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AN ASSESSMENT OF THE NGUYEN AND PINDER METHOD FOR SLUG TEST ANALYSIS

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ABSTRACT

The Nguyen and Pinder method is one of four techniques commonly used in the field for the analysis of response data from slug tests. Limited field research has raised questions about the reliability of the parameter estimates obtained using this method. A theoretical evaluation of this technique reveals that errors were made in the derivation of the analytical solution upon which the technique is based. Simulation and field examples show that the errors result in parameter estimates that can differ from actual values by orders of magnitude. These findings indicate that the Nguyen and Pinder method should no longer be a tool in the repertoire of the field hydrogeologist. If data from a slug test performed in a partially penetrating well in a confined aquifer need to be analyzed, the best currently available method is that of Hvorslev.

INTRODUCTION

At sites of suspected groundwater contamination, the slug test is often the preferred method for obtaining in-situ estimates of hydraulic conductivity. In addition to its clear logistical and economic advantages over alternative approaches such as pumping tests, the slug test can also provide useful information about spatial variations in flow properties. Such information about the degree of heterogeneity that exists at a site, which is quite difficult to obtain from conventional constant-rate pumping tests (e.g., Butler and Liu, 1993), can be very valuable for the prediction of contaminant movement and the design of remediation schemes.

Currently, most analyses of response data from slug tests are performed using one of four techniques. These techniques are 1) the method of Hvorslev (1951) for slug tests in fully and partially penetrating wells in confined aquifers, 2) the method of Bouwer and Rice (Bouwer and Rice, 1976; Bouwer, 1989) for slug tests in wells in unconfined aquifers screened below the water table, 3) the method of Cooper et al. (1967) for slug tests in fully penetrating wells in confined aquifers, and 4) the method of Nguyen and Pinder (1984) for slug tests in partially penetrating wells in confined aquifers. Note that the first two methods are based on approximate representations of the slug-induced flow system, while the latter two techniques utilize more complete descriptions of the relevant physics.

The focus of this article is on the Nguyen and Pinder method for slug-test analysis. At the time of its development, this method appeared to be the first rigorous approach for the analysis of response data from slug tests in partially penetrating wells in confined aquifers. Analytical solutions for slug tests in partially penetrating wells that have been developed since the introduction of this method (e.g., Dougherty and Babu, 1984; Hayashi et al., 1987) have not been widely adopted for parameter estimation, so the Nguyen and Pinder method is still considered the most appropriate approach for analysis of slug tests in partially penetrating wells in confined aquifers. Although used a moderate amount by field practitioners and currently taught in industry short courses on aquifer-test analysis (e.g., NGWA, 1993), the Nguyen and Pinder method has not undergone the same degree of theoretical and field evaluation as the other three commonly used approaches. The limited field research on the technique that has been reported has raised questions about the reliability of the parameter estimates (e.g., Nichols, 1985; Campbell et al., 1990; Brother and Christians, 1993). These researchers reported that the Nguyen and Pinder estimates of hydraulic conductivity were not consistent with those obtained using other approaches. Given that this method is currently being used in the field and that there are questions concerning the reliability of the estimated parameters, it is clear that a more thorough assessment of this approach is needed. Such an assessment is the primary objective of this paper.

In this paper, a complete theoretical evaluation of the Nguyen and Pinder method will be presented. This evaluation will demonstrate that the parameter estimates obtained using this method will be of very low quality due to errors in the derivation of the solution upon which the technique is based. A field evaluation will also be presented in order to substantiate the results of the theoretical assessment. This paper will conclude with recommendations concerning the field applicability of the technique and possible alternative approaches.

OVERVIEW OF NGUYEN AND PINDER MODEL

Model Definition

Although Nguyen and Pinder present a general mathematical model that can be employed for both pumping and slug tests, the focus of this work will be on the slug-test case. Therefore, the problem of interest here is that of the head response produced by the instantaneous introduction of a slug of water into the screened or open section of a well partially penetrating the confined aquifer shown in Figure 1. For the purposes of this development, the aquifer of Figure 1 is considered homogeneous and isotropic. The partial differential equation representing the flow of groundwater in response to an instantaneous introduction of a slug at a central well can be written as

$$\frac{\partial^2 s}{\partial r^2}+\frac{1}{r}\frac{\partial s}{\partial r}+\frac{\partial^2 s}{\partial z^2}=\left(\frac{S_s}{K}\right)\frac{\partial s}{\partial t} \qquad (1)$$

where

s = change in head relative to static, [L];

K = hydraulic conductivity, [L/T];

S_s = specific storage, [1/L];

t = time, [T];

r = radial direction, [L];

z = vertical direction, $z=0$ at the bottom of the aquifer and increases upward, [L].

