane and Wurstner (1993). The use of combined type curves and derivative plots for the analysis of slug tests is discussed in Ostrowski and Kloska (1989) and Spane and Wurstner (1993). Figure 4.5 shows the results of the combined type curve and derivative plot analysis. As indicated a T value of 7.5 m^2/d was calculated. This compares favorably with the pumping test analysis result of 8.5 m^2/d reported in Section 3.1. As was the case for the pumping test analysis, values for S and K_D were assumed (i.e., 0.0001 and 0.1, respectively). Predicted slug test response, however, (for partially penetrating well conditions) is relatively insensitive to these hydraulic parameters.

For comparison purposes, the slug test response was also analyzed using the technique described in Bouwer (1989) for partially penetrating wells in unconfined aquifers. Analysis results using this method (not shown) provided a T estimate of 6.2 m^2/d, which is approximately 25 percent lower than the reported pumping test derived value.

4.3 Well 699-43-42K - Monitor Zone 4 Analysis

Figure 4.6 shows the pressure history and slug interference test 3 response observed at Monitor Zone 4 within well 699-43-42K. The figure clearly shows an associated response at Monitor Zone 4 during the fluid column pressurization phase and subsequent slug initiation upon release of the fluid column gas pressure at stress well 699-42-42B. Comparison with Figure 4.2 indicates that the pressure history response pattern for Monitor Zone 4 is nearly identical to the pattern recorded at the stress well. A noticeable difference is the small abrupt rise and rapid decline recorded at Monitor Zone 4 immediately prior to initiation of the slug withdrawal phase of the test. This pattern was not recorded at the stress well, and appears to be associated with minor instrument noise that was accentuated by the concurrent increase in data recording rate.

Figure 4.7 shows a comparison of the pumping test recovery data and slug test data converted to an equivalent constant-rate head response for Monitor Zone 4. As discussed in this section, the equivalent head response was normalized to the pumping test stress level using the procedure outlined in Section 3.1. As shown in Figure 4.7, a close correspondence between the two tests is indicated over slug test time duration $\approx$ 30 min. This correspondence indicates that the test conditions for the slug interference test were the same as those existing during the early stages of the pumping test. Because of the similarity in test response, similar hydrologic property estimates from the respective test analyses is also expected.

To analyze the slug interference response observed for Monitor Zone 4 at well 699-43-42K, slug interference test type curves were developed from unconfined aquifer pumping test type curves following the procedure outlined in Section 4.1. The analysis procedure proceeded iteratively by adjusting the hydraulic property input values until a suitable match with the observed interference response was obtained. Figure 4.8 shows the results of the final type-curve match. As indicated in the figure, analysis values were calculated for T, S, and K_D of 7.8 m^2/d, 0.00003, and 0.33, respectively. The

