

# Analysis of Slug Tests in Formations of High Hydraulic Conductivity

by James J. Butler Jr.<sup>1,3</sup>, Elizabeth J. Garnett<sup>2</sup>, and John M. Healey<sup>1</sup>

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## Abstract

A new procedure is presented for the analysis of slug tests performed in partially penetrating wells in formations of high hydraulic conductivity. This approach is a simple, spreadsheet-based implementation of existing models that can be used for analysis of tests from confined or unconfined aquifers. Field examples of tests exhibiting oscillatory and nonoscillatory behavior are used to illustrate the procedure and to compare results with estimates obtained using alternative approaches. The procedure is considerably simpler than recently proposed methods for this hydrogeologic setting. Although the simplifications required by the approach can introduce error into hydraulic-conductivity estimates, this additional error becomes negligible when appropriate measures are taken in the field. These measures are summarized in a set of practical field guidelines for slug tests in highly permeable aquifers.

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## Introduction

Slug tests in formations of high hydraulic conductivity ( $K$ ) are often affected by mechanisms that are not considered in models for tests in less permeable formations (Hvorslev 1951; Cooper et al. 1967; Bouwer and Rice 1976). Although a number of specialized models have been developed for slug tests in this hydrogeologic setting (Van der Kamp 1976; Kipp 1985; Springer and Gelhar 1991; McElwee and Zenner 1998; Zurbuchen et al. 2002), there is still no consensus regarding the analysis of tests in partially penetrating wells, the most common condition faced in practice. The result is that inappropriate methods are often used for the analysis of such tests, thereby introducing error into  $K$  estimates. In addition, published field guidelines for slug tests in highly permeable formations are incomplete, so many tests are performed in a manner that, at best, significantly increases the complexity of the analysis process and, at worst, yields  $K$  estimates of low reliability. The purpose of this paper is to present new analysis and field procedures that should help resolve these problems.

The major focus of this paper will be on the presentation of a new procedure for the analysis of slug tests per-

formed in partially penetrating wells in highly permeable formations. This procedure is considerably simpler than recently proposed alternatives, and can be used for tests in both confined and unconfined aquifers. However, the effectiveness of the method strongly depends on the use of appropriate measures in the field. An additional focus of this paper, therefore, is the definition of field guidelines for slug tests in highly permeable systems. If these guidelines are used in conjunction with the more general guidelines previously proposed by Butler et al. (1996) and Butler (1998), the analysis method presented here will yield hydraulic-conductivity estimates that, for all practical purposes, are indistinguishable from those obtained using considerably more involved approaches.

The procedure described in this paper is a spreadsheet implementation of a modification of the analysis approach proposed by Butler (1998) for slug tests in highly permeable aquifers. This procedure is based on models previously described by Springer and Gelhar (1991) and Butler (1998) for tests in unconfined and confined formations, respectively. These two models are straightforward extensions of those of Bouwer and Rice (1976) and Hvorslev (1951) to slug tests in highly permeable aquifers and are therefore designated in this article as the high- $K$  Bouwer and Rice and high- $K$  Hvorslev models, respectively, to emphasize their relationship to those earlier models. The spreadsheet method described here was devised to make the proposed analysis procedure more accessible to the field practitioner. Although spreadsheet implementations of the Van der

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<sup>1</sup>Kansas Geological Survey, 1930 Constant Ave., Campus West, University of Kansas, Lawrence, KS 66047

<sup>2</sup>Department of Geology, University of Kansas, Lawrence, KS 66045

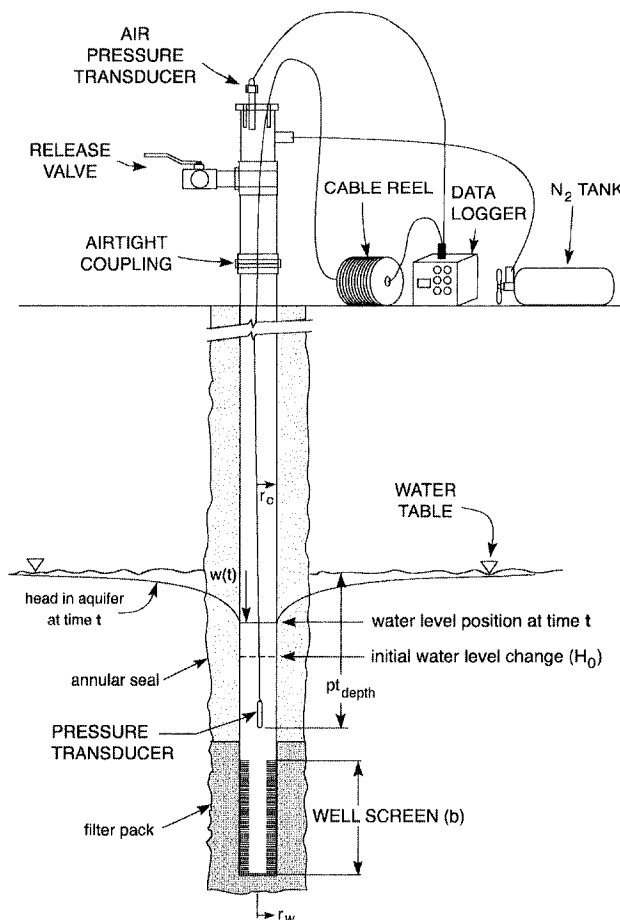
<sup>3</sup>Corresponding author: (785) 864-2116; jbutler@kgs.ku.edu  
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Kamp and Kipp methods for slug tests in fully penetrating wells are available (Wylie and Magnuson 1995; Weight and Wittman 1999), simple spreadsheet approaches for analysis of tests in partially penetrating wells have not been presented previously.