Note that except for the designation of spatial and temporal derivatives the notation employed here will be that of Nguyen and Pinder.

The initial and boundary conditions are as follows:

$$s(r,z,0) = 0, \; r_s<r<\infty, \; 0\leq z\leq B \tag{2}$$

$$\frac{\partial s(r,0,t)}{\partial z} = \frac{\partial s(r,b,t)}{\partial z} = 0, \; r_s<r<\infty, \; t>0 \tag{3}$$

$$s(\infty,z,t) = 0, \; 0\leq z\leq B, \; t>0 \tag{4}$$

$$\frac{1}{(z_2-z_1)}\int_{z_1}^{z_2} s(r_s,z,t)\,dz = H(t), \; t>0 \tag{5}$$

$$2\pi r_s K \int_{z_1}^{z_2} \frac{\partial s(r_s,z,t)}{\partial r} dz = \pi r_c^2 \frac{dH(t)}{dt} \quad (6)$$

where

b = aquifer thickness, [L];

r_s = radius of well screen, [L];

r_c = radius of well casing, [L];

z_1 = distance from the bottom of the aquifer to the bottom of the screen, [L];

z_2 = distance from the bottom of the aquifer to the top of the screen, [L];

$z_2 - z_1$ = screen length, [L];

$H(t)$ = head in well relative to static, [L].

Although not explicitly stated, the following additional initial and boundary conditions are also employed in the later mathematical development:

$$H(0) = H_0 \quad (7)$$

$$\frac{\partial s(r_s,z,t)}{\partial r} = 0,\ 0<z<z_1,\ z_2<z<b,\ t>0 \quad (8)$$

where

H_0 = height of initial slug, [L].

Note that equation (6), which is the boundary condition at the well screen, is presented in an integral form. Most contributions in the well hydraulics literature concerned with the transient response of partially penetrating wells have assumed a constant hydraulic gradient within the well screen as a mathematical convenience (e.g., Hantush, 1964; Dougherty and Babu, 1984). The error that is introduced by this assumption has been shown to be very small for wells commonly employed in field applications (e.g., Butler et al., 1993). More importantly, this simplification allows a solution to be readily found, thus avoiding the problems that are discussed in the following section.

Model Solution

Equations (1)-(8) describe the flow conditions of interest to Nguyen and Pinder. These authors attempt to derive an analytical solution to this mathematical model using conventional integral transform methodology. The key points of this derivation are given in the Appendix. In summary, a Laplace transform in time followed by a finite Fourier cosine transform in the z direction produces a modified Bessel equation in Fourier-Laplace space. Transform-space analogues of boundary conditions (4) and (6) are then employed to evaluate the equation constants. The basic problem with the Nguyen and Pinder method for slug-test analysis is that equation (6) is undefined (i.e. cannot be written in terms of the dependent variable) in Fourier-Laplace space. As shown in the Appendix, the authors attempt to circumvent this problem by performing an inverse Fourier transform prior to evaluation of one of the constants. This step introduces an error that causes the remainder of the mathematical manipulations described by Nguyen and Pinder to be incorrect.

The problems produced by the undefined boundary condition do not allow Nguyen and Pinder to present a solution in the conventional sense. All of their equations are given in terms of the deviation from static being a function of the temporal derivative of this same deviation. However, they are able to manipulate these equations to obtain expressions for use in estimation of specific storage and hydraulic conductivity. Their expressions for parameter estimation are

$$S_s = \frac{r_c^2 C_3}{r_s^2 (z_2 - z_1)} \tag{9}$$

$$K = \frac{r_c^2 C_3}{4 C_4 (z_2 - z_1)} \tag{10}$$

where

C_3 = the absolute value of the slope of a log-log H(t) versus t plot;

C_4 = the absolute value of the slope of a semilog -dH(t)/dt versus 1/t plot.

The estimation procedure proposed by the authors is quite straightforward. The slope of a log-log H(t) versus time plot is used to estimate specific storage from equation (9). That slope along with the slope of a semilog -dH(t)/dt versus 1/t plot is then used to estimate hydraulic conductivity with equation (10). In the field example presented by Nguyen and Pinder a straight line is fit to the large-time data and the early-time data are ignored. Unfortunately, because of the errors in the model derivation, the estimates produced by the procedure outlined above must be viewed with considerable skepticism.

Ramifications of Model Error

Nichols (1985) shows that there is a theoretical inconsistency in equation (9). A slightly augmented version of his analysis is briefly given here.

