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7. Abstract

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1.0 BACKGROUND

During 1992, a series of hydrologic characterization tests were conducted at the well 4A - 4T test facility complex. Details concerning these tests are described in Swanson (1992). Two of the tests, a constant-rate discharge test conducted on March 30, 1992 and a slug interference test performed on April 15, 1992, are the focus of this report.

Preliminary analysis results presented in Swanson (1992) indicated a significant divergence in hydraulic property estimates (i.e., transmissivity and storativity/specific yield) obtained for the pumping test and slug interference test. The divergence in hydraulic property estimates is attributed to several deficiencies in the original slug interference analysis. The original slug interference test analysis was based on the procedure presented in Novakowski (1990), which is dependent on fully penetrating wells within isotropic confined aquifer conditions. Subsequent to this analysis, analytical methods have been developed, which provide the opportunity of extending slug interference analysis to a variety of test conditions including:

- Unconfined aquifers
- Partially penetrating wells
- Anisotropic conditions
- Wellbore storage effects (for the pumped well).

In addition, it is also noted that an incorrect stress level, i.e., H_o value of 0.536 m (1.76 ft), for the slug interference test was used in the original analysis presented in Swanson (1992).

As part of the re-analysis effort, the results from the pumping test conducted at well 4T and observed at well 4A were re-examined. While significant changes were not expected from the pumping test re-analysis for estimates of transmissivity and specific yield, a revised estimate for storativity was anticipated. An amended value for storativity was expected because the original pumping test analysis method did not take into account the effects of wellbore storage in observation well 4A. It is important to note that the storativity or elastic storage characteristics of the aquifer exert a strong influence on slug interference amplitude, as noted previously in Novakowski (1990) and Spane (1992). For these reasons, the pumping test results for well 4A were re-analyzed.

2.0 PUMPING TEST RE-ANALYSIS

The re-analysis procedure for the drawdown portion of the pumping test at well 4A included the following analysis elements:

- An initial diagnostic drawdown derivative analysis
- A late-time, Neuman Type B curve analysis
- A complete unconfined aquifer type-curve analysis, including wellbore storage effects.

2.1 DIAGNOSTIC ANALYSIS

Combined drawdown and drawdown derivative plots have been shown to be a powerful diagnostic tool in identifying operative flow conditions and factors influencing drawdown during constant discharge pumping tests (e.g., Bourdet et al. 1983, 1989; Spane 1993). Figure 1 shows the combined drawdown and drawdown derivative plot for observation well 4A. The drawdown derivatives were calculated using the DERIV program described in Spane and Wurstner (1993). Based on a diagnostic analysis of the pattern exhibited in Figure 1, the following operative flow conditions during the test were interpreted:

- Combined wellbore storage and delayed-yield response conditions during the early phases of the test (i.e., up to ≈4 min)
- Unconfined aquifer, Type B curve response characteristics between 4 and 500 min
- Variable drawdown/derivative pattern after 500 min, most likely attributable to discharge fluctuations.

2.2 TYPE B CURVE ANALYSIS

To provide an initial estimate of transmissivity and specific yield, drawdown data during the test period indicative of Neuman unconfined aquifer, Type B curve behavior were analyzed (i.e., for test times ≥4 min). The combined Type B drawdown and drawdown derivative plot matching procedure described in Spane (1993) was used in the test analysis. Drawdown type curves were generated using the WTAQ1 program described by Moench (1993). As discussed in Moench (1993), the WTAQ1 program runs faster and does not exhibit some of the test instabilities that are sometimes exhibited with the DELAY2 program described by Neuman (1975) for analysis of unconfined aquifer pumping tests. Associated derivative plots of the Type B curves were generated, as discussed previously, using the DERIV program.

The combined drawdown and derivative plot match for the test is shown in Figure 2. As indicated in Figure 2, a very close match was obtained for the combined drawdown and derivative plot for the identified test period exhibiting Type B drawdown behavior (i.e., ≥4 min). Results of the analysis indicate estimates for transmissivity and specific yield of 254 m^2/d (2,730 ft^2/d) and 0.025, respectively. A qualitative estimate for vertical anisotropy (K_D) of 0.15 is also suggested. These results compare favorably with preliminary unconfined aquifer analysis results for transmissivity (269 m^2/d), specific yield (0.016), and vertical anisotropy (0.11) reported in Swanson (1992), which were obtained from automated type-curve analysis of the entire drawdown record using the ISOAQX program (HydraLogic 1989).

Figure 1. Diagnostic Drawdown and Drawdown Derivative Plot for Well 4A.