This paper begins with a general overview of the analysis procedure, followed by a description of the spreadsheet implementation of the approach. Two field examples are then presented to demonstrate the method for the analysis of both oscillatory and nonoscillatory response data. Field measures required to ensure that the underlying assumptions of the approach can be justified are then described. The paper concludes with a brief summary of the major points. All of the files needed to implement the procedure are included in a Kansas Geological Survey (KGS) report (Butler and Garnett 2000) that can be readily obtained from the KGS Web site ([www.kgs.ku.edu](http://www.kgs.ku.edu)).

## General Overview of Analysis Procedure

Regardless of whether a slug test has been performed in an unconfined or confined aquifer, the general approach for the processing and analysis of data from a test in a highly permeable formation is the same. This approach consists of the following four steps (see Figure 1 for a schematic of the setup for a test performed in a highly permeable aquifer):



**Figure 1. Schematic of a well in which the pneumatic method is being used for slug-test initiation (after McLane et al. 1990; Butler 1998; notation explained in text; not to scale).**

**1. Test data are processed into the form required for analysis.** The processing begins by plotting pressure transducer readings versus the time since some arbitrary starting point (Figure 2a). The time at which the test began and the pressure head corresponding to static conditions are estimated from this plot. The static pressure head and the test start time are then subtracted from the head and time records, respectively, to obtain a plot of the deviation of the pressure head from static conditions ( $H(t)$ ) versus the time since test initiation (Figure 2b). The deviation data are divided by the change in water level that initiated the test ( $H_0$ ) to obtain the normalized head required for the analysis (Figure 2c). For tests performed using the pneumatic method (Figure 1), this initial water-level change is best estimated using the air-pressure transducer.

### 2. A graph of theoretical type curves is prepared.

These type curves are in the form of plots of the normalized deviation of the water level from static conditions versus dimensionless time (Figure 3). The same set of type curves is used for analysis of tests in unconfined and confined aquifers. The type curves are generated using the damped spring solution of classical physics (Kreyszig 1979):

$$w_d(t_d) = e^{-\frac{C_D}{2} t_d} \left[ \cos(\omega_d t_d) + \frac{C_D}{2\omega_d} \sin(\omega_d t_d) \right], C_D < 2 \quad (1)$$

$$w_d(t_d) = e^{-t_d} (1 + t_d), C_D = 2 \quad (2)$$

$$w_d(t_d) = \left( \frac{1}{\beta_1 - \beta_2} \right) [\beta_1 e^{\beta_2 t_d} - \beta_2 e^{\beta_1 t_d}], C_D > 2 \quad (3)$$

where

$C_D$  = dimensionless damping parameter

$g$  = gravitational acceleration

$H_0$  = change in water level initiating a slug test (initial displacement)

$L_e$  = effective length of water column in well

$t_d$  = dimensionless time parameter  $((g/L_e)^{1/2} t)$ ,  $t$  = time

$w$  = deviation of water level from static level in well

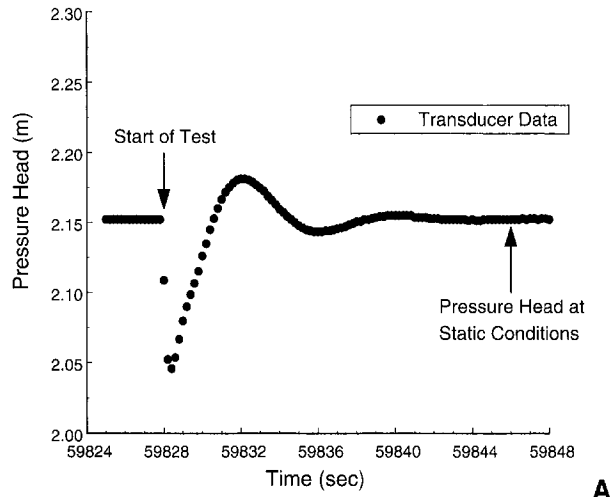
$w_d$  = normalized water-level deviation ( $w/H_0$ )

$\omega_d$  = dimensionless frequency parameter  $(= |1 - (C_D/2)^2|^{1/2})$

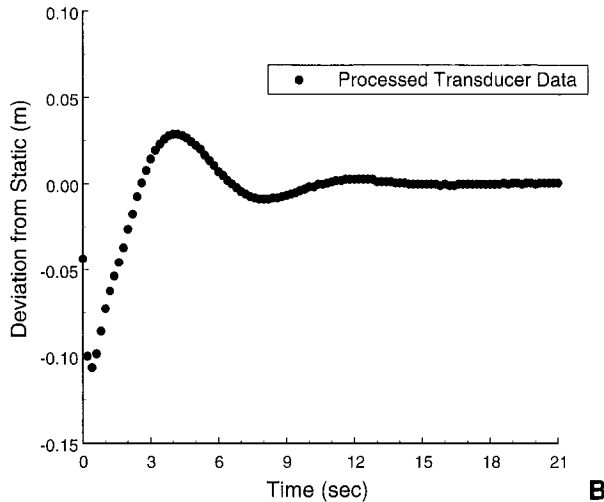
$$\beta_1 = -\frac{C_D}{2} - \omega_d, \beta_2 = -\frac{C_D}{2} + \omega_d$$