If C_3 is the absolute value of the slope of the log-log H(t) versus time plot, then the following equation can be written:

$$\ln(H(t)) = -C_3 \ln(t) + \ln(A) \tag{11}$$

where

A = arbitrary constant.

Equation (11) can be rewritten as

$$H(t) = At^{-C_3} \tag{12}$$

which, after substituting for C_3 using equation (9), produces the following expression for the head in the well:

$$H(t) = At^{-\frac{(r_s^2(z_2-z_1)S_s)}{r_c^2}} \qquad (13)$$

Equation (13) states that the head in the well is independent of hydraulic conductivity. This implies that two aquifers having the same specific storage but differing in hydraulic conductivity will have the same response to the instantaneous introduction of a slug. This is clearly incorrect. Note that equation (13) also states that the head in the well is equal to the static head at t=0. This also is incorrect as it is in conflict with the initial condition given in equation (7), which states that the head in the well will equal H_0 at t=0. Thus, the model error produces theoretical inconsistencies in the expressions used for parameter estimation. Note that an analogous approach could also be used to demonstrate theoretical inconsistencies arising from equation (10).

In order to explore the ramifications of the model error for parameter estimation, a simple numerical experiment was performed in which a slug test in a partially penetrating well in a confined aquifer was simulated using a semianalytical solution. Parameter estimates were then computed from the simulated response data using equations (9) and (10) and compared to the original parameter values employed in the semianalytical solution. In this work, the semianalytical solution of Hyder et al. (in review), which has been extensively checked using both analytical and numerical approaches, was employed for the simulation of the slug test. The aquifer and well-construction parameters given in Table 1 were used for this simulation. A well of a small aspect ratio (screen length/well radius) was employed in order to accentuate the partially penetrating nature of the well. Figure 2a displays a log-log H(t) versus time plot of the simulated responses. Note that straight lines have been fit to the steepest (late time) and flattest (early time) portions of the plot in order to bound the specific storage estimates that might be obtained using equation (9). Specific storage estimates of .007433 ft^{-1} and 3.644 ft^{-1} were obtained using the early and late time slopes, respectively. Note that the estimate obtained from the late time slope, which is the slope used by Nguyen and Pinder in their example, lies outside the range of physical plausibility.

A semilog -dH(t)/dt versus 1/t plot of the simulated responses is given in Figure 2b. Again, straight lines have been fit to the steepest (late time) and flattest (early time) portions of the plot in order to bound the hydraulic conductivity estimates that might be obtained using equation (10). Note that four separate estimates of hydraulic conductivity can be obtained from combinations of the specific storages estimated from Figure 2a using equation (9) and the two slope choices on Figure 2b. Table 2 lists the parameter estimates obtained using the various approaches. Based on the procedure outlined by Nguyen and Pinder, the most appropriate conductivity value would be 1.20 ft/d, which is 42% of the hydraulic conductivity employed in the semianalytical solution. However, given the lack of a clear cut slope on Figure 2b, the fact that a physically implausible storage estimate was employed for the conductivity estimate, and the considerable spread of estimates shown on Table 2, it is apparent that the closeness of the conductivity estimate to the actual value is simply a function of chance.

This numerical experiment clearly shows that the estimates obtained using equations (9) and (10) can be quite different from the actual parameter values. The results of this experiment coupled with the theoretical inconsistencies discussed previously indicate that the ramifications of the model error are quite severe.

FIELD EVALUATION

The theoretical findings of the previous section can be substantiated using field data. Recently, a program of well testing has been carried out by the Kansas Geological Survey as part of a regional study of the Dakota aquifer in Kansas. At one site in Lincoln County, Kansas, two wells (.333 ft and .167 ft in diameter (r_c), r_s=2r_c), screened over similar intervals, are located 21.2 feet apart. A series of slug tests were carried out in order to obtain estimates of both the hydraulic conductivity and specific storage of the Dakota aquifer at this site. These tests consisted of introducing a slug at the larger of the two wells and measuring the responses both at the test well and at the observation well. Measurements from the observation well were taken using a transducer placed below a packer located just above the top of the screen. The packer enabled effects associated with wellbore storage at the observation well to be kept very small. Note that an observation well was employed in these tests as a result of the theoretical work of McElwee et al. (1991) that shows that use of observation wells with slug tests can greatly improve the reliability of the parameter estimates.

The response data were analyzed using an augmented version of the method of Cooper et al. (1967) that allows inclusion of observations from points other than the test well. Plots of the measured data and the best-fit Cooper et al. model for both the test and observation wells are given in Figure 3. The small difference between the measured data and the best-fit model in conjunction with the results of the theoretical work of McElwee et al. (1991) indicates that the reliability of the parameter estimates (given in Table 3) is quite good. The model fitting, which was done using an automated well-test analysis package developed at the Kansas Geological Survey (Bohling and McElwee, 1992), also produces approximate confidence intervals for the estimated parameters. Those confidence intervals are given in Table 3.