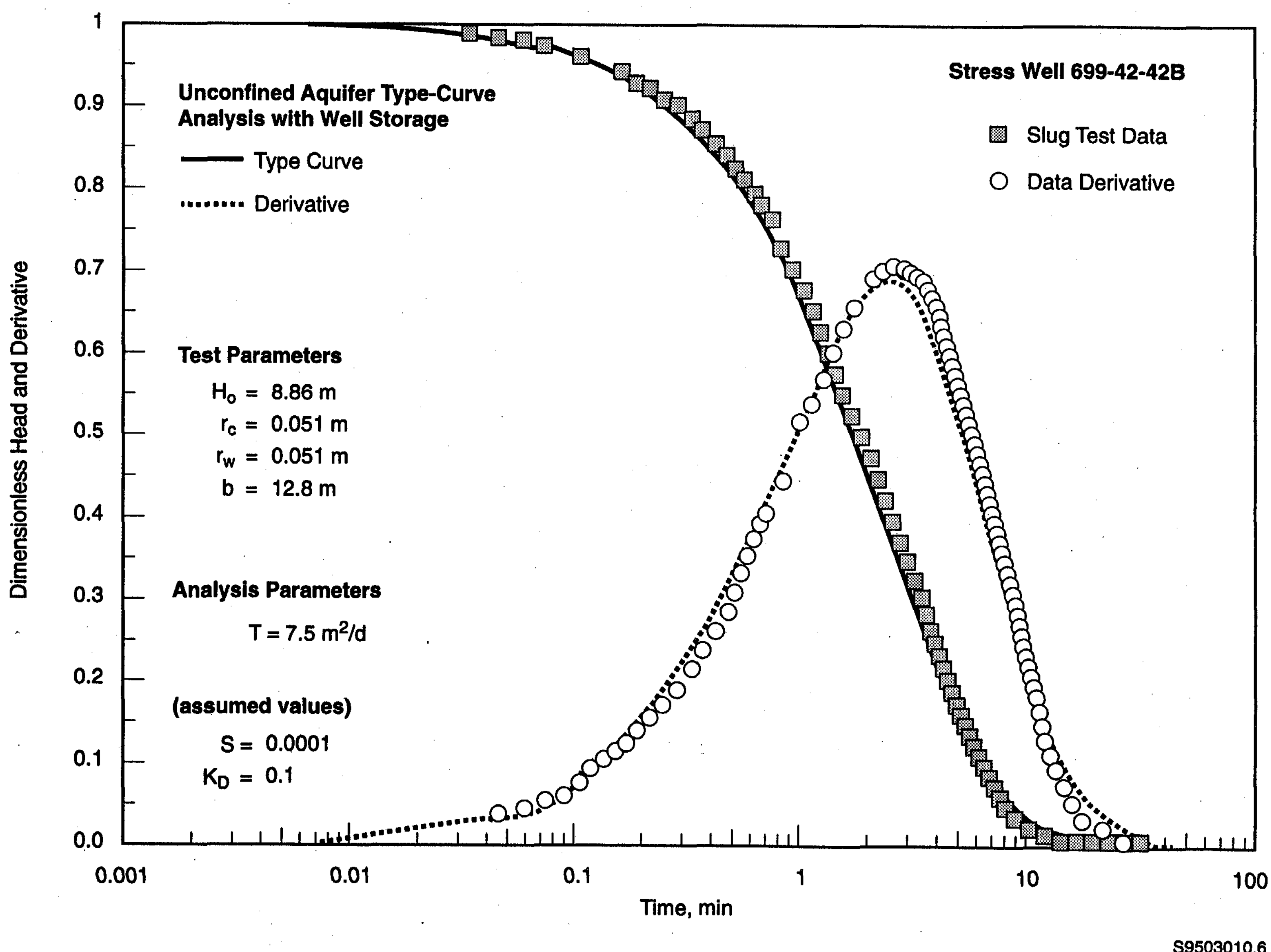

Figure 4.5. Slug Test Type-Curve Analysis for Stress Well 699-42-42B

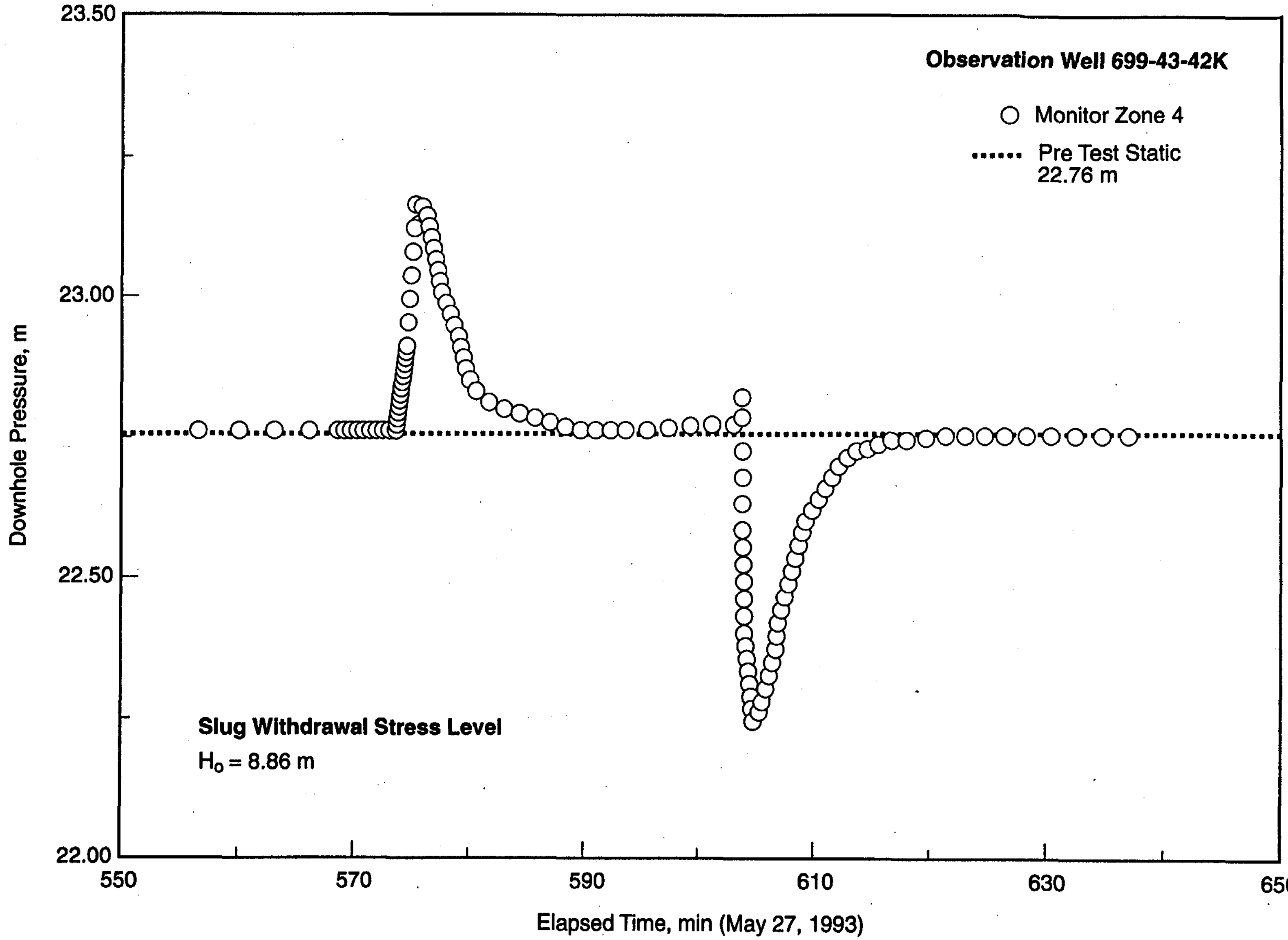

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Figure 4.6. Downhole Pressure History Response at Observation Well 699-43-42K - Monitor Zone 4 During Slug Interference Testing