**3. The  $C_D$  type curves are superimposed on a plot of the test data.** The dimensionless time axis is expanded or contracted until a reasonable match is obtained between a curve for a particular  $C_D$  ( $C_D^*$ ) and the test data (Figures 4a through 4c). Time match points are then determined by reading the corresponding values from the actual ( $t^*$ ) and dimensionless ( $t_d^*$ ) time axes (Figure 4c). Note that a near-unique match can be obtained because the  $C_D$  value controls the shape of the response (degree of oscillatory behavior or curvature), while the  $t_d$  value controls the duration (period). Different users can obtain different manual curve matches, but these differences will be quite small due to the sensitivity of the match to variations in  $t_d$  (change of

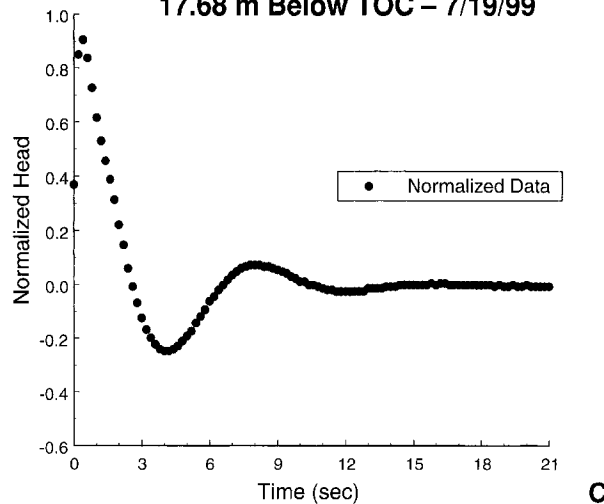
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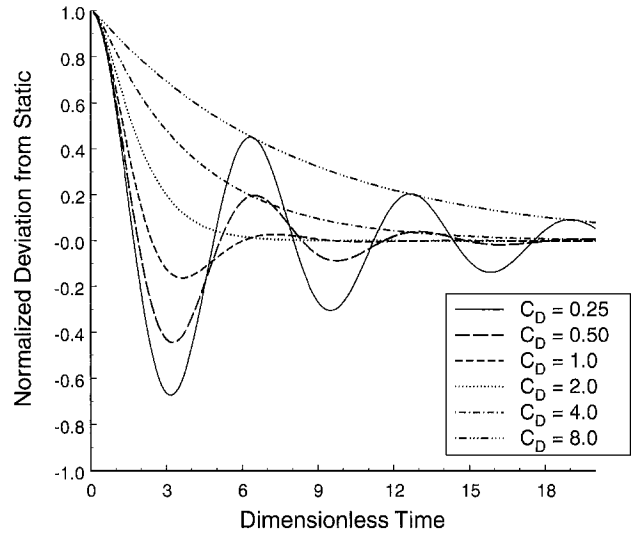


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**Figure 2.** (A) Example plot of pressure head versus time since some arbitrary starting point (in this case, 12:00:00 am); (B) example plot of deviation of pressure head from static conditions ( $H(t)$ ) versus time since test initiation; (C) example plot of normalized head ( $H(t)/H_0$ ) versus time since test initiation.

**Type Curves for High-K Media**



**Figure 3.** Normalized deviation from static ( $w/H_0$ ) versus dimensionless time type curves ( $C_D$  and dimensionless time defined in text).

18% between Figures 4b and 4c) and  $C_D$  (type curves for  $C_D^*$  and  $C_D^* \pm 20\%$  are shown in Figure 4c).

**4. Hydraulic conductivity is estimated from the type-curve match.** The radial hydraulic conductivity ( $K_r$ ) is estimated by substituting values for the well-construction parameters,  $C_D^*$ , and the time match-point ratio ( $t_d^*/t^*$ ) into the equation appropriate for test conditions:

Unconfined — High- $K$  Bouwer and Rice Model (Springer and Gelhar 1991)

$$K_r = \frac{t_d^* r_c^2 \ln[R_e/r_w]}{t^* 2bC_D^*} \quad (4)$$

Confined — High- $K$  Hvorslev Model (Butler 1998)

$$K_r = \frac{t_d^* r_c^2 \ln[b/(2r_w) + (1 + (b/(2r_w))^2)^{0.5}]}{t^* 2bC_D^*} \quad (5)$$

where

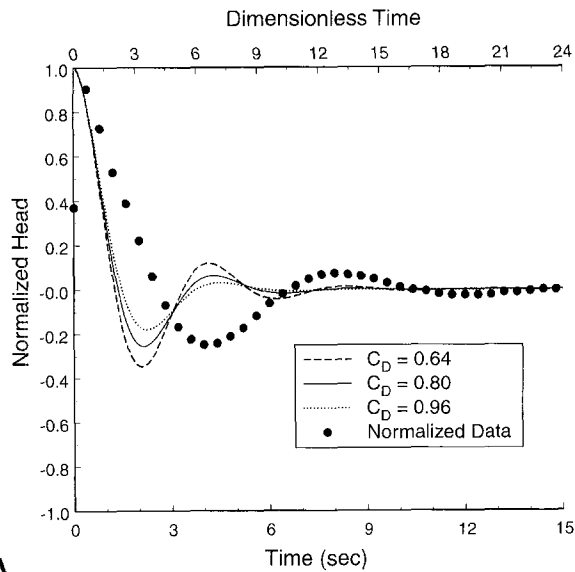
$b$  = screen length;  $R_e$  = effective radius parameter of Bouwer and Rice (1976)

$r_c$  = effective radius of well casing (corrected for radius of transducer cable)

$r_w$  = radius of well screen or borehole in isotropic aquifers, for anisotropic aquifers  $r_w$  should be replaced by  $r_w \sqrt{K_z/K_r}$ , where  $K_z$  is vertical hydraulic conductivity (Zlotnik 1994).