Figure 4a presents the log-log normalized head versus time plot of the data from the test well. As with Figure 2a, straight lines have been fit to the steepest (late time) and flattest (early time) portions of the plot in order to bound the specific storage estimates that might be obtained using equation (9). Table 4 lists the two specific storage estimates. The specific storage estimate obtained using the late-time straight line (.0218 ft^{-1}) is close to four orders of magnitude larger than the specific storage estimated from the Cooper et al. analysis.

Figure 4b displays the semilog normalized -dH(t)/dt versus 1/t plot of the data. Again, straight lines have been fit to the steepest (late time) and flattest (early time) portions of the plot in order to bound the hydraulic conductivity estimates that might be obtained using equation (10). Note that, as with the numerical example, four separate estimates of hydraulic conductivity can be obtained from combinations of the specific storages estimated from Figure 4a using equation (9) and the two slope choices on Figure 4b. Table 4 lists the parameter estimates obtained using the various approaches. Based on the procedure outlined by Nguyen and Pinder, the most appropriate conductivity value would be .039 ft/d, which is about two orders of magnitude smaller than the hydraulic conductivity estimated using the Cooper et al. solution.

SUMMARY AND CONCLUSIONS

A theoretical and field evaluation of the Nguyen and Pinder method for the analysis of response data from slug tests in partially penetrating wells in confined aquifers was presented here. The major results of this evaluation are as follows:

1) The Nguyen and Pinder method is not on a firm theoretical foundation as a result of the use of a boundary condition that is undefined in the transform space in which a solution was proposed. An attempt to circumvent this undefined boundary condition introduces further error that propagates into the expressions used

for parameter estimation;

2) The errors in the theoretical development produce parameter estimates that may differ from the actual parameter values by orders of magnitude. The limited assessment done here indicates that the specific storage estimates tend to be too high while the hydraulic conductivity estimates are spread over a wide range.

The major conclusion of this evaluation is that the Nguyen and Pinder method should not be used for slug-test analysis. If response data from a slug test performed in a partially penetrating well in a confined aquifer are to be analyzed, the best approach would be to use one of the existing analytical solutions that consider variants of this configuration (e.g., Dougherty and Babu, 1984; Hayashi et al., 1987; Hyder et al., in review). Since these solutions are not widely available, the next best approach would be to employ the model of Hvorslev (1951). Recent work (Hyder et al., in review) has shown that the Hvorslev method should produce very reasonable approximations of hydraulic conductivity for the same conditions covered by the Nguyen and Pinder method. The Hvorslev method, however, is not a panacea and must be used with care in cases of high specific storage, low-permeability well skins, and anisotropy (Chirlin, 1989; Demir and Narasimhan, in press; Hyder et al., in review).

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APPENDIX

In this section, a brief overview of the mathematical derivation of the solution discussed in the main text is presented. The equation numbering will be the same as that given in Appendix A of Nguyen and Pinder (1984). The only difference between the equations given here and those of Nguyen and Pinder will be the notation used for derivatives and constants, and the neglecting of their pumping-rate term (Q).

Equations (1)-(8) in the main text constitute the mathematical model of interest here. Nguyen and Pinder attempt to find a solution to this model by employing classical integral transform techniques (Churchill, 1972). Using initial conditions (2) and (7), the authors apply the Laplace transform to equations (1) and (3)-(6) to produce the following set of equations in Laplace space:

$$\frac{\partial^2 \overline{s}}{\partial r^2} + \frac{1}{r}\frac{\partial \overline{s}}{\partial r} + \frac{\partial^2 \overline{s}}{\partial z^2} = \left(\frac{S_s}{K}\right) p\overline{s} \qquad \textbf{(A1)}$$

$$\frac{\partial \overline{s}(r,0)}{\partial z} = \frac{\partial \overline{s}(r,b)}{\partial z} = 0 \qquad \textbf{(A2)}$$

$$\overline{s}(\infty,z) = 0 \qquad \textbf{(A3)}$$

$$\frac{1}{(z_2-z_1)}\int_{z_1}^{z_2}\overline{s}(r_s,z)\,dz = \overline{H} \tag{A4}$$

$$2\pi r_s K\int_{z_1}^{z_2}\frac{\partial\overline{s}(r_s,z)}{\partial r}dz = \pi r_c^2(p\overline{H}-H_0) \tag{A5}$$

where

$\overline{s}$, $\overline{H}$ = the Laplace transform of s and H(t), respectively;

p = the Laplace transform variable.