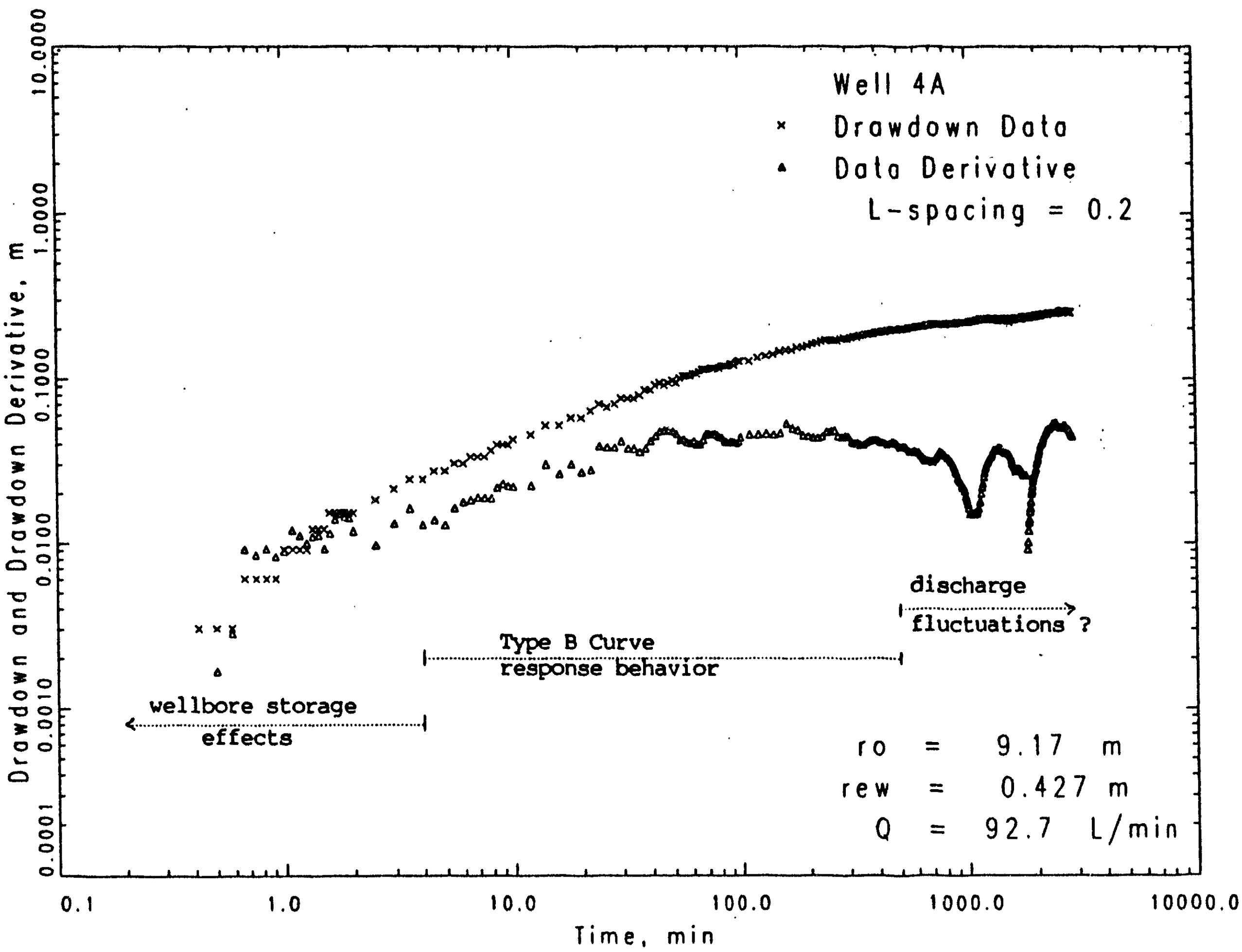
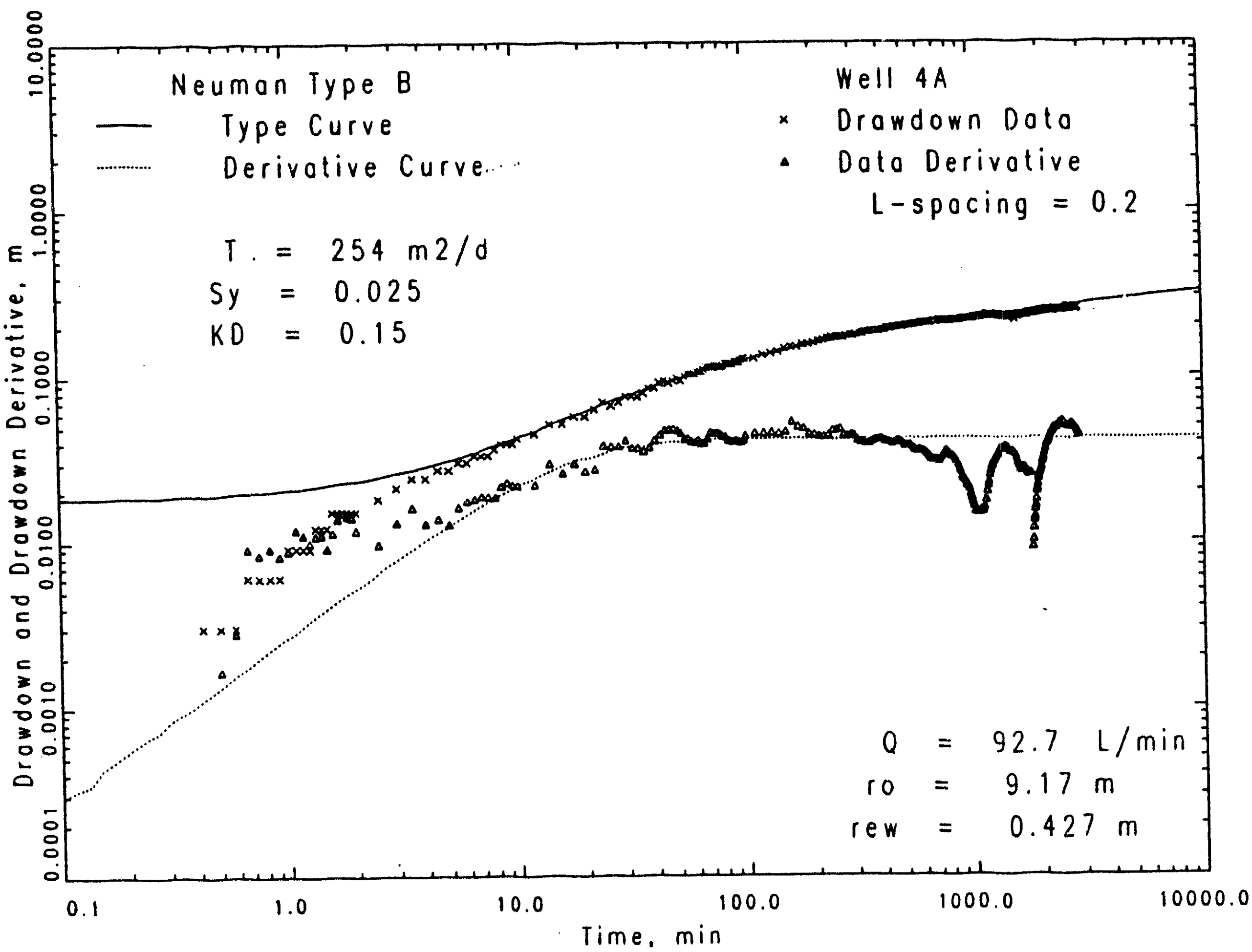


Figure 2. Combined Drawdown and Drawdown Derivative, Type B Curve Analysis for Well 4A.



2.3 COMPLETE UNCONFINED AQUIFER TYPE-CURVE ANALYSIS

An additional analysis was also attempted that analyzed the entire time drawdown data set. The complete data analysis followed the same procedure described in Section 2.2 for the Type B curve analysis. The complete unconfined aquifer analysis procedure, however, includes the effects of wellbore storage, which would be expected to be exhibited during the early phases of the test. Wellbore storage effects were accounted for, utilizing an undocumented program that simulates wellbore storage effects, which is based on the procedure described in Fenske (1977). The undocumented program can be used to account for pumping and observation wellbore storage effects. A comparison of results obtained with the Fenske-based program indicated nearly identical results when compared with predictive responses (i.e., for pumping well wellbore storage) generated with the Novakowski (1990) program for confined aquifers, and the program provided in Dawson and Istok (1991) for unconfined aquifer Type A curve response.

To fully account for the effects of wellbore storage, the "effective" well radius, r_{ew}, for the pumped and observation wells is required. As will be shown, the effective well radius for the pumped well 4T is considerably greater than for observation well 4A. The early-time drawdown pattern in the vicinity of the pumping well (i.e., within a distance of ≈100 wellbore radii), therefore, is expected to be affected more by pumping well (rather than observation well) wellbore storage effects.

For wells with sand/gravel pack installations, the effective well radius can be calculated using the following relationship presented in Bouwer (1989):

$$r_{ew} = [(1-n)r_c^2 + n\ r_w^2]^{1/2} \qquad (1)$$

where

r_c = radius of the well screen

r_w = radial distance from center of well to the outside sand/gravel pack

n = porosity of the sand/gravel pack.

For well 4A, given a well screen radius of 0.051 m (0.1667 ft), a radial gravel pack distance of 0.102 m (0.333 ft), and an assumed porosity of 30%, yields a r_{ew} for well 4A of 0.070 m (0.230 ft).

A calculation of the r_{ew} for the pumped well (well 4T), however, is more difficult because of the "natural" sand/gravel pack that was developed around the well, during previous wellbore developmental pumping. As noted in Swanson (1992), several barrels of sand and silt were removed from well 4T during the developmental pumping phase. The presence of an extensive zone of "enhanced" permeability surrounding the immediate wellbore is indicated also by the bi-linear response exhibited at well 4T during the slug test (Figure 3). As a means of estimating possible values for the r_{ew} for well 4T, the radial distance, r_w, to the outside boundary of the developed "natural" sand/gravel pack calculated based on the known displacement, $V_t = 0.027\ m^3$ (0.96 ft^3) and initial stress response, $H_o = 0.168$ m (0.55 ft) observed at well 4T during the April 14, 1992 slug test (see Figure 3). For this calculation, the following relationships were developed:

$$V_t = V_{wc} + V_{wa} \quad (2)$$

where

V_t = slug test volume displacement (0.027 m^3)

V_{wc} = displacement volume within well screen

V_{wa} = displacement volume within natural sand/gravel pack zone

where

$V_{wc} = \pi\ r_{ct}^2\ H_o = 0.0067$ m; (0.237 ft^3)

where

r_{ct} = radius of well 4T well screen; 0.113 m (0.370 ft).