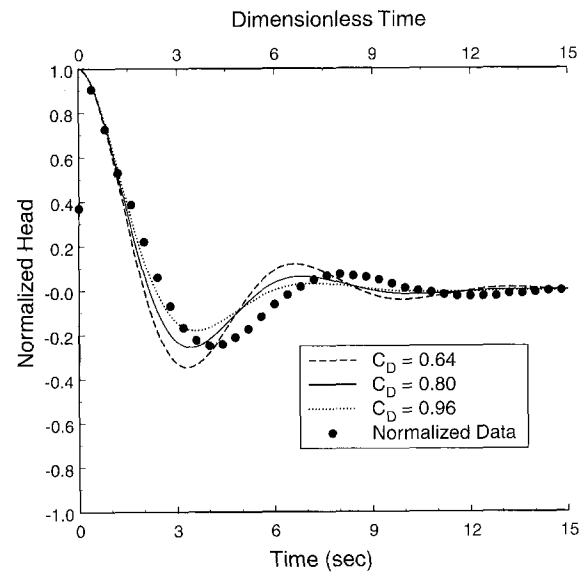
Although the unconfined model (Equation 4) applies for wells screened either away from or up against an impermeable lower boundary, the confined model (Equation 5) does not apply to wells in which the screen abuts an impermeable boundary. In that case, a modified version of the Hvorslev model should be used in which the  $2r_w$  terms in

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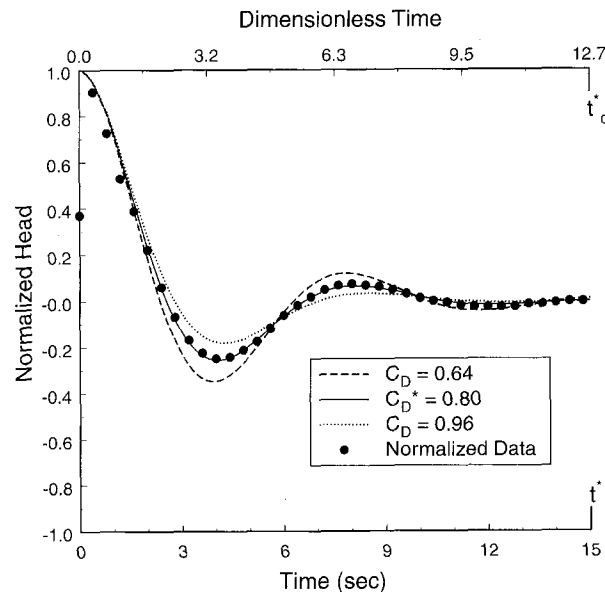
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B

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C

Figure 4. (A) Superposition of type curve and normalized data plots (type curve plots reference upper  $x$ -axis while normalized data plot references lower  $x$ -axis; every second data point plotted; type curves not relevant for analysis are hidden from view); (B) superposition of type curve and normalized data plots (maximum value for upper  $x$ -axis reduced from Figure 4a in an attempt to improve match); (C) final match between type curve and normalized data plots (maximum values for  $x$ -axis used as time match points; note maximum value for upper  $x$ -axis reduced from Figure 4b; starred (\*) quantities are match parameters).

the numerator of Equation 5 are replaced by  $r_w$ . Note that Butler (2002) has proposed a correction for slug tests in small diameter wells in highly permeable formations that can be readily incorporated into the proposed procedure.

The definition of dimensionless time following Equation 3 includes a parameter ( $L_e$ , the effective length of the water column) that arises from the derivation of the

momentum balance for the wellbore (Kipp 1985). Zurbuchen et al. (2002) and others have analyzed slug-test data assuming that  $L_e$  can be computed from well-construction information and considered as a known quantity for the analysis. That approach, however, does not generally produce a good match between the type curve and the response data, indicating that the relevant physical processes are not

completely described with existing definitions of  $L_e$ . Given the complexity of slug-induced flow in a well in a highly permeable aquifer, it is difficult to account for all contributions to the  $L_e$  term. Thus, in the approach described here,  $L_e$  is calculated as part of the analysis:

$$L_e = \left( \frac{t^*}{t_d^*} \right)^2 g \quad (6)$$

In most cases, the analysis-calculated  $L_e$  value will be somewhat larger than the nominal value computed from the well-construction parameters (Kipp 1985). McElwee and Zenner (1998) discuss possible mechanisms that could be responsible for this difference.