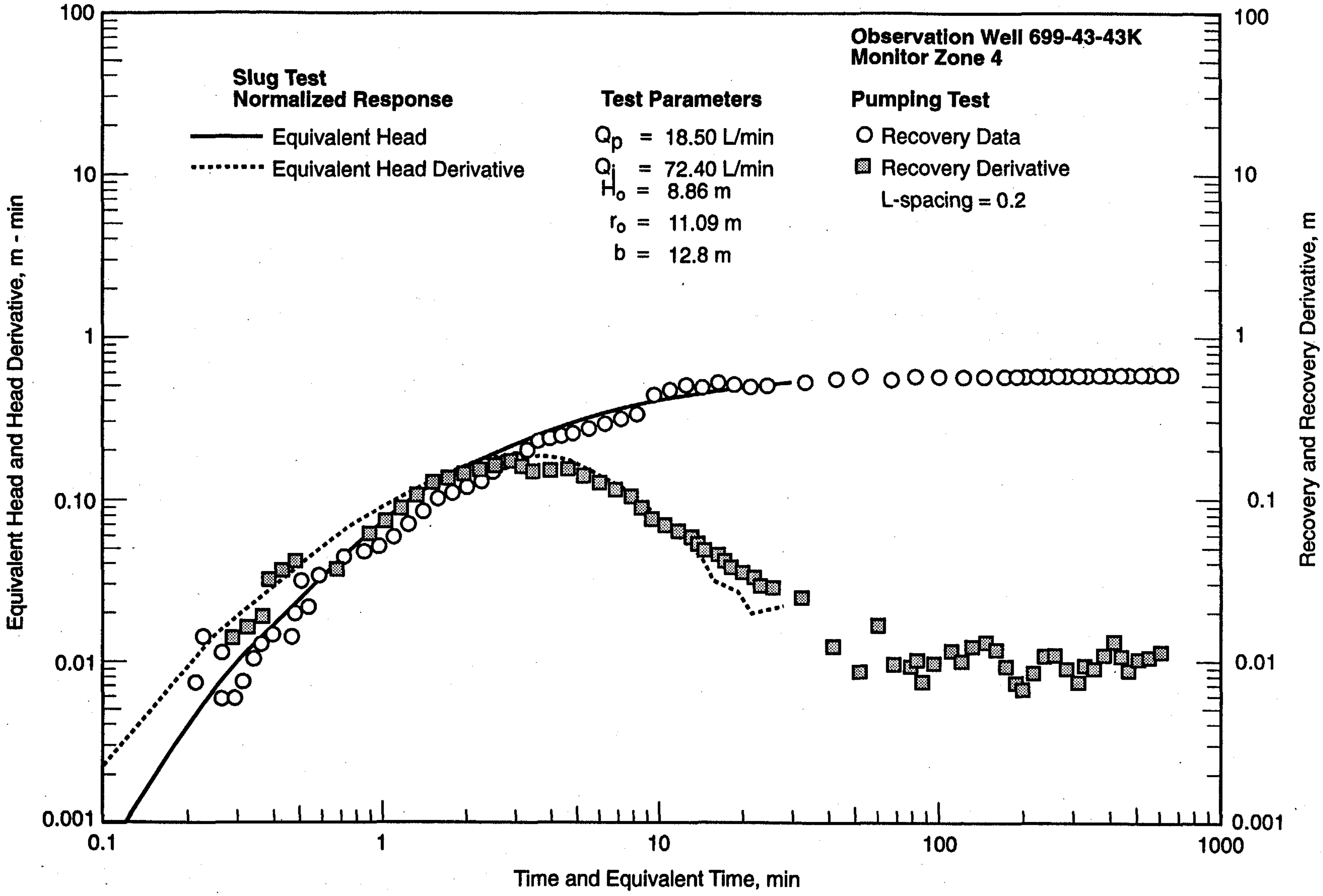

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Figure 4.7. Comparison of Normalized Slug Equivalent Head Response and Pumping Test Recovery for Observation Well 699-43-42K - Monitor Zone 4

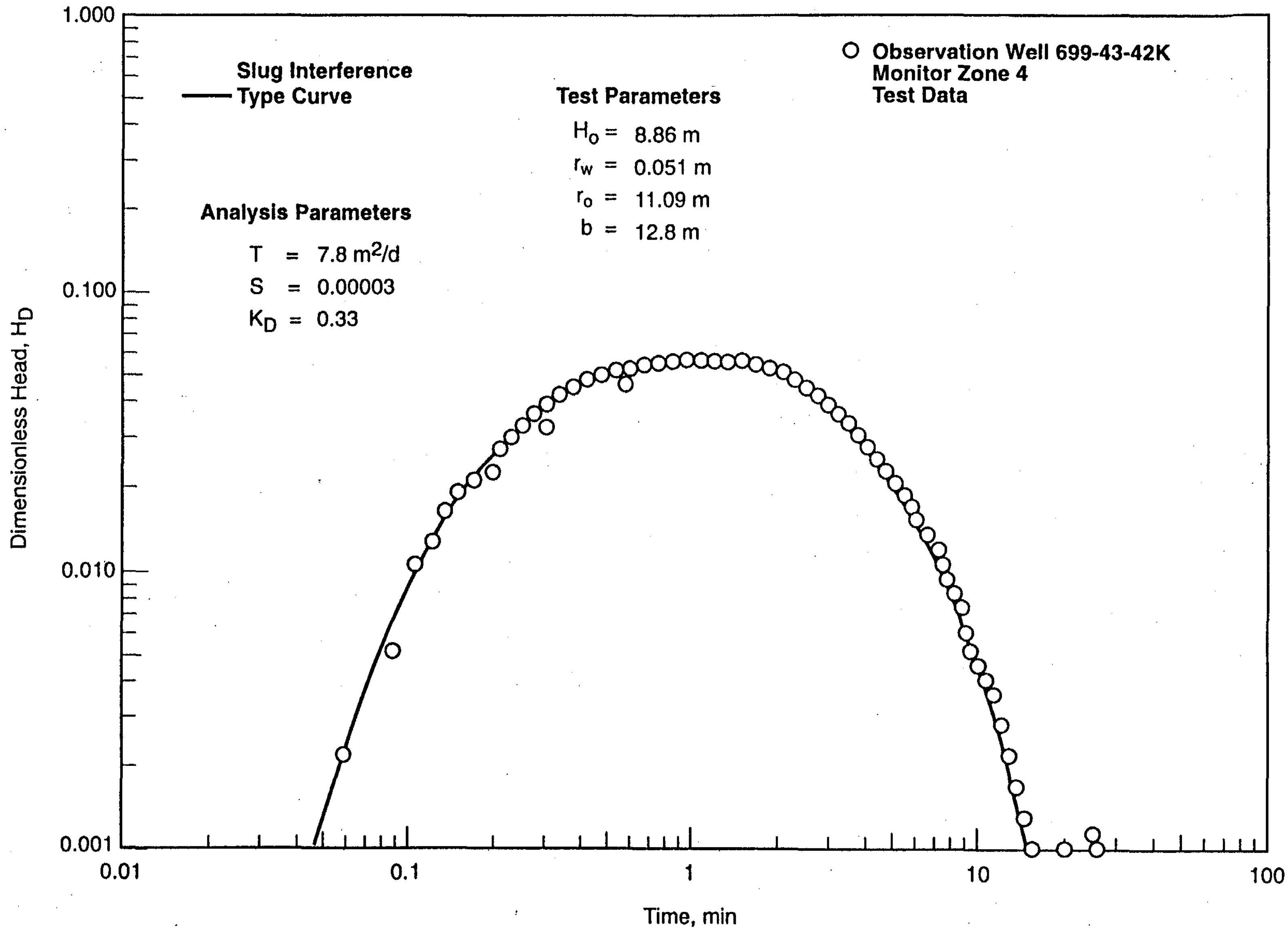

Figure 4.8. Slug Interference Test Type-Curve Analysis for Observation Well 699-43-42K - Monitor Zone 4

slug interference test analysis results compare favorably with those obtained from the pumping test recovery analysis (i.e., T = 5.8 m^2/d, S = 0.000023, K_D = 0.45). To examine the sensitivity of the predicted slug interference response at Monitor Zone 4 to various hydrologic property combinations, individual type curves were generated by systematically varying selected parameter estimates. Figures 4.9, 4.10, and 4.11 show the results of the sensitivity analysis for T, S, and K_D, respectively. For the existing test site conditions, the predicted slug interference response at Monitor Zone 4 is insensitive to variations of specific yield. The final type-curve solution shown in Figure 4.8 is included on each of the sensitivity analysis figures for comparison purposes.

The results of the sensitivity analysis are consistent with findings previously reported in Spane (1994) concerning the effect of hydraulic properties on predicted slug interference response. As indicated, transmissivity exerts a strong influence on the travel time of the slug interference response (Figure 4.9), while storativity primarily influences the shape and amplitude of the interference response (Figure 4.10). Like storativity, vertical anisotropy exerts a pronounced influence on the shape and amplitude of the slug interference response. In contrast to storativity effects, however, vertical anisotropy also exerts a profound influence on the recessional limb following the peak amplitude of the initial elastic interference response (Figure 4.11).