Re-arranging Equation 2,

$$V_{wa} = V_t - V_{wc} = 0.020\ m^3;\ (0.723\ ft^3)$$

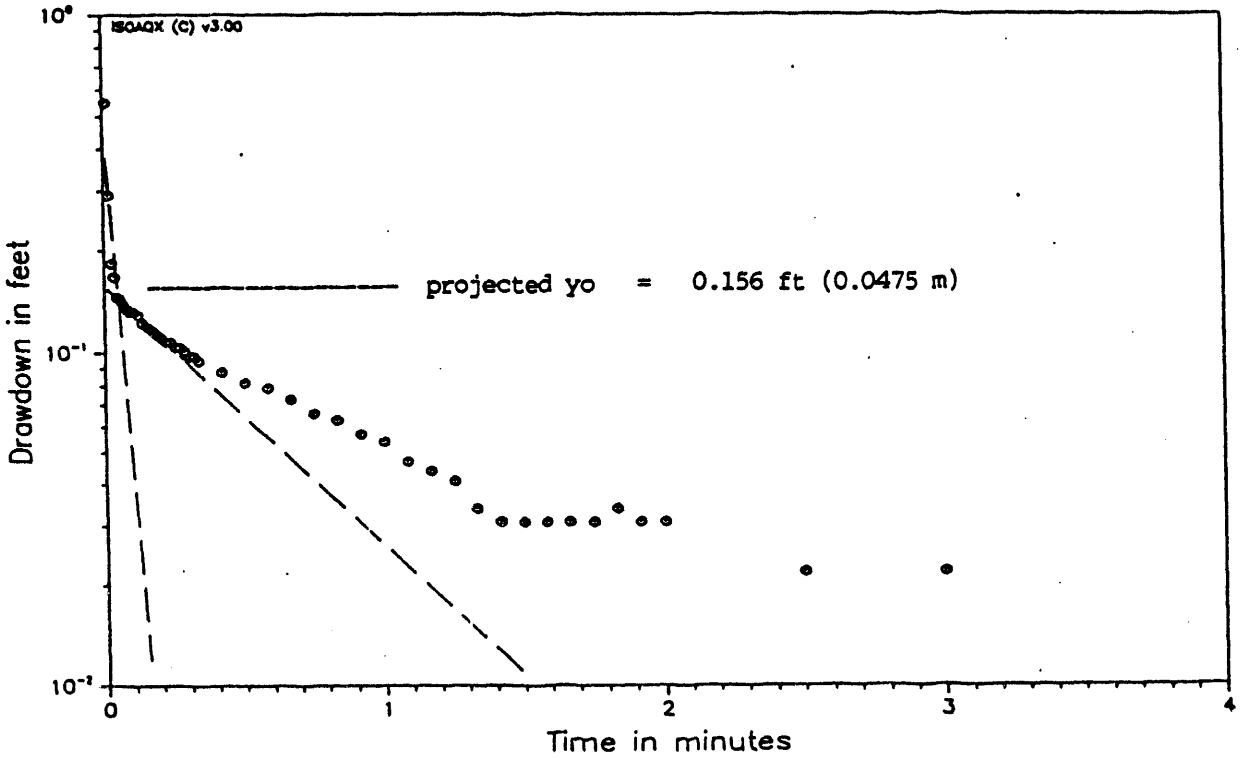
Also note that from a modification of a relationship in Bouwer (1989)

$$V_{wa} = \pi\ (r_w^2 - r_c^2) n\ H_o \quad (3)$$

For n values ranging from 15% to 30%, calculated r_w values range between 0.521 m to 0.378 m (1.71 ft to 1.24 ft), respectively. Using these range of r_w and n values in Equation 1 yields an estimated effective well radius, r_{ew}, of 0.229 m (0.75 ft).

The effective well radius value of 0.229 m would be expected to provide a valid prediction of wellbore storage effects for test conditions where the hydraulic properties of the natural sand/gravel pack zone are similar to that of the surrounding test formation. However, as shown in Figure 3, the "double straight-line pattern" displayed during the slug test at well 4T indicates that the developed zone around the well possesses a significantly greater transmissivity than the surrounding formation. This developed inner zone of greater transmissivity causes the surrounding test formation response to react

Figure 3. Slug Test Response at Well 4T; Test Date: April 14, 1992 (adapted from Swanson 1992).



more rapidly. In the petroleum industry, wells with inner zones of enhanced permeability are referred to as having a negative skin effect. As indicated by Earlougher (1977), the effective well radius, r_{ew}, for wells exhibiting negative skins is greater than the observed or calculated well radius, r_w.

To estimate the "enhanced" effective well radius, r_{eew}, at well 4T, an analysis technique presented in Bouwer (1989) was adapted. When double straight-line conditions are exhibited during slug testing, Bouwer (1989) states that the observed initial stress value (y_t) should not be used in the analysis, but rather the projected initial stress value (y_o) as shown in Figure 4. The projected y_o stress value is what is actually imposed on the test formation (i.e., outside the inner developed zone of enhanced permeability). The projected y_o value of 0.0475 m (0.156 ft) from Figure 3 and known slug test stress volume (i.e., slugging rod volume = 0.027 m^3) can then be used in the following re-arrangement of the volume equation for a cylinder to provide an "enhanced" effective well radius estimate.

$$r_{eew} = [V_t/(\pi\ y_o)]^{½} \qquad (4)$$

Based on this procedure, an r_{eew} estimate of 0.427 m (1.4 ft) was obtained. This estimate for the "enhanced" effective well radius was used in the re-analysis of the constant-rate pumping test (i.e., complete unconfined aquifer type-curve analysis) and slug interference test.

Figure 5 shows the final result of matching the observed drawdown and drawdown derivative with a complete unconfined aquifer type curve and derivative plot. As indicated, a close match was obtained for the combined drawdown and drawdown derivative plot. Results from the completed unconfined aquifer curve analysis indicated the following hydraulic parameter estimates: transmissivity = 254 m^2/d (2,730 ft^2/d), specific yield = 0.025, storativity = 0.001, and vertical anisotropy = 0.10. These results are very similar to results obtained with the Type B curve analysis and to those previously reported by Swanson (1992). It should be noted, however, that the estimate for storativity is considered to be very qualitative, primarily because of the lack of early-time data (i.e., the first 25 seconds) and the lack of sensitivity for small drawdown measurements (note the "stair-stepped" pattern for drawdowns <0.015 m).

3.0 SLUG INTERFERENCE TEST RE-ANALYSIS

As noted in Section 1.0, the original slug interference test analysis was based on the analysis procedure presented in Novakowski (1990), which is dependent on fully penetrating wells within isotropic confined aquifer conditions. Subsequent to this analysis, analytical methods have been developed, which provide the opportunity of extending slug interference analysis to a variety of test conditions including unconfined aquifers, partially penetrating wells, anisotropic conditions, and wellbore storage effects. The analysis extension is based on analytical discussions presented

Figure 4. Schematic of Slug Test Double Straight-Line Effect (adapted from Bouwer 1989).