The type curves of Figure 3 represent the theoretical deviation of the water level in the well from the static position during a slug test. The general approach outlined in the preceding paragraphs is based on the assumption that a pressure transducer in the water column will provide an accurate record of the water-level position. However, McElwee (2001) and Zurbuchen et al. (2002) have recently pointed out that a transducer may not provide an accurate record of water-level position in conditions of high water-column accelerations. The accuracy of the apparent water-level record obtained from a pressure transducer in an accelerating water column is a function of, among other things, the length of the water column above the transducer. Zurbuchen et al. (2002) proposed the following type-curve correction to account for the position of the transducer in an accelerating water column:

$$H_d(t_d)_{\text{corr}} = w_d + (pt_{\text{depth}} + H_0 w_d)'' (w_d''/L_e) \quad (7)$$

where

$H_d(t_d)_{\text{corr}}$  = theoretical normalized head corrected for transducer position

$pt_{\text{depth}}$  = depth of pressure transducer below static

$w_d''$  = second derivative of  $w_d$  with respect to time

This correction requires an estimate of  $L_e$ , which, as discussed in the previous paragraph, is usually not known prior to the analysis, so error can be introduced into the correction process. Fortunately, the need for this correction can generally be avoided by placing the transducer close to the static level as discussed in a later section.

## Spreadsheet Implementation

The general procedure outlined in the previous section is implemented using two Excel 97 (Microsoft, Redmond, Washington) spreadsheets. Spreadsheet "Type Curve Generator" is used to generate type curves with Equations 1 through 3, and spreadsheet "High K Estimator" is used to process and analyze the slug-test data. Both spreadsheets are included in the file "High K Slug Tests.xls," which can be obtained from Butler and Garnett (2000). The workings of each of these spreadsheets will be briefly described in this section. Note that the processing and analysis of individual tests can be readily completed within a few minutes, so no attempt has been made here to fully automate the procedure.

Figure 5a is a view of a portion of spreadsheet "Type Curve Generator." The  $C_D$  value for which a type curve is to be generated is entered in cell B12. The theoretical normalized responses are then calculated in column H using the appropriate equation (Equations 1 through 3, depending on  $C_D$  value). A plot of dimensionless time versus the theoretical normalized response (type curve) is automatically generated as Chart 1 (Figure 3).

Figures 5b and 5c are views of spreadsheet "High K Estimator." The time and pressure records are entered in columns C and D and then automatically plotted as Chart 2 (Figure 2a). The start time for the test and the static level are determined from these records and entered in cells C12 and C9, respectively. The time since test initiation and the deviation from static are then calculated in columns F and G. The initial change in water level is entered in cell C11 and the normalized deviation from static (normalized head) is calculated in column J. The time since test initiation and the normalized head are then automatically plotted in Chart 3 along with the type curve generated in spreadsheet "Type Curve Generator" (Figure 4a). The appropriate type curve ( $C_D^*$ ) is determined through iterative curve generation and comparison of theoretical and actual normalized head plots. The focus of the comparison is on the peak and trough values for  $C_D < 2$ , whereas the emphasis is on plot curvature for  $C_D > 2$ . Even when trough and peak values correspond, the type curve and response data plots will usually be offset (Figure 4a). To obtain a match, the dimensionless times are adjusted using a modulation factor. This factor is entered in cell N13 and the adjusted dimensionless times are calculated in column O. Chart 3 is then automatically replotted using the new adjusted dimensionless time. The time adjustment continues in an iterative fashion until an acceptable match is obtained (Figure 4c). The ratio of the time match points ( $t_d^*/t^*$ ) is automatically computed in cell L6, and the  $K_t$  estimate is then calculated using the values for this ratio,  $C_D^*$ , and the well-construction parameters. The estimate obtained with the high- $K$  Hvorslev model (Equation 5) is given in various units in cells S9–11 and U10, while that obtained with the high- $K$  Bouwer and Rice model (Equation 4) is given in cells S28–30 and U29. The effective length of the water column is calculated in N8 and compared to the nominal value computed from well construction parameters (Equation 6 of Kipp 1985) in cell N10.

The spreadsheet "High K Estimator" shown in Figures 5b and 5c is for slug tests in wells in which the screen does not abut an impermeable boundary. If the well is screened up to an impermeable boundary, the version of "High K Estimator" in the file "High K Slug Tests Boundary.xls" should be used. English-unit equivalents of "High K Slug Tests.xls" and "High K Slug Tests Boundary.xls" are also provided in Butler and Garnett (2000).

## Example Field Applications

This spreadsheet-based procedure is demonstrated using field data from a research site of the Kansas Geological Survey. To illustrate the range of conditions that can be observed in tests in highly permeable aquifers, both oscillatory and nonoscillatory response data are consid-