Using the no-flow boundary condition given in (A2), the authors then apply a finite Fourier cosine transform in the z direction to equations (A1) and (A3) to produce the following equations in Fourier-Laplace space:

$$\frac{\partial^2\overline{s_c}}{\partial r^2}+\frac{1}{r}\frac{\partial\overline{s_c}}{\partial r}-\left(\frac{S_s}{K}p+\left(\frac{\pi n}{b}\right)^2\right)\overline{s_c} = 0 \tag{A6}$$

$$\overline{s_c}(\infty) = 0 \tag{A7}$$

where

$\overline{s_c}$ = the Fourier-Laplace transform of s;

n = the Fourier-transform variable.

Note that the authors do not apply a Fourier transform to the well-bore flow condition given by equation (A5) because this condition is undefined in Fourier-Laplace space, i.e. the application of a finite Fourier cosine transform to (A5) will not produce an expression in terms of $\overline{s_c}$.

The Fourier-Laplace solution to (A6) is quite straightforward, as (A6) is simply a form of the modified Bessel equation (Haberman, 1987). The solution can be written as

$$\overline{s_c}(r) = A_{1n}I_0(\alpha_n r) + A_{2n}K_0(\alpha_n r) \qquad \textbf{(A8)}$$

where

$$\alpha_n^2 = \frac{S_s}{K}p + \left(\frac{\pi n}{b}\right)^2, \ n=0,1,2,...$$

A_{1n}, A_{2n} = constants;

I_0 = modified Bessel function of the first kind of order 0;

K_0 = modified Bessel function of the second kind of order 0.

Note that the equation constants are a function of n and p.

The standard procedure for the evaluation of the constants in an equation such as (A8) is to employ the boundary conditions. Application of (A7), the boundary condition at an infinite radial distance from the well, to (A8) results in constant A_{1n} being equal to 0 for all n. Thus, (A8) is reduced to

$$\overline{s_c}(r) = A_{2n}K_0(\alpha_n r) \qquad \textbf{(A9)}$$

At this point, the authors face a problem because the boundary condition at $r=r_s$ is undefined in Fourier-Laplace space. Rather than redefining the wellbore boundary condition into a form that yields an expression in terms of $\bar{s}_c$, the authors incorrectly attempt to circumvent this problem by applying an inverse finite Fourier cosine transform to (A9) prior to evaluation of the constant. The expression that the authors give for the inverse finite Fourier cosine transform is

$$\bar{s}(r,z) = \frac{A_{2n}}{b}[K_0(\alpha_0 r) + 2\sum_{n=1}^{\infty} K_0(\alpha_n r)\cos(\frac{n\pi z}{b})] \qquad \textbf{(A10)}$$

Note that the constant A_{2n}, which is a function of n, has been taken out of the infinite series summation. Although moving A_{2n} out of the infinite series summation greatly simplifies the problem and allows the constant to be readily evaluated, this manipulation is mathematically incorrect and introduces further error into the proposed solution. Thus, even though the remaining manipulations outlined by the authors in their Appendix A are performed without error, the errors described above make all remaining expressions derived by the authors, including the expressions for parameter estimation, incorrect and, therefore, of little practical value.

In summary, the derivation of Nguyen and Pinder has two interrelated problems. First, the boundary condition at the well screen is undefined in the transform space in which the authors propose a solution to their mathematical model. Second, an attempt to circumvent this problem through an application of an inverse Fourier transform is in error because a constant coefficient in Fourier-Laplace space is assumed to be independent of n. The theoretical and practical ramifications of these two problems are discussed in the main text.

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TABLE 1 - PARAMETER SET FOR SLUG TEST SIMULATION

$K = 2.83$ ft/day
$S_s = 3.05e{-6}\ ft^{-1}$
$r_w = r_c = .082$ ft
$z_2 - z_1 = .82$ ft
$b = 52.5$ ft
$H_0 = 1.0$ ft
$z_1 = 25.84$ ft

TABLE 2 - NGUYEN AND PINDER ESTIMATES FROM SIMULATED SLUG TEST

Parameter Estimates	Slopes Employed in Calculation
S_s = .007433 ft^{-1}	C_{31}
S_s = 3.644 ft^{-1}	C_{32}
K = .00245 ft/day	C_{31}, C_{41}
K = 12.8 ft/day	C_{31}, C_{42}
K = 1.20 ft/day	C_{32}, C_{41}
K = 630. ft/day	C_{32}, C_{42}

TABLE 3 - COOPER ET AL. ESTIMATES FROM LINCOLN COUNTY SLUG TEST

	Estimated Value[a]	Lower Bound[b]	Upper Bound[b]
K	3.81 ft/day	3.79 ft/day	3.83 ft/day
S_s	2.85e-6 ft^{-1}	2.78e-6 ft^{-1}	2.91e-6 ft^{-1}

[a] Root-mean-squared deviation of .0035 ft. Well screened for 20 ft.