4.4 Well 699-43-42K - Monitor Zone 3 Analysis

Figure 4.12 shows the pressure history and slug interference test 3 response observed at Monitor Zone 3 within well 699-43-42K. Comparison with Figure 4.6 indicates a similar pressure history pattern for both monitor zones, with the fluid column pressurization and pressure release phases clearly indicated. Figure 4.13 shows a comparison of the pumping test recovery data with slug test data converted to an equivalent constant-rate head response for Monitor Zone 3. The normalized equivalent head response was calculated as previously described in this section. As shown in Figure 4.13, a general correspondence between the two tests is indicated over the slug test time duration of ≈ 30 min. The slug interference response, while similar, appears to respond slightly more rapidly than the pumping test recovery response. As noted in Section 3.3, the recovery phase exhibited a delayed response in comparison to its drawdown counterpart. The reason for this delayed recovery response is currently not known. However, because of the general similarity in the slug interference and pumping test response patterns, similar hydrologic property estimates from the respective test analyses are still expected.

The slug interference response observed at Monitor Zone 3 within well 699-43-42K was analyzed using the same procedure described for the analysis of Monitor Zone 4, which follows the method outlined in Section 4.1. Examination of the early slug interference response recorded at Monitor Zone 3 clearly displays a composite formation test response behavior; with an initial rapid recovery (0 to 0.1 min), followed by a slower recovery period (0.1 min to 0.3 min), which was followed by a final more rapid recovery phase (≥ 0.3 min). As noted in Section 3.3, this same type of composite test behavior was exhibited during the pumping test recovery for Monitor Zone 3, and may be attributed to a local heterogeneity (e.g., a zone of higher permeability) within the monitor zone test interval.

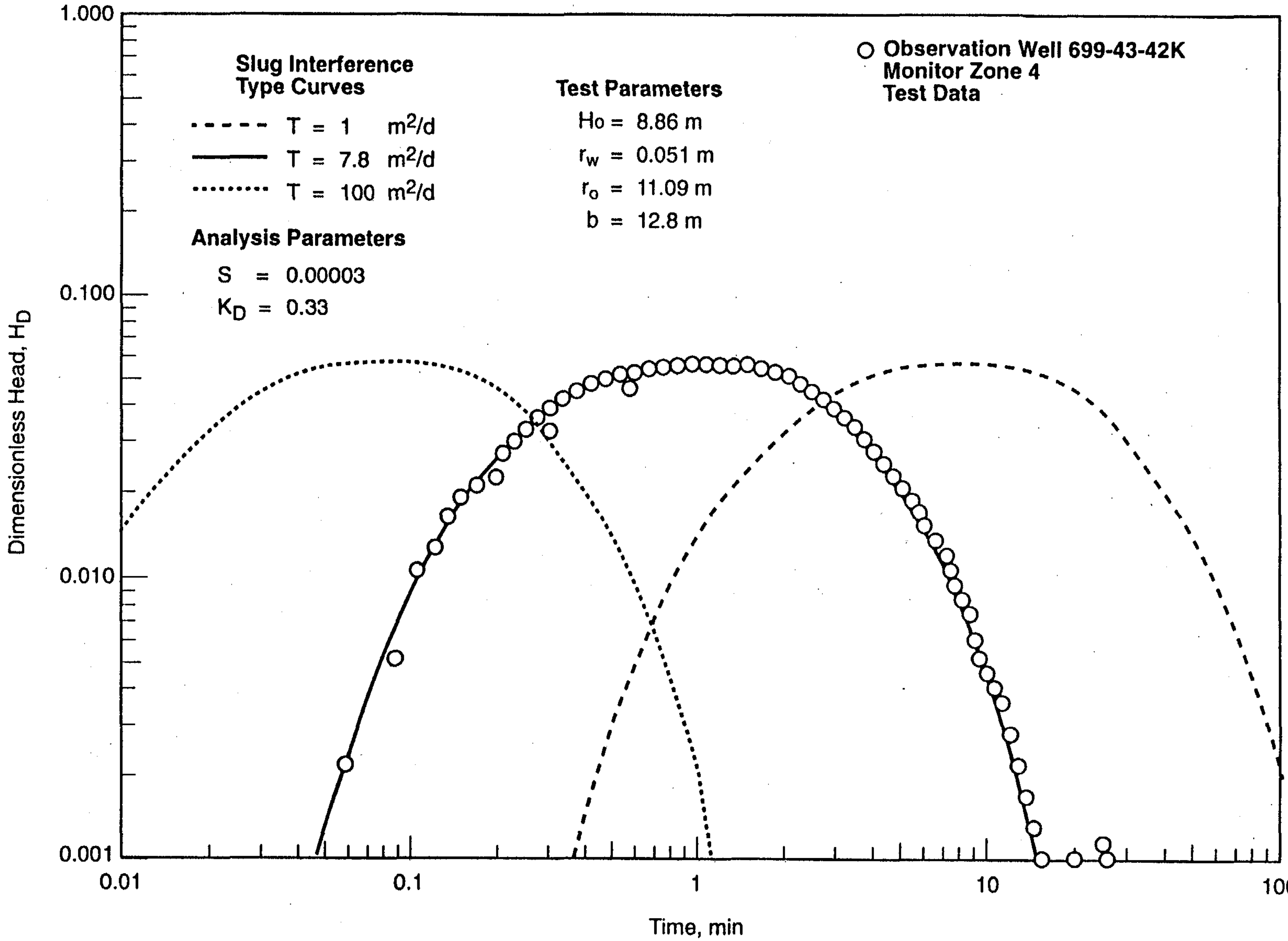

Figure 4.9. Sensitivity of Predicted Slug Interference Response to Varying Transmissivity (S = 0.00003; K_D = 0.33) for Observation Well 699-43-42K - Monitor Zone 4