|    |                                                                                                          |          |           |           |                      |   |   |              |   |   |   |
|----|----------------------------------------------------------------------------------------------------------|----------|-----------|-----------|----------------------|---|---|--------------|---|---|---|
|    | A                                                                                                        | B        | C         | D         | E                    | F | G | H            | I | J | K |
| 1  | <b>Spreadsheets and Charts</b>                                                                           |          |           |           |                      |   |   |              |   |   |   |
| 2  | prepared by                                                                                              |          |           |           |                      |   |   |              |   |   |   |
| 3  | <i>E. Garnett and J. Butler for</i>                                                                      |          |           |           |                      |   |   |              |   |   |   |
| 4  | Butler, J.J., Jr., and E.J. Garnett, 2000, Simple procedures for analysis of slug tests in formations of |          |           |           |                      |   |   |              |   |   |   |
| 5  | high hydraulic conductivity using spreadsheet and scientific graphics software, Kansas Geological        |          |           |           |                      |   |   |              |   |   |   |
| 6  | Survey Open-File Rept. 2000-40, Lawrence, Ks.                                                            |          |           |           |                      |   |   |              |   |   |   |
| 7  | <b>Type Curve Generator Spreadsheet</b>                                                                  |          |           |           |                      |   |   |              |   |   |   |
| 8  |                                                                                                          |          |           |           |                      |   |   |              |   |   |   |
| 9  |                                                                                                          |          |           |           |                      |   |   |              |   |   |   |
| 10 |                                                                                                          |          |           |           |                      |   |   |              |   |   |   |
| 11 | $C_D$                                                                                                    | $\omega$ | $\beta_2$ | $\beta_1$ | <b>Dimensionless</b> |   |   | $C_D =$      |   |   |   |
| 12 | 0.775                                                                                                    | 0.9219   | 0.5344    | -1.3094   | <b>Time</b>          |   |   | <b>0.775</b> |   |   |   |
| 13 |                                                                                                          |          |           |           | 0                    |   |   | 1.0000       |   |   |   |
| 14 |                                                                                                          |          |           |           | 0.1                  |   |   | 0.9951       |   |   |   |
| 15 |                                                                                                          |          |           |           | 0.2                  |   |   | 0.9811       |   |   |   |
| 16 |                                                                                                          |          |           |           | 0.3                  |   |   | 0.9586       |   |   |   |
| 17 |                                                                                                          |          |           |           | 0.4                  |   |   | 0.9286       |   |   |   |
| 18 |                                                                                                          |          |           |           | 0.5                  |   |   | 0.8919       |   |   |   |
| 19 |                                                                                                          |          |           |           | 0.6                  |   |   | 0.8494       |   |   |   |
| 20 |                                                                                                          |          |           |           | 0.7                  |   |   | 0.8019       |   |   |   |
| 21 |                                                                                                          |          |           |           | 0.8                  |   |   | 0.7502       |   |   |   |
| 22 |                                                                                                          |          |           |           | 0.9                  |   |   | 0.6951       |   |   |   |
| 23 |                                                                                                          |          |           |           | 1                    |   |   | 0.6375       |   |   |   |
| 24 |                                                                                                          |          |           |           | 1.1                  |   |   | 0.5780       |   |   |   |
| 25 |                                                                                                          |          |           |           | 1.2                  |   |   | 0.5175       |   |   |   |
| 26 |                                                                                                          |          |           |           | 1.3                  |   |   | 0.4564       |   |   |   |
| 27 |                                                                                                          |          |           |           | 1.4                  |   |   | 0.3956       |   |   |   |
| 28 |                                                                                                          |          |           |           | 1.5                  |   |   | 0.3354       |   |   |   |
| 29 |                                                                                                          |          |           |           | 1.6                  |   |   | 0.2765       |   |   |   |
| 30 |                                                                                                          |          |           |           | 1.7                  |   |   | 0.2194       |   |   |   |

**Figure 5a. View of a portion of spreadsheet Type Curve Generator.**

|    | A                            | B | C                     | D                             | E                                                                | F            | G                        | H | I            | J                  | K |
|----|------------------------------|---|-----------------------|-------------------------------|------------------------------------------------------------------|--------------|--------------------------|---|--------------|--------------------|---|
| 1  | High K Estimator Spreadsheet |   |                       |                               | Test Well Specs - "d" not used in confined case                  |              |                          |   |              |                    |   |
| 2  | Metric Units                 |   |                       |                               | Depth to Bottom of Screen (from toc):                            |              |                          |   |              | 19.8               | m |
| 3  |                              |   |                       |                               | Screen Length (b):                                               |              |                          |   |              | 0.229              | m |
| 4  | General Test Data            |   |                       |                               | Depth to Static Water Level (from toc):                          |              |                          |   |              | 6.274              | m |
| 5  | Site Location:               |   | GEMS                  |                               | Top of Screen to Water Table (d):                                |              |                          |   |              | 5                  | m |
| 6  | Date:                        |   | 4/27/00               |                               | Radius of Well Screen ( $r_w$ ):                                 |              |                          |   |              | 0.017              | m |
| 7  | Time:                        |   |                       |                               | Nominal Radius of Well Casing ( $r_{nc}$ ):                      |              |                          |   |              | 0.019              | m |
| 8  | Test Designation:            |   | BB426 D3-6            |                               | Radius of Transducer Cable ( $r_{tc}$ ):                         |              |                          |   |              | 0.003              | m |
| 9  | Static Level:                |   | 0.45                  | m                             | Effective Casing Radius ( $r_c = (r_{nc}^2 - r_{tc}^2)^{0.5}$ ): |              |                          |   |              | 0.019              | m |
| 10 | Initial Water Level          |   |                       |                               | Modified Screen Radius ( $r_w^*$ ):                              |              |                          |   |              | 0.017              | m |
| 11 | Change ( $H_0$ ):            |   | -0.054                | m                             | Aspect Ratio ( $b/r_w^*$ ):                                      |              |                          |   |              | 13.713             |   |
| 12 | Start Time for Test:         |   | 55932.5               | sec                           | Formation Thickness (B):                                         |              |                          |   |              | 10.67              | m |
| 13 |                              |   |                       |                               |                                                                  |              |                          |   |              |                    |   |
| 14 |                              |   |                       |                               |                                                                  |              |                          |   |              |                    |   |
| 15 |                              |   | Time<br>in<br>seconds | Pressure<br>Head<br>in meters |                                                                  |              |                          |   |              |                    |   |
| 16 |                              |   |                       |                               |                                                                  | Test<br>Time | Deviation<br>from Static |   | Test<br>Time | Normalized<br>Head |   |
| 17 |                              |   |                       |                               |                                                                  |              |                          |   |              |                    |   |
| 18 |                              |   | 55932.7               | 0.394                         |                                                                  | 0.2          | -0.052                   |   | 0.2          | 0.969              |   |
| 19 |                              |   | 55932.9               | 0.397                         |                                                                  | 0.4          | -0.049                   |   | 0.4          | 0.909              |   |
| 20 |                              |   | 55933.1               | 0.398                         |                                                                  | 0.6          | -0.048                   |   | 0.6          | 0.894              |   |
| 21 |                              |   | 55933.3               | 0.401                         |                                                                  | 0.8          | -0.045                   |   | 0.8          | 0.836              |   |
| 22 |                              |   | 55933.5               | 0.405                         |                                                                  | 1            | -0.041                   |   | 1            | 0.763              |   |
| 23 |                              |   | 55933.7               | 0.409                         |                                                                  | 1.2          | -0.037                   |   | 1.2          | 0.695              |   |
| 24 |                              |   | 55933.9               | 0.414                         |                                                                  | 1.4          | -0.032                   |   | 1.4          | 0.603              |   |
| 25 |                              |   | 55934.1               | 0.418                         |                                                                  | 1.6          | -0.028                   |   | 1.6          | 0.517              |   |
| 26 |                              |   | 55934.3               | 0.423                         |                                                                  | 1.8          | -0.023                   |   | 1.8          | 0.425              |   |
| 27 |                              |   | 55934.5               | 0.428                         |                                                                  | 2            | -0.018                   |   | 2            | 0.335              |   |
| 28 |                              |   | 55934.7               | 0.433                         |                                                                  | 2.2          | -0.013                   |   | 2.2          | 0.248              |   |
| 29 |                              |   | 55934.9               | 0.437                         |                                                                  | 2.4          | -0.009                   |   | 2.4          | 0.164              |   |
| 30 |                              |   | 55935.1               | 0.442                         |                                                                  | 2.6          | -0.004                   |   | 2.6          | 0.083              |   |