[b] Lower and upper bounds represent approximate 95% confidence intervals.

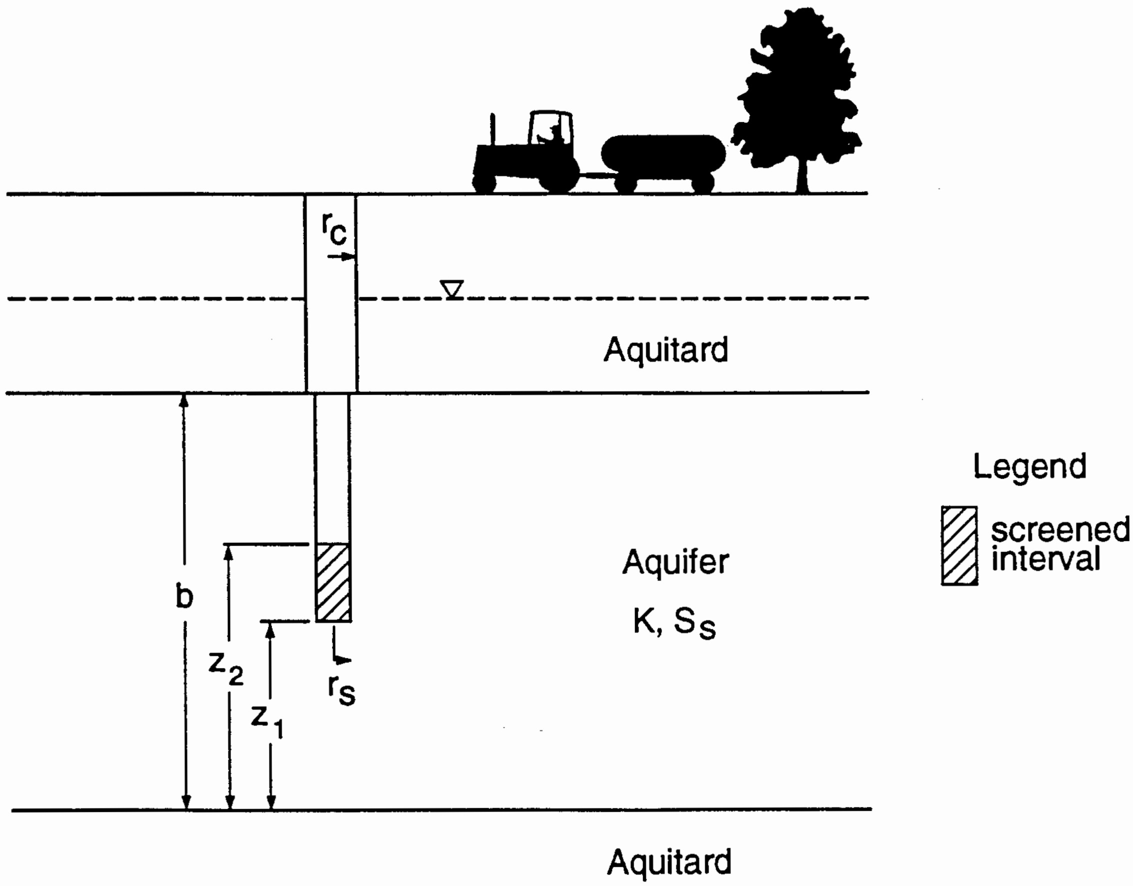


Figure 1 - Cross-sectional view of a hypothetical confined aquifer (notation explained in text).