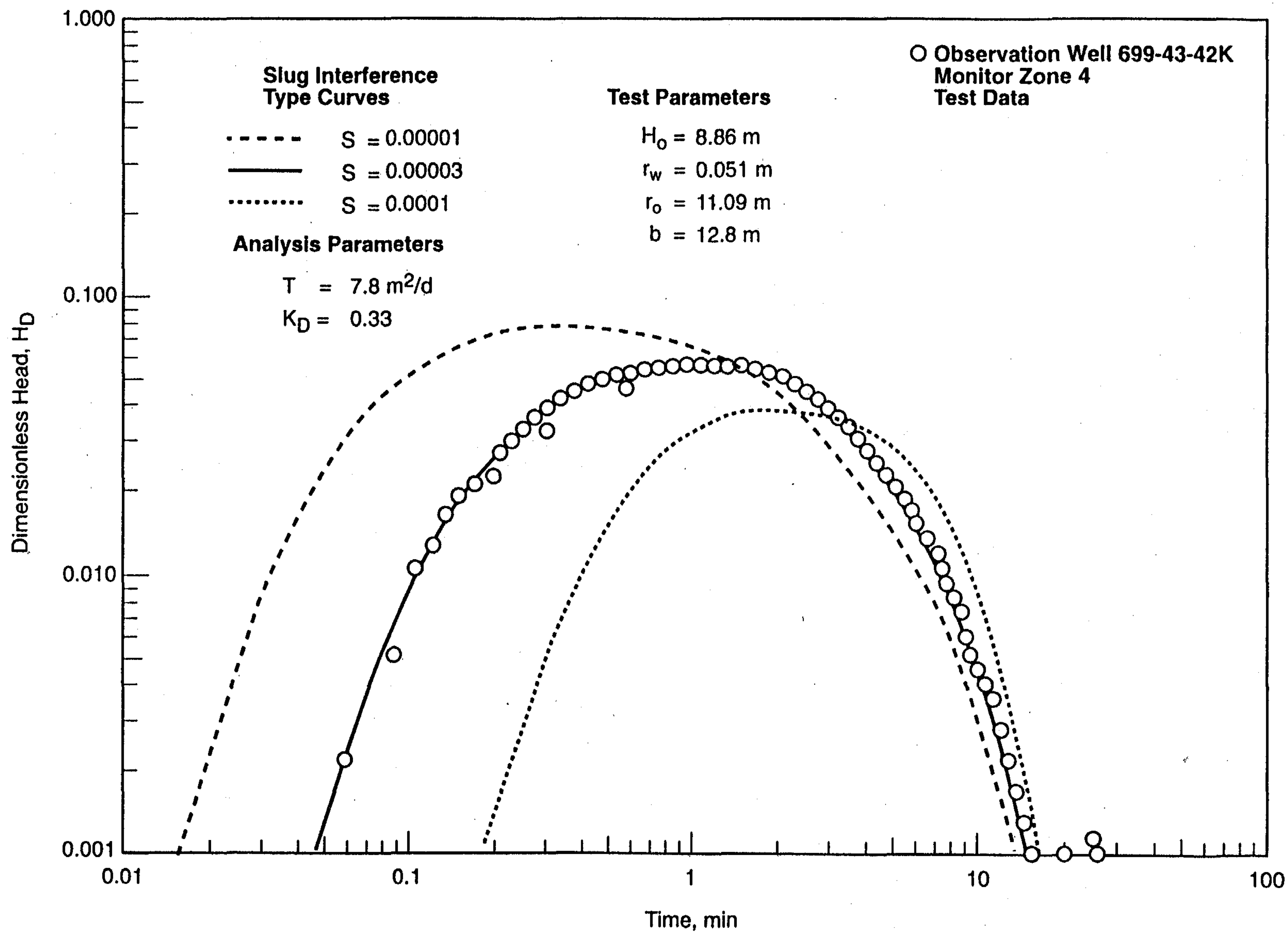

Figure 4.10. Sensitivity of Predicted Slug Interference Response to Varying Storativity (T = 7.8 m^2/d; K_D = 0.33) for Observation Well 699-43-42K - Monitor Zone 4

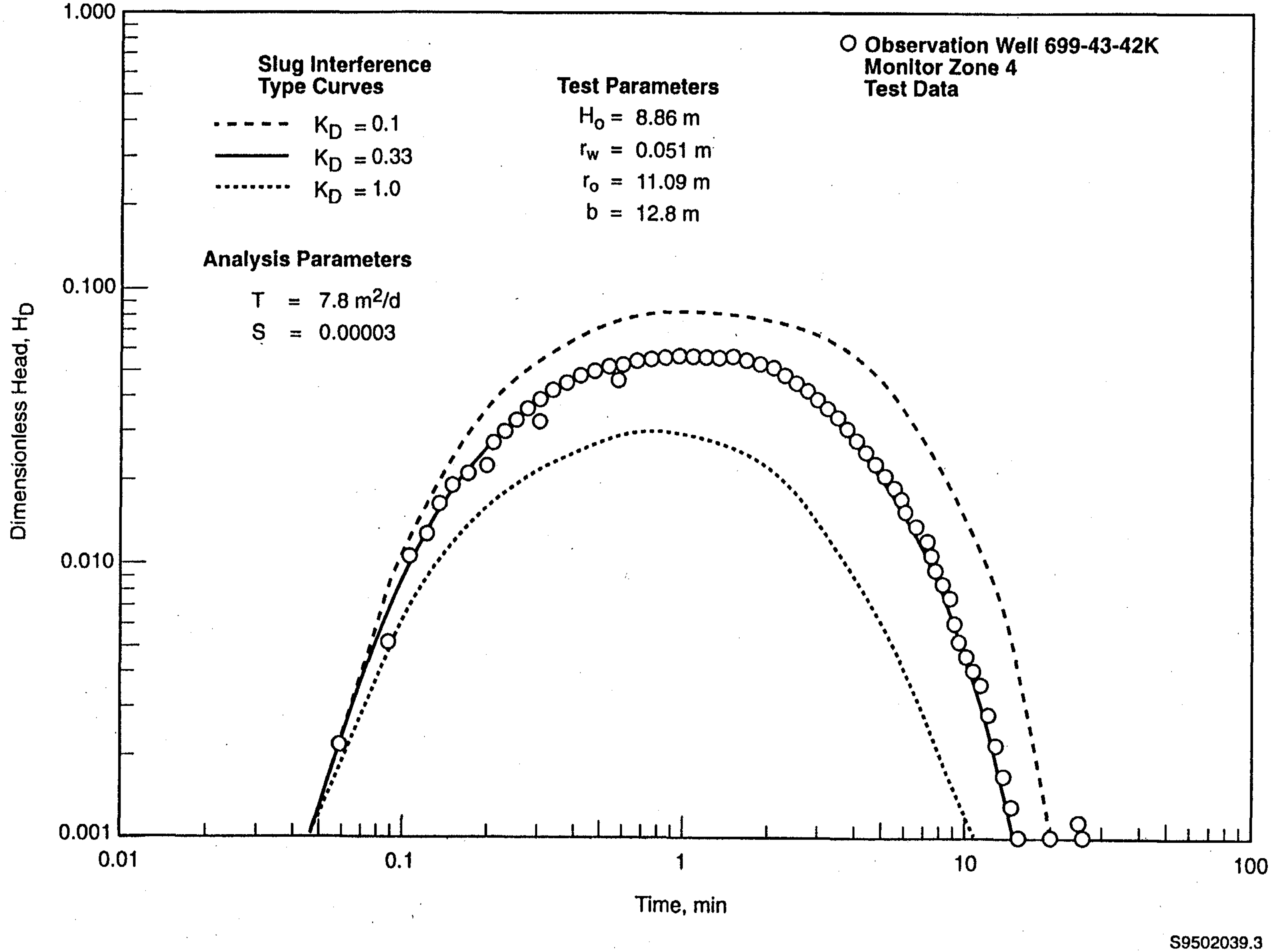

Figure 4.11. Sensitivity of Predicted Slug Interference Response to Varying Vertical Anisotropy (T = 7.8 m^2/d; S = 0.00003) for Observation Well 699-43-42K - Monitor Zone 4