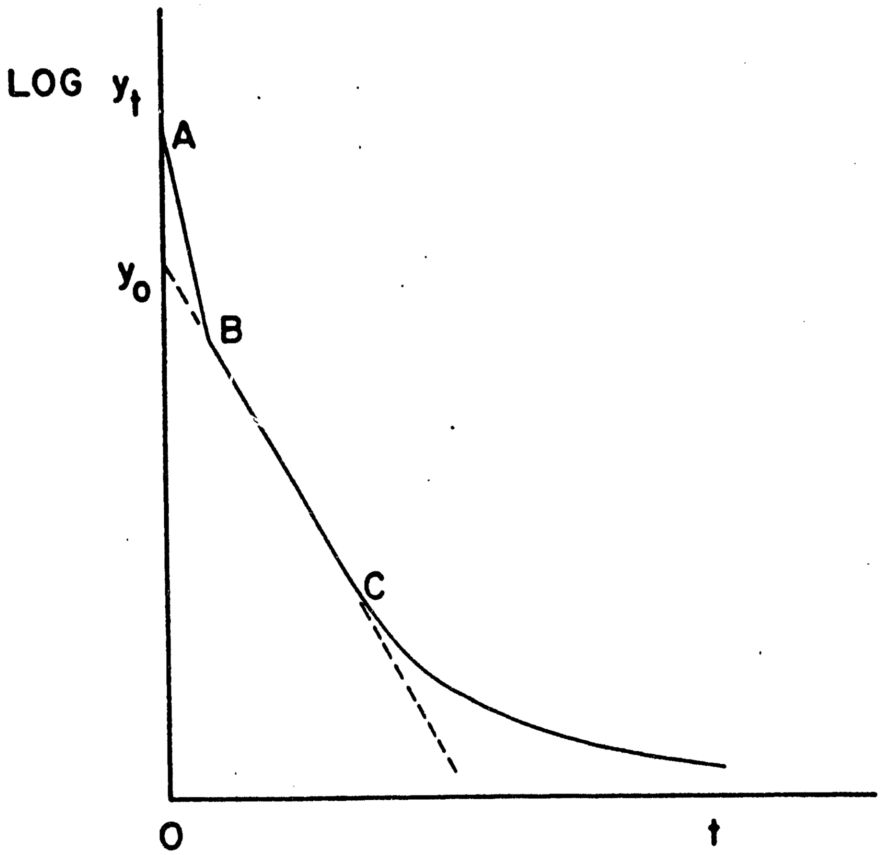
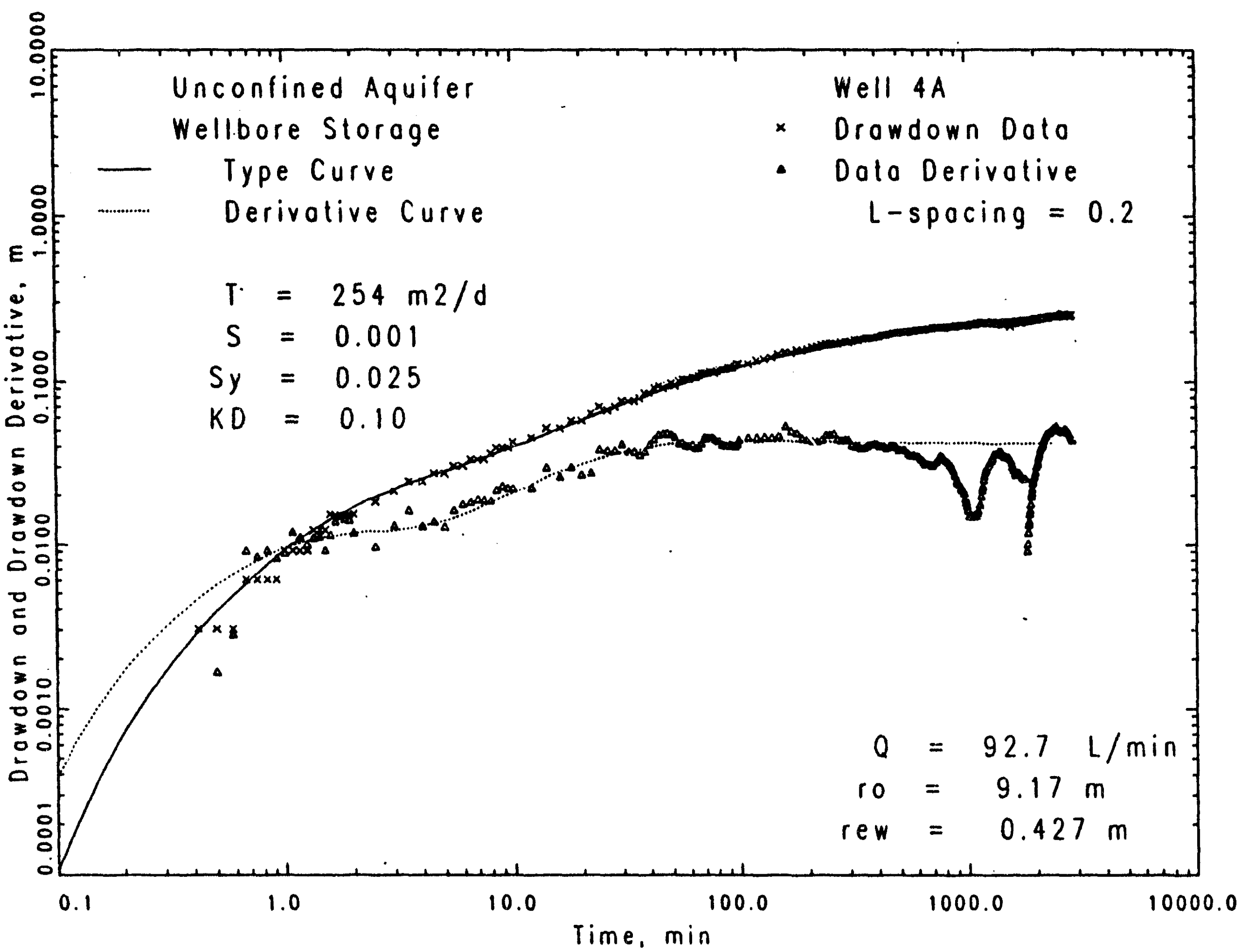


Figure 5. Combined Drawdown and Drawdown Derivative, Complete Unconfined Aquifer Type-Curve Analysis for Well 4A.



in Novakowski (1989), Peres (1989), and Peres et al. (1989), which demonstrate that slug tests can be represented as a specialized form of constant-rate pumping tests. As noted in Peres (1989), the slug test wellbore solution can be "... obtained directly from the time derivative of the constant rate wellbore storage solution ... (and that this relationship) is also valid for any reservoir/well system and holds at any position within the reservoir."

A detailed description of the procedures for slug test conversion is not presented here. The reader should consult the aforementioned references for analytical justification of the slug test conversion method. Briefly stated, however, slug test data were converted to equivalent head (pumping test) drawdown data by integrating the observed slug test head data over the observed test time, as indicated in Peres et al. (1989). Multiplication of the observed slug test head data by the observed test time yields the logarithmic derivative of the equivalent head change for a constant-rate pumping test.

Figure 6 shows a comparison of the drawdown and drawdown derivative response observed at well 4A during the constant-rate pumping test with the converted equivalent head and head derivative response obtained during the slug interference test. As indicated in Figure 6, similar pattern shapes are exhibited. To equate the two test responses, however, the stress levels for the two tests need to be normalized.

As noted in Novakowski (1989) and Peres et al. (1989), the instantaneous discharge rate, Q_i, (gal/min), imposed by a slug test can be calculated directly by the displacement volume, V_t. For a displacement volume of 0.027 m^3 (0.96 ft^3), a Q_i value of 27.2 L/min (7.18 gal/min) is indicated. To normalize the slug test derived results to the drawdown observed during the constant-rate pumping test, the equivalent head drawdown data were multiplied by a factor of 3.41, which represents the ratio of the two discharge rates (i.e., 92.7 L/min/27.2 L/min). As indicated by the normalized equivalent head response, a close correspondence between the pumping test drawdown and equivalent head/slug test results is indicated. It should also be noted that the time period of slight drawdown departure (i.e., after ≈7 min) represents a time period during the test when the slug interference response had decayed to a value of 0.0006 m (0.002 ft) or less. No great significance, therefore, should be placed on this slight deviation.

3.1 TYPE-CURVE ANALYSIS

For generating predicted slug interference unconfined aquifer type curves for the given well site test conditions, predicted pumping test drawdown curves were first generated using the WTAQ1 program, using given test site conditions (e.g., r_o, Q, r_{ew}) and selected hydraulic parameter values (e.g., T, S, S_y, K_D). Effects of wellbore storage were accounted for using the program described in Section 2.3, which is based on the Fenske (1977) method. Drawdown derivatives were calculated using the DERIV program presented in Spane and Wurstner (1993). Slug interference responses were then generated by dividing the calculated pumping test derivative by the test time. The well 4A test response was analyzed by matching the generated slug interference type curves to the observed slug interference data. The type-curve analysis procedure continued iteratively by varying the value for input parameters T, S, S_y, and K_D until a visually acceptable match was obtained.

Figure 6. Comparison of Pumping Test Drawdown and Drawdown Derivatives and Equivalent Head and Head Derivative Slug Interference Test Response for Well 4A.