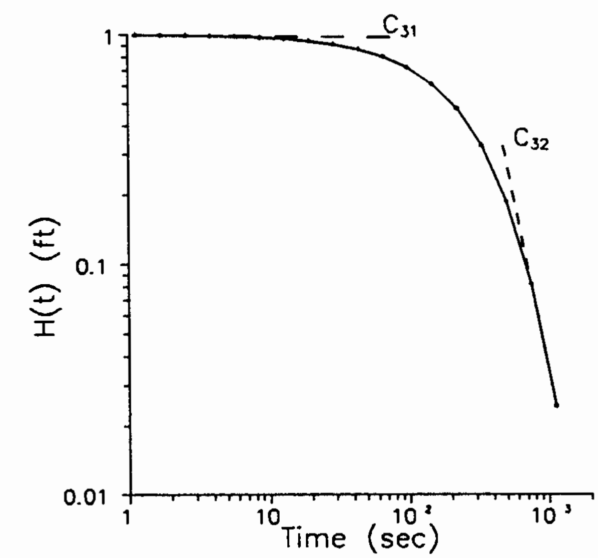
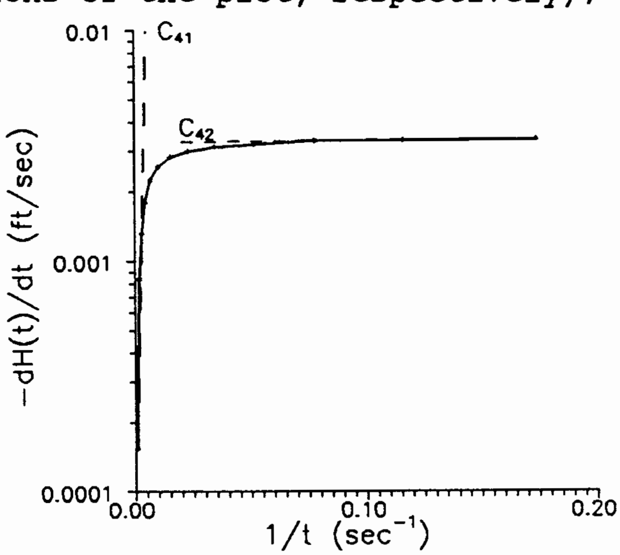


Figure 2 - Nguyen and Pinder data plots for simulated slug test: a) Log-log H(t) versus time plot (C_{31} and C_{32} designate the absolute values of the slopes of straight lines fit to the early and late-time portions of the plot, respectively);



b) Semilog negative head derivative (-dH(t)/dt) versus inverse time plot (C_{41} and C_{42} designate the absolute values of the slopes of straight lines fit to the small and large inverse time portions of the plot, respectively).