**Figure 5b. View of a portion of spreadsheet High K Estimator.**

|    | L                          | M                      | N                    | O               | P | Q | R                                                | S                                                          | T                                           | U                          | V      | W |
|----|----------------------------|------------------------|----------------------|-----------------|---|---|--------------------------------------------------|------------------------------------------------------------|---------------------------------------------|----------------------------|--------|---|
| 1  |                            |                        |                      |                 |   |   |                                                  |                                                            |                                             |                            |        |   |
| 2  |                            |                        | <b>Best Fit</b>      |                 |   |   | <b>Confined - High-K Hvorslev Model</b>          |                                                            |                                             |                            |        |   |
| 3  | <b>Time</b>                |                        | <b>Type Curve</b>    |                 |   |   |                                                  |                                                            |                                             |                            |        |   |
| 4  | <b>Correlation Ratio</b>   |                        | <b>C<sub>D</sub></b> |                 |   |   | $K_r =$                                          | $t_d^* r_c^2 \ln[b/(2r_w^*) + (1 + (b/(2r_w^*))^2)^{0.5}]$ |                                             |                            |        |   |
| 5  | $t_d^*/t^*$                |                        | 0.775                |                 |   |   |                                                  | $t^* \quad 2bC_D$                                          |                                             |                            |        |   |
| 6  | 0.760                      |                        |                      |                 |   |   |                                                  |                                                            |                                             |                            |        |   |
| 7  |                            |                        |                      |                 |   |   | Bracketted quantity                              |                                                            |                                             |                            | 13.786 |   |
| 8  | computed from ratio        | Le =                   | 16.984               | m               |   |   |                                                  |                                                            |                                             |                            |        |   |
| 9  | nominal                    | Le =                   | 13.443               | m               |   |   | $K_r =$                                          | 1.95E-03                                                   | m/sec                                       |                            |        |   |
| 10 | % difference               |                        | 26%                  |                 |   |   |                                                  | 1.68E+02                                                   | m/day                                       | 5.52E+02                   | ft/day |   |
| 11 |                            |                        |                      |                 |   |   |                                                  | 1.95E-01                                                   | cm/sec                                      |                            |        |   |
| 12 |                            |                        |                      |                 |   |   |                                                  |                                                            |                                             |                            |        |   |
| 13 | <b>Modulation Factor =</b> |                        | 1.3158               |                 |   |   | <b>Unconfined - High-K Bouwer and Rice Model</b> |                                                            |                                             |                            |        |   |
| 14 |                            |                        |                      |                 |   |   |                                                  |                                                            |                                             |                            |        |   |
| 15 |                            |                        |                      |                 |   |   | $K_r =$                                          | $t_d^* r_c^2 \ln[R_0/r_w^*]$                               |                                             |                            |        |   |
| 16 | <b>Dimensionless</b>       | <b>C<sub>D</sub> =</b> |                      | <b>Adjusted</b> |   |   |                                                  | $t^* \quad 2bC_D$                                          |                                             |                            |        |   |
| 17 | <b>Time</b>                | <b>0.775</b>           |                      | <b>Time</b>     |   |   |                                                  |                                                            |                                             |                            |        |   |
| 18 | 0                          | 1                      |                      | 0               |   |   | $\ln(R_0/r_w^*) =$                               | 2.161                                                      |                                             | <b>A =</b>                 | 1.942  |   |
| 19 | 0.1                        | 0.995131               |                      | 0.1316          |   |   |                                                  |                                                            |                                             | <b>B =</b>                 | 0.307  |   |
| 20 | 0.2                        | 0.981057               |                      | 0.2632          |   |   |                                                  | first term                                                 | $1.1/(\ln((d+b)/r_w^*))$                    |                            |        |   |
| 21 | 0.3                        | 0.958601               |                      | 0.3947          |   |   |                                                  |                                                            | 0.191                                       |                            |        |   |
| 22 | 0.4                        | 0.928603               |                      | 0.5263          |   |   |                                                  | second term                                                | $(A + B^*(\ln[(B-(d+b))/r_w^*]))/(b/r_w^*)$ |                            |        |   |
| 23 | 0.5                        | 0.891914               |                      | 0.6579          |   |   |                                                  |                                                            | 0.271                                       |                            |        |   |
| 24 | 0.6                        | 0.849386               |                      | 0.7895          |   |   |                                                  | $\ln[(B-(d+b))/r_w^*]$                                     | 5.788                                       |                            |        |   |
| 25 | 0.7                        | 0.801863               |                      | 0.9211          |   |   |                                                  |                                                            |                                             | Cannot exceed 6.           |        |   |
| 26 | 0.8                        | 0.750175               |                      | 1.0526          |   |   |                                                  |                                                            |                                             | See Butler (1998) - p.108. |        |   |
| 27 | 0.9                        | 0.695129               |                      | 1.1842          |   |   |                                                  |                                                            |                                             |                            |        |   |
| 28 | 1                          | 0.637505               |                      | 1.3158          |   |   | $K_r =$                                          | 1.60E-03                                                   | m/sec                                       |                            |        |   |
| 29 | 1.1                        | 0.578049               |                      | 1.4474          |   |   |                                                  | 1.39E+02                                                   | m/day                                       | 4.55E+02                   | ft/day |   |
| 30 | 1.2                        | 0.517469               |                      | 1.5790          |   |   |                                                  | 1.60E-01                                                   | cm/sec                                      |                            |        |   |