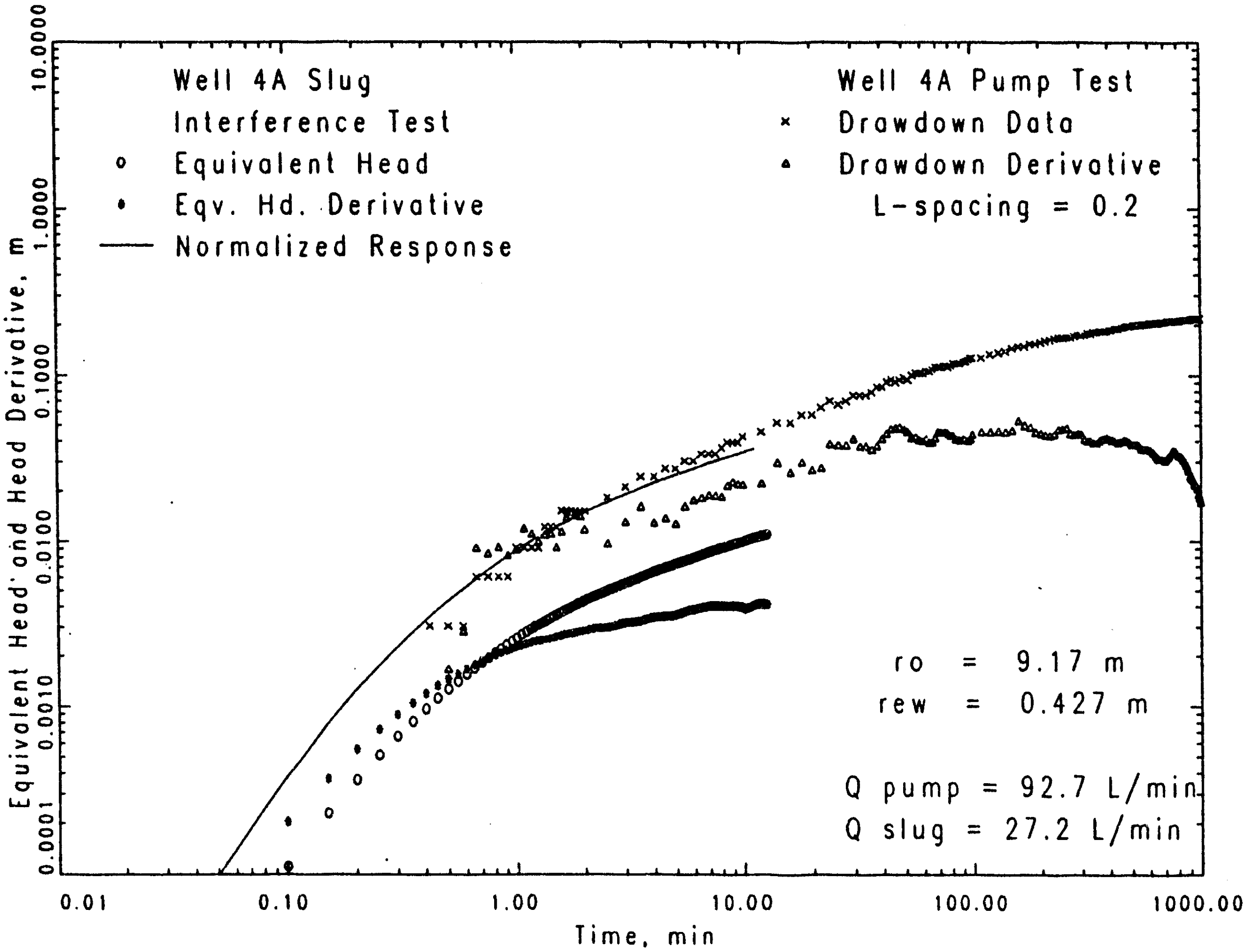


Figure 7 shows the resulting best-fit unconfined aquifer type curve match. Emphasis in the analysis was primarily placed on matching the observed response in the central portion (i.e., the "hump") of the slug interference response. Less emphasis was placed on matching late-time (i.e., ≥7 min), because of the extremely small (i.e., ≤0.0006 m) and somewhat erratic nature of the observed measurements. As indicated in Figure 7, a close match was obtained for most of the observed slug interference response. Results of the analysis indicate estimates for transmissivity and storativity of 242 m^2/d (2,600 ft^2/d) and 0.0005, respectively. A more qualitative estimate for vertical anisotropy (K_D) of 0.14 and for specific yield of 0.028 is also suggested. These results compare favorably with results obtained from the unconfined aquifer type-curve analyses presented in Sections 2.2 and 2.3.

3.2 SENSITIVITY ANALYSIS

Slug interference test response is a function of the applied stress, test well/aquifer relationships (i.e., well diameter, radial distance, aquifer thickness, well penetration characteristics), and test formation hydraulic properties (i.e., T, S, S_y, and K_D). If it is assumed that the applied stress and test well/aquifer relationships are known for the test, an infinite number of predictive response shapes are still possible. The number of predictive responses can be greatly reduced, however, if expected (common) bounds can be applied for some of the formation hydraulic properties. Limits used for slug interference type curves generated for the analysis of the well 4A test response included S_y = 0.005 to 0.4, S = 10^{-4} to 10^{-1}, K_D = 0.01 to 1.0, and T = 10^1 to 10^4 m^2/d (10^2 to 10^5 ft^2/d).

To examine the sensitivity of the predicted slug interference response to various hydraulic property combinations, individual type curves were generated by systematically varying selected parameter estimates. Figures 8 through 12 show the results of the sensitivity analysis. As expected, variation in the selected hydraulic property values causes significant changes in the shape and amplitude of the predicted slug interference response. The following general observations are provided that summarize the sensitivity of the predicted slug interference response to hydraulic property variation (i.e., given well 4A test site conditions).

- Transmissivity is the principal parameter controlling the transmission (i.e., arrival time) of the interference response (Figure 8).

- Storativity exerts a significant influence on the amplitude and shape of the initial slug interference "hump" (Figures 9 and 10).

- Wellbore storage effects dampen and delay transmission of the initial slug interference response observed (Figure 10).

Figure 7. Unconfined Aquifer Type-Curve Analysis for Slug Interference Test Response for Well 4A.