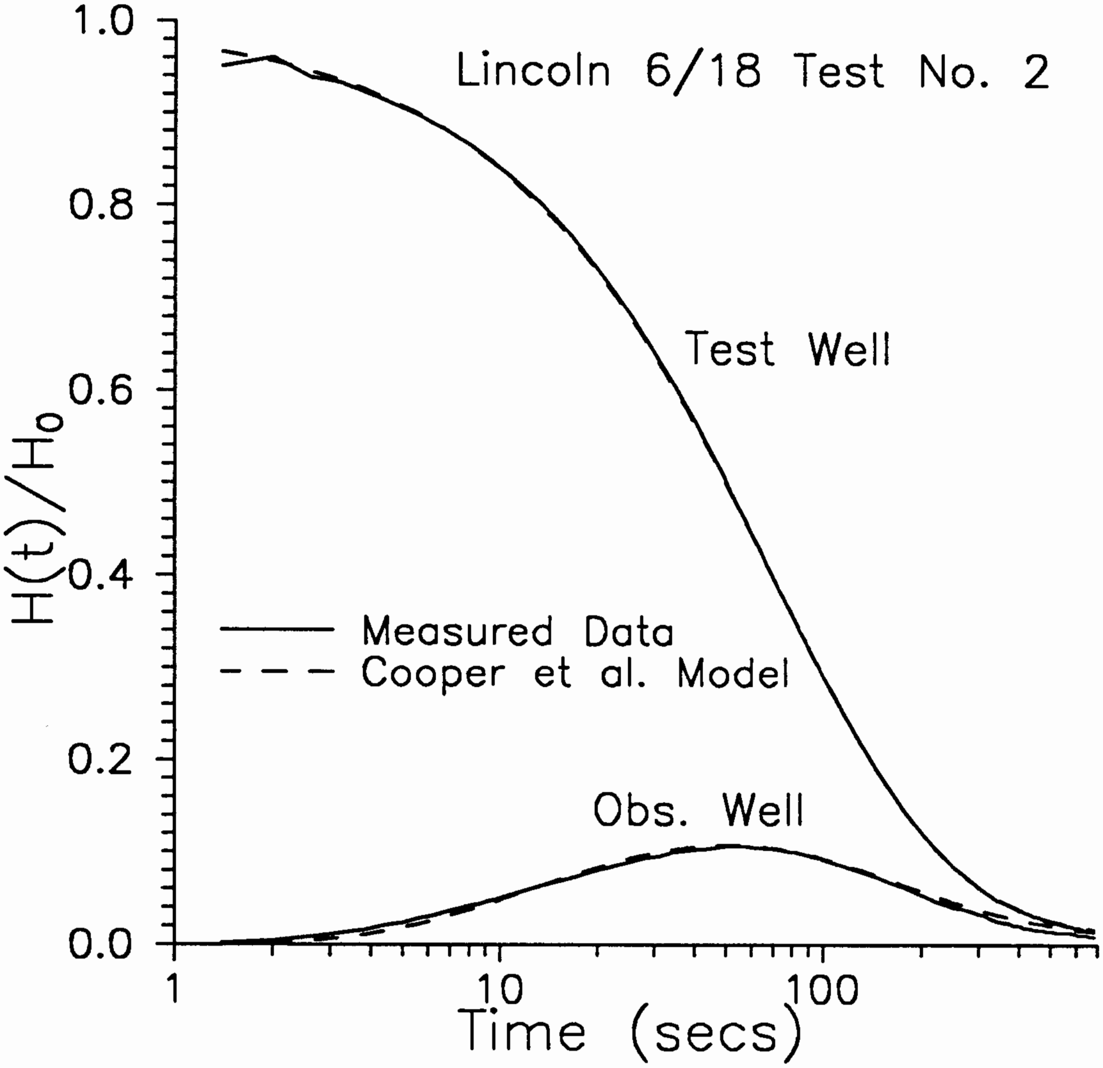


Figure 3 - Semilog normalized head ($H(t)/H_0$) versus time plot of Lincoln County slug-test data and best-fit Cooper et al. model.

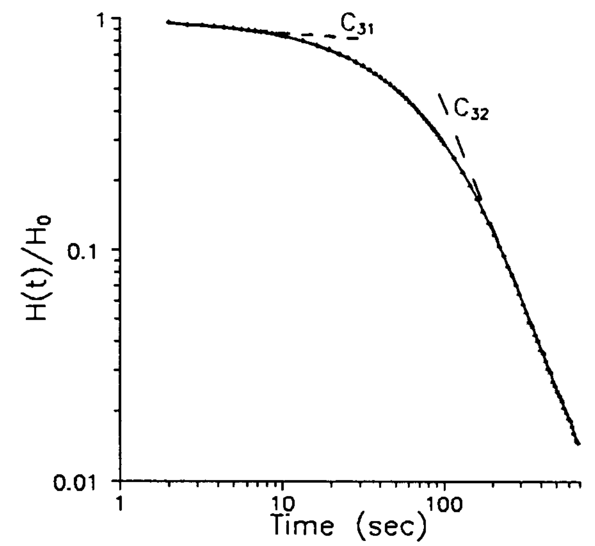
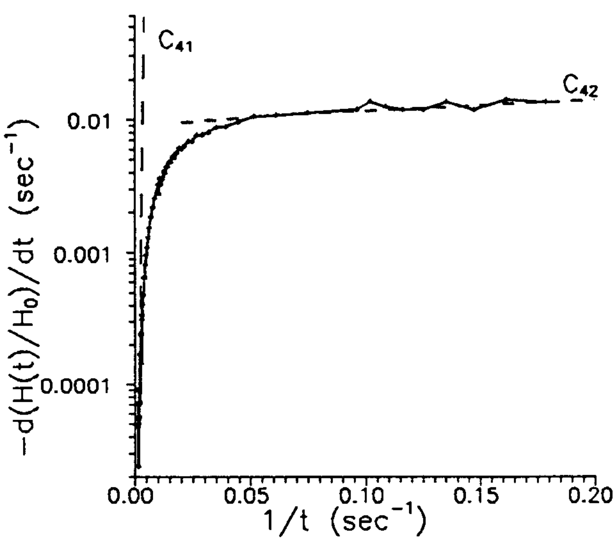


Figure 4 - Nguyen and Pinder data plots for Lincoln County slug test: a) Log-log normalized head ($H(t)/H_0$) versus time plot (C_{31} and C_{32} designate the absolute values of the slopes of straight lines fit to the early and late-time portions of the plot, respectively);



b) Semilog negative normalized head derivative ($-d(H(t)/H_0)/dt$) versus inverse time plot (C_{41} and C_{42} designate the absolute values of the slopes of straight lines fit to the small and large inverse time portions of the plot, respectively).

TABLE 4 - NGUYEN AND PINDER ESTIMATES FROM LINCOLN COUNTY SLUG TEST

Parameter Estimates	Slopes Employed in Calculation
S_s = .000595 ft^{-1}	C_{31}
S_s = .0218 ft^{-1}	C_{32}
K = .00107 ft/day	C_{31}, C_{41}
K = 1.58 ft/day	C_{31}, C_{42}
K = .0393 ft/day	C_{32}, C_{41}
K = 58.0 ft/day	C_{32}, C_{42}