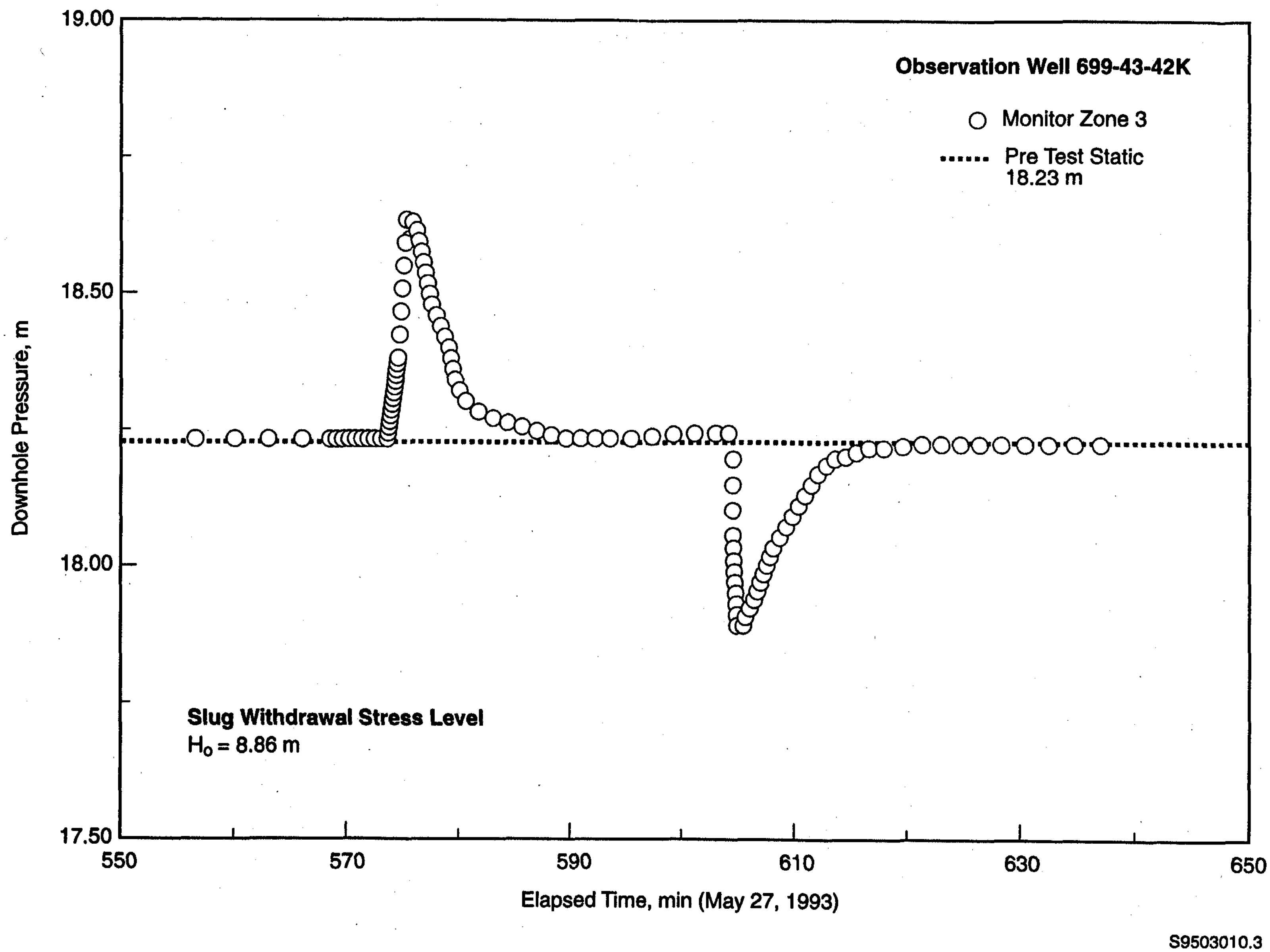

Figure 4.12. Downhole Pressure History Response at Observation Well 699-43-42K - Monitor Zone 3 During Slug Interference Testing