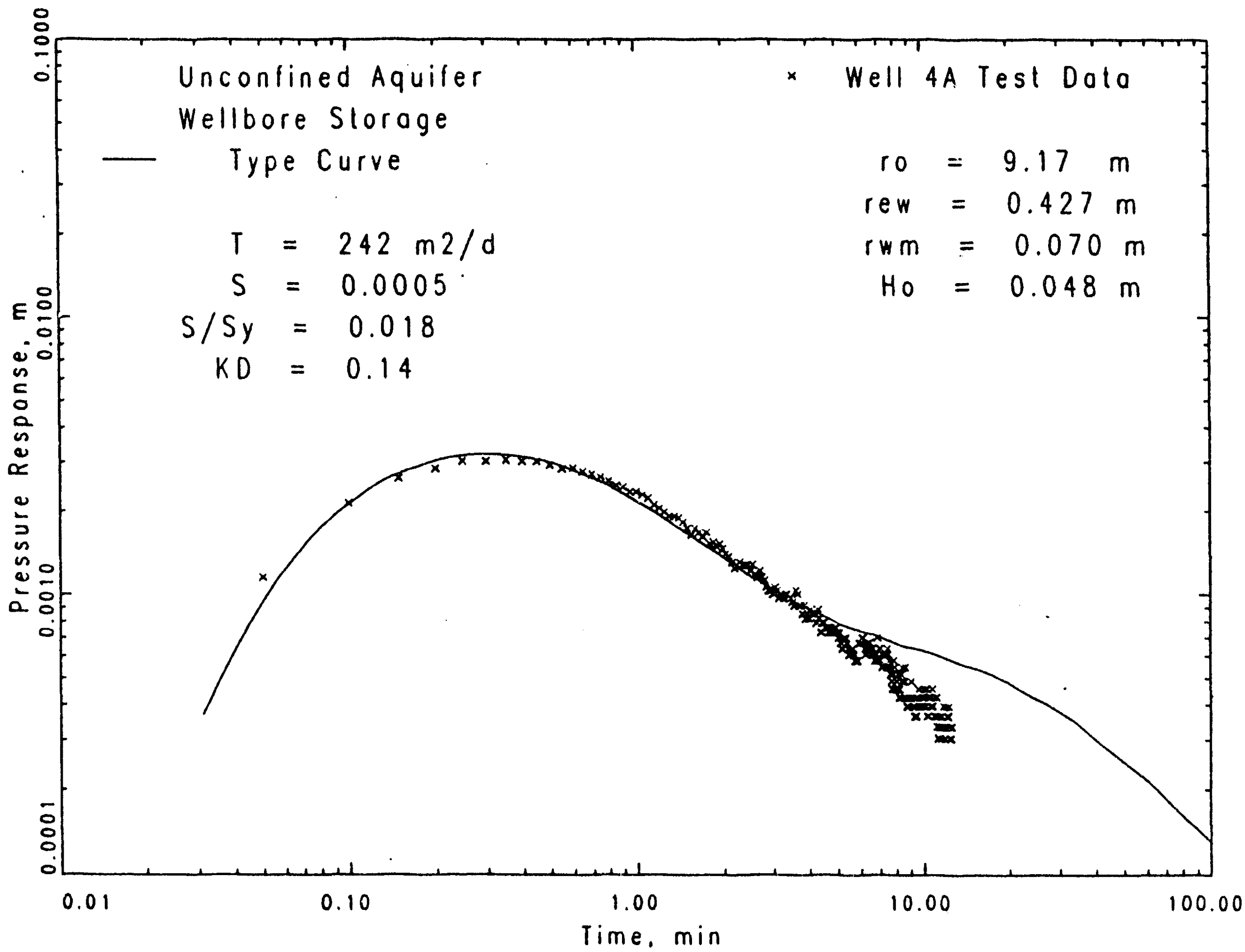


Figure 8. Sensitivity of Predicted Slug Interference Response for Well 4A to Varying Transmissivity (S = 0.0005, S/S_y = 0.018, K_D = 0.14).

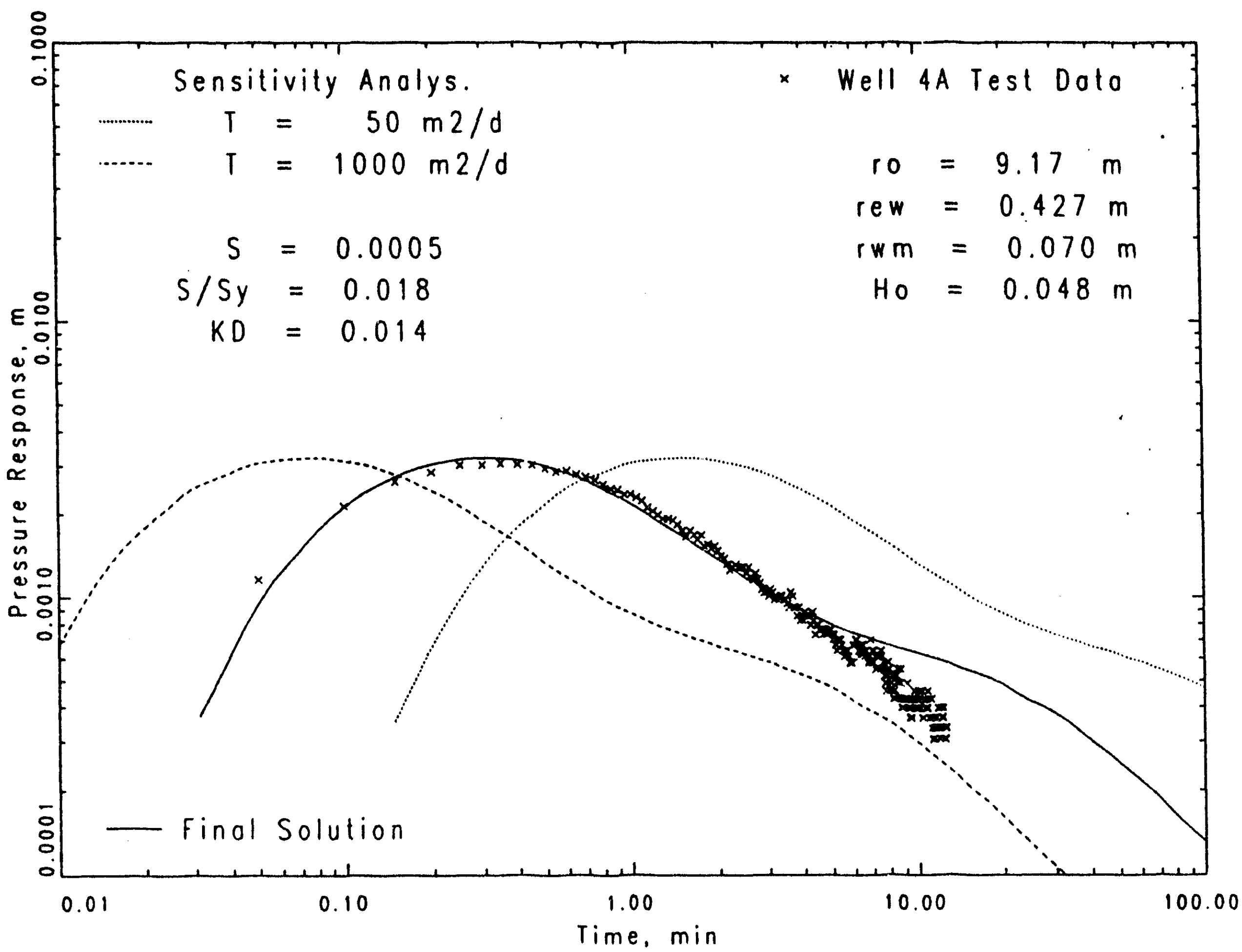


Figure 9. Sensitivity of Predicted Slug Interference Response for Well 4A to Varying Storativity (T = 242 m^2/d, S/S_y = 0.018, K_D = 0.14) (wellbore storage effects are included).