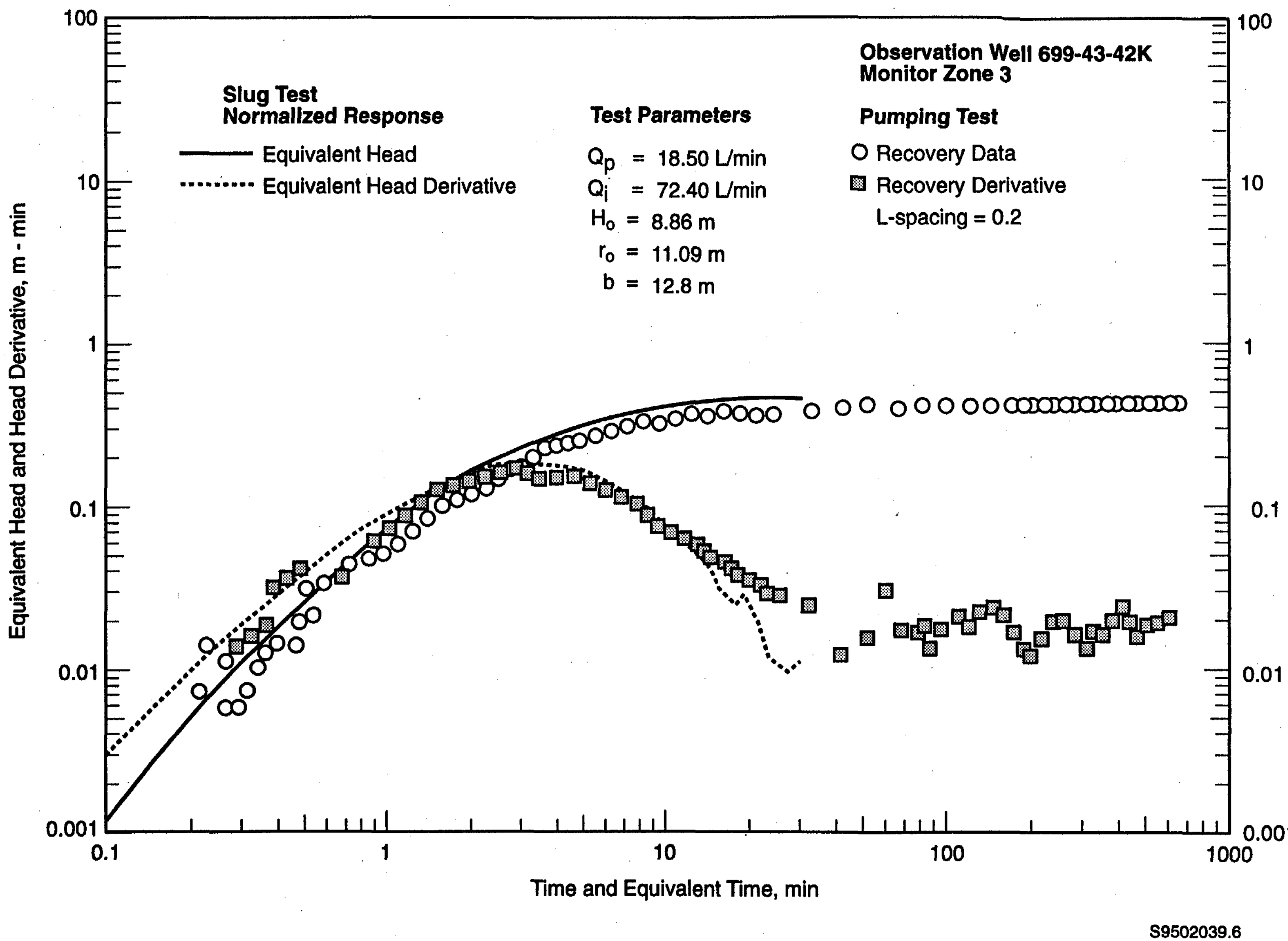

Figure 4.13. Comparison of Normalized Slug Equivalent Head Response and Pumping Test Recovery for Observation Well 699-43-42K - Monitor Zone 3

Because type curves are not readily available for composite formation test responses, it is not possible to completely match the entire slug interference response recorded at Monitor Zone 3. To proceed with the Monitor Zone 3 analysis, using type curves based on a homogeneous formation response, a slightly different matching approach was required. The standard approach focuses on matching the initial rising limb and peak amplitude by adjusting values of T and S, and then matching the later-time recessional limb response by adjusting K_D and S/Sy. The alternate analysis method was to match the slug interference response after the period reflecting composite formation response (i.e., after 0.3 min). Figure 4.14 shows the results of the two type-curve analysis approach. As indicated, analysis values for T and K_D were identical, yielding values of 7.0 m^2/d and 0.40, respectively, for both type-curve matches. Storativity values ranged between 0.000016 and 0.000027 for the first and second type-curve analysis methods. The alternate approach provided a more representative analysis of larger-scale formation conditions.

4.5 Composite Equivalent Head Analysis

As discussed in Section 3.4, simultaneous analysis of multiple well responses to a single test event (i.e., composite test response analysis) has been shown to be extremely useful for the determination of large-scale aquifer hydraulic properties and for assessing aquifer homogeneity. Normally composite test analysis pertains to the simultaneous analysis of pumping test responses observed at different monitoring locations, as illustrated in Figure 3.8. However, this type of analysis can also be extended to slug interference test data, converted to constant-rate equivalent head data.

Figure 4.15 shows the composite equivalent head response data for Monitor Zones 3 and 4 at well 699-43-42K and stress well 699-42-42B. Predicted test responses are also shown in Figure 4.15 and were based on the approximate average for hydraulic property values determined from individual pumping test analyses. These values include: transmissivity = 7.5 m^2/d, storativity = 0.00003, specific yield = 0.075, and vertical anisotropy = 0.40. The hydraulic property values used are identical to those used for predicting pumping test response in Figure 3.8, except that vertical anisotropy was decreased slightly from 0.45 to 0.4 for the slug interference test equivalent head analysis.

The relative correspondence between observed and predicted test response in Figure 4.15 corroborates results of the composite pumping test analysis (Section 3.4) and indicates the aquifer can be adequately characterized with a homogeneous porous media model at this location.

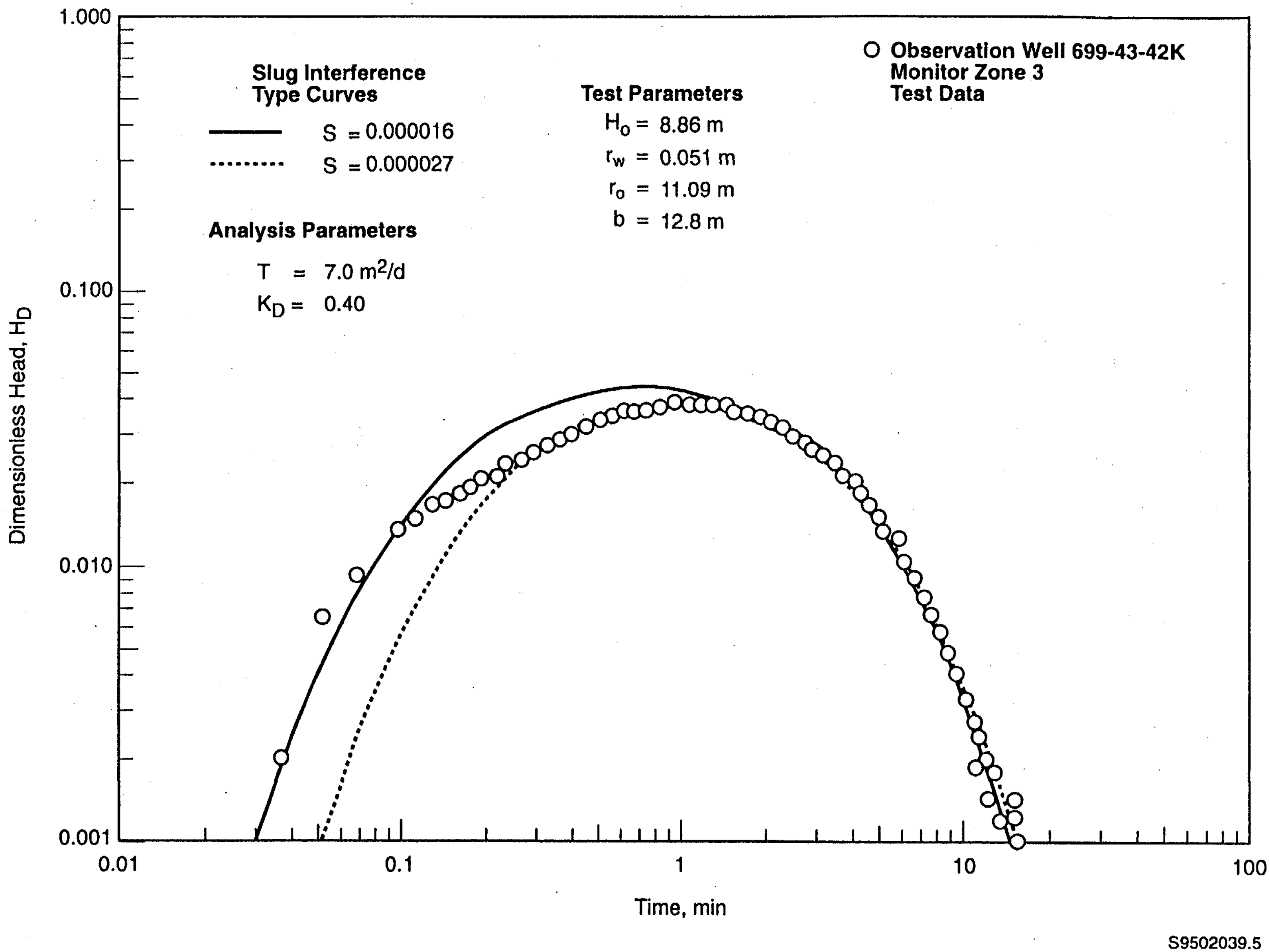

Figure 4.14. Slug Interference Test Type-Curve Analysis for Observation Well 699-43-42K - Monitor Zone 3

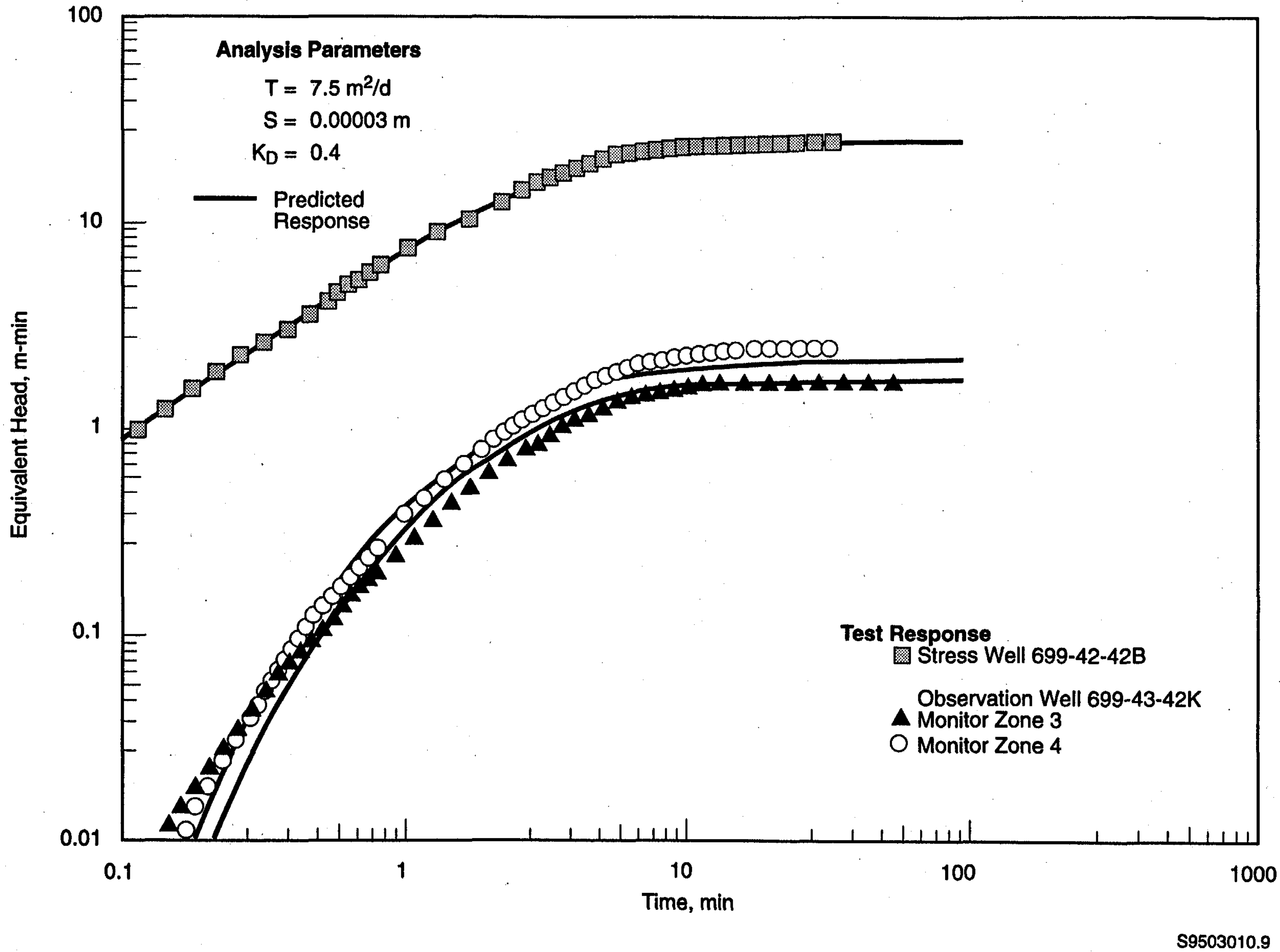

Figure 4.15. Composite Equivalent Head Test Response Analysis

5.0 Hydraulic Test Result Summary

Table 5.1 lists hydrologic property values estimated from analysis of the constant-rate pumping and slug interference tests. Comparison of the results indicates a close correspondence between hydrologic property values obtained from the two test methods. Estimates for transmissivity ranged from 5.8 m^2/d to 8.5 m^2/d, while estimates for vertical anisotropy ranged between 0.33 and 0.45. Storativity values obtained from the analyses ranged from 0.000016 to 0.00005. A quantitative estimate for specific yield was not possible, due to the short duration of the tests and the test site conditions. Based on results of the pumping test recovery, however, a qualitative estimate value of specific yield of $\geq$ 0.075 is suggested. The correspondence between observed and predicted test response for the composite analysis of pumping test recovery (Section 3.4) and composite analysis of slug interference test equivalent head response (Section 4.5) suggests that the aquifer can be adequately characterized with a homogeneous porous media model at this locality. Average hydraulic properties of $T = 7.5\ m^2/d$, $S = 0.00003$, $S/Sy \leq 0.0004$, $K_D = 0.45$ were determined from the composite analyses.

The close correspondence in hydrologic property values obtained using the two test methods suggests that slug interference testing can provide representative aquifer characterization results, under favorable test conditions (e.g., observation well distances $\leq$ 30 m). The quality and extent of test data obtained also indicates the usefulness of multilevel test facilities for three-dimensional hydrologic characterization.

Table 5.1. Summary of Hydraulic Property Values From Constant-Rate Pumping and Slug Interference Test Analysis

Well Site	Test Method	Transmissivity m^2/d	Storativity	Specific Yield	Vertical Anisotropy
699-42-42B	Pumping Test	8.5	NA	NA	NA
	Slug Test	7.5	NA	NA	NA
699-43-42K Monitor Zone 4	Pumping Test	5.8	0.000023	≥ 0.1	0.45
	Slug Interference Test	7.8	0.00003	NA	0.33
699-43-42K Monitor Zone 3	Pumping Test Recovery	7.8	0.00005	≥ 0.07	0.45
	Pumping Test Drawdown	7.5	0.00002	≥ 0.2	0.45
	Slug Interference Test	7.0	0.000016 0.000027	NA	0.40

NA not applicable to analysis

6.0 References

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