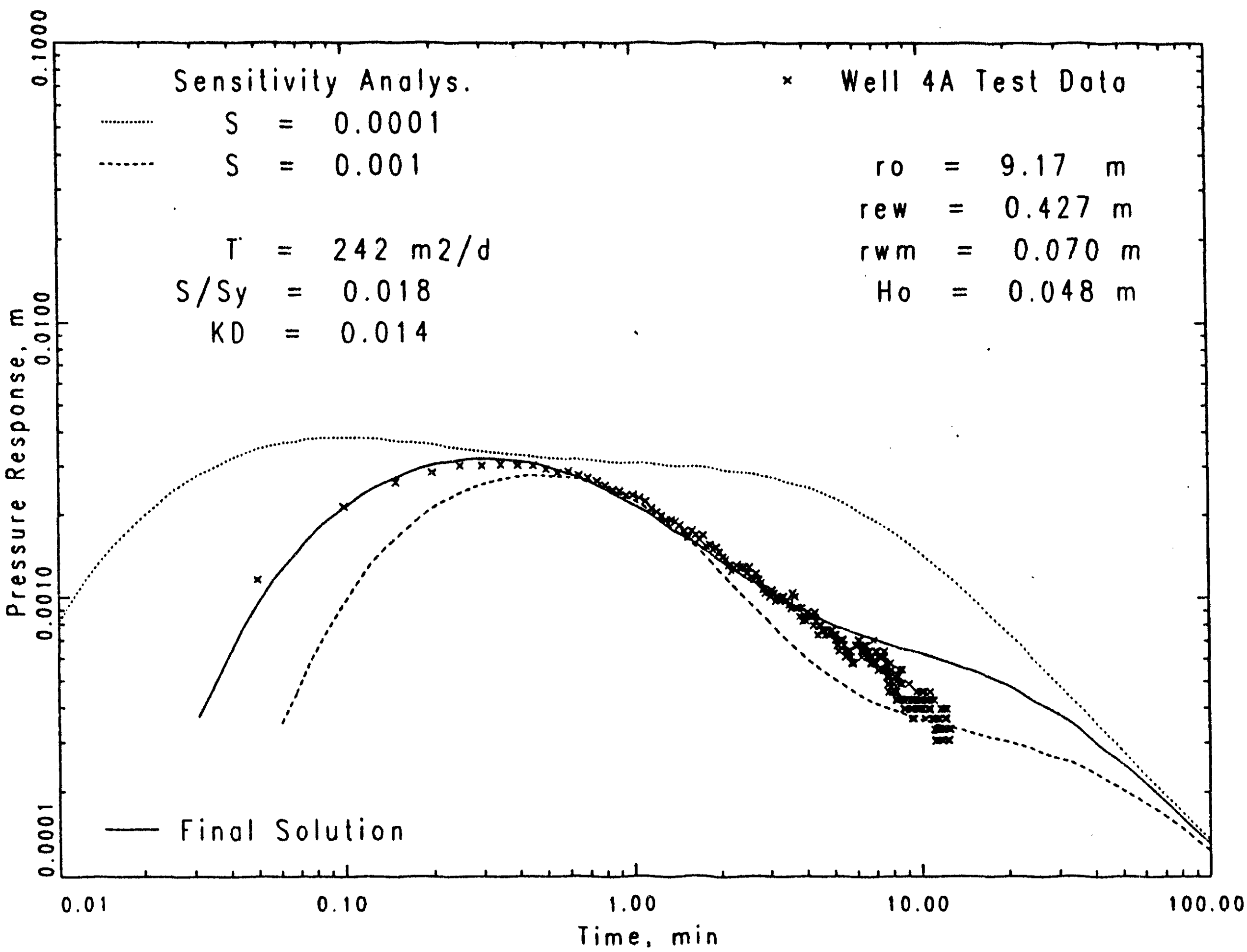


Figure 10. Sensitivity of Predicted Slug Interference Response for Well 4A to Wellbore Storage Effects ($T = 242\ m^2/d$, $S/S_y = 0.018$, $K_D = 0.14$).

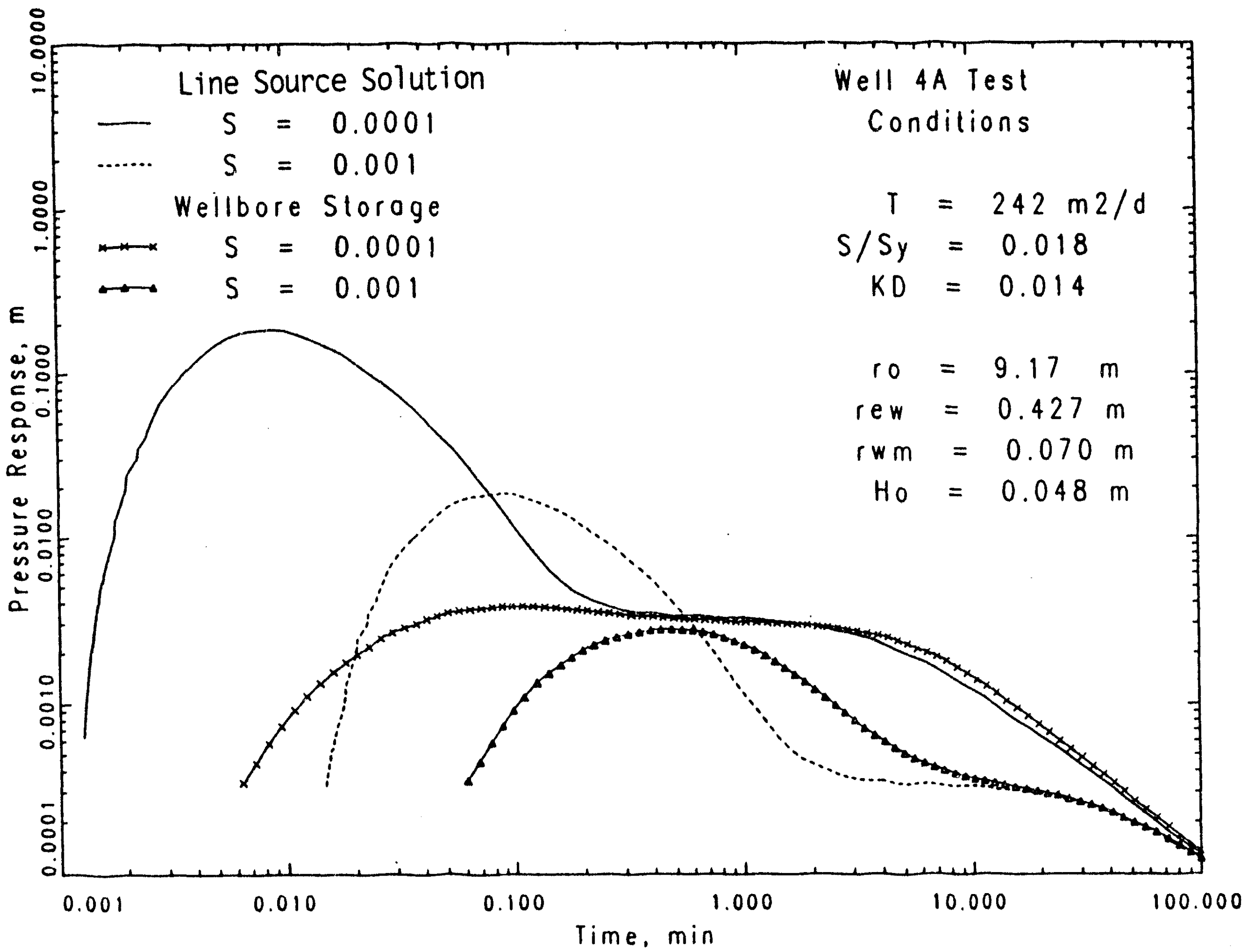


Figure 11. Sensitivity of Predicted Slug Interference Response for Well 4A to Varying S/S_y (T = 242 m^2/d, S = 0.0005, K_D = 0.14).

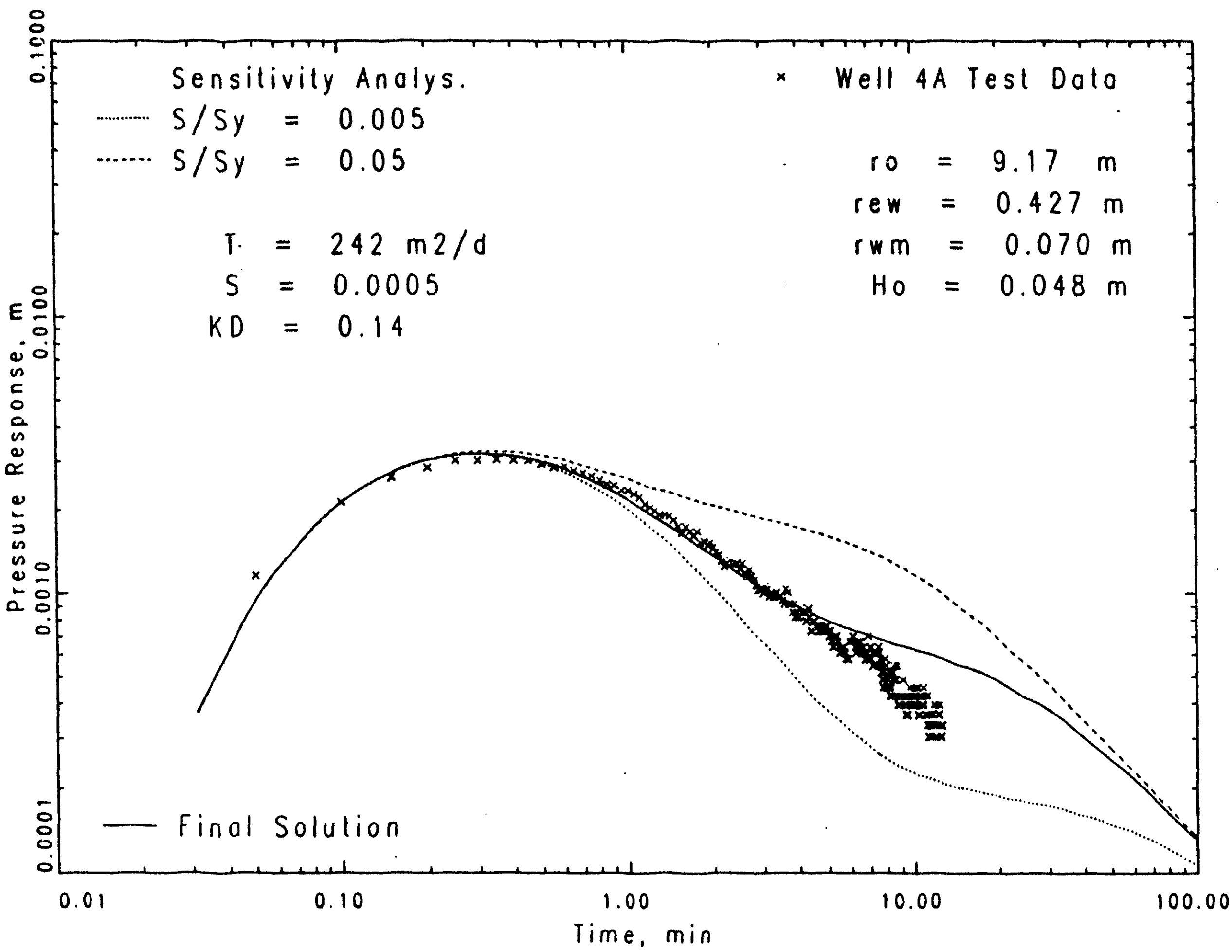
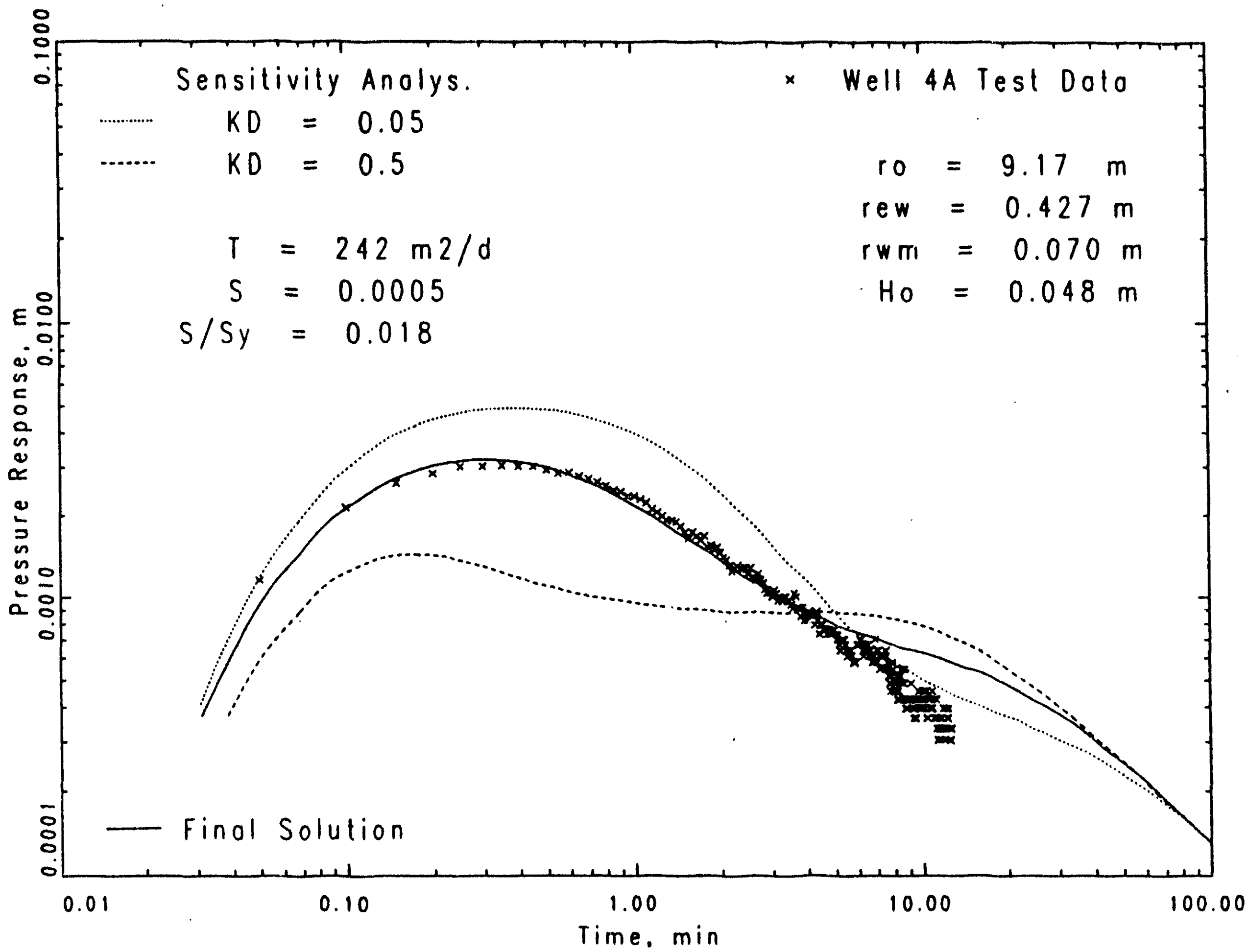


Figure 12. Sensitivity of Predicted Slug Interference Response for Well 4A to Varying K_D (T = 242 m^2/d, S = 0.0005, S/S_y = 0.018).



- The storativity/specific yield ratio affects primarily the slope of the recessional limb of the initial slug interference "hump" response (Figure 11).

- Vertical anisotropy, like storativity, exerts a significant influence on the amplitude and shape of the initial slug interference response (Figure 12); however, the predominant region of influence is the peak amplitude and recessional limb of the interference response.

4.0 SUMMARY

A general procedure is outlined for generation of slug interference test responses within anisotropic, unconfined aquifers with partially penetrating well configurations. The procedure is based on conversion of available unconfined aquifer constant-rate pumping test type curves, which have been modified to account for the affects of pumping well wellbore storage. Results of sensitivity analyses indicated that variations in T, S, S_y, K_D exert significant influence (in varying degrees) on the transmission, amplitude, and shape of the slug interference response.

A comparison of hydraulic property estimates obtained from the re-analysis of the constant-rate pumping and slug interference tests (shown in Table 1) indicates a close correspondence. The close correspondence in hydraulic property estimates suggests that slug interference tests can provide similar characterization results, under favorable test conditions.

Table 1. Comparison of Hydraulic Test Analysis Results for Well 4A.

Test analysis	Re-analysis results				Previous analysis results[a]			
	T m^2/d	S	S_y	K_D	T m^2/d	S	S_y	K_D
Constant-rate pumping test								
Type B curve analysis	254	NA	0.025	0.15	NA	NA	NA	NA
Complete unconfined aquifer curve analysis	254	0.001	0.025	0.10	269	0.0045	0.016	0.11
Slug interference test[b]	242	0.0005	0.028	0.14	763	NA	0.012	NA

[a]Previous analysis reported in Swanson (1992).
[b]Previous analysis based on the fully penetrating confined aquifer solution method presented in Novakowski (1990); re-analysis based on the partial penetration unconfined aquifer solution method presented in this document.
NA = not applicable.

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