Figure 5c. View of a portion of spreadsheet High K Estimator.

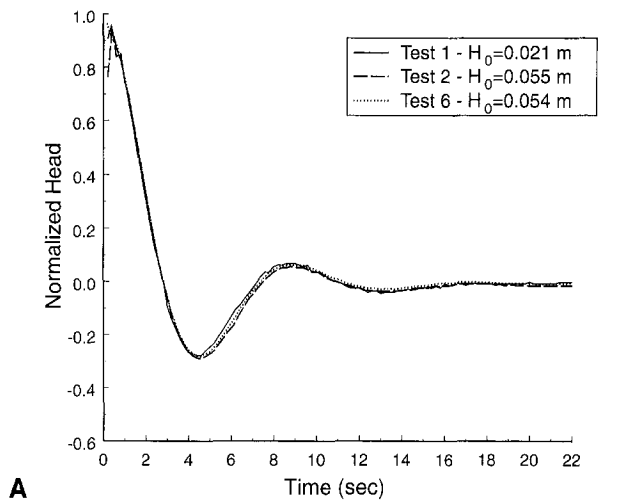
ered. Note that in both cases the hydraulic-conductivity estimates agreed well with estimates obtained using the dipole flow probe (Zlotnik and Zurbuchen 1998) in the same (nonoscillatory example) or adjacent (oscillatory example) wells.

**Oscillatory Example.** Figure 6a displays the normalized head versus time plot for three of a series of slug tests performed in a direct-push installation screened in the confined coarse sand and gravel aquifer underlying the Kansas River floodplain near Lawrence, Kansas (Butler et al. 2002). The coincidence of the normalized plots indicates that dynamic-skin effects and any dependence on the magnitude of the initial displacement can be neglected for these tests (Butler et al. 1996; Butler 1998). Figure 6b shows the type-curve fit determined using the spreadsheet procedure. In this case, a  $C_D^*$  value of 0.775 and time match points of 16.72 ( $t_d^*$ ) and 22.0 ( $t^*$ ) are obtained. Substituting these values and those for the well-construction parameters ( $b = 0.229$  m,  $r_c = 0.019$  m,  $r_w = 0.017$  m) into Equation 5 yields a  $K_r$  value of 168 m/day. To verify the appropriateness of this estimate, a joint analysis of all three tests of Figure 6a was performed with the McElwee and Zenner (1998) model coupled to an optimization routine. This analysis yielded a  $K_r$  estimate ~4% higher, a negligible difference given that a visual match was used in the spreadsheet procedure. Note that tests in partially penetrating wells in high- $K$  aquifers are often analyzed with the Van der Kamp (1976) method for tests in fully penetrating wells or the conventional forms of the Hvorslev (1951) and Bouwer and Rice (1976) methods. In this case, the Van der Kamp method yields a very

significant overestimation of  $K_r$  (factor of 3.9), as would be expected when a method developed for fully penetrating wells is used to analyze a test in a partially penetrating well (Butler 1998). An analysis with the conventional form of the Hvorslev or Bouwer and Rice method using the initial falling limb of the test data will also lead to a significant overestimation of  $K_r$  (overestimation by a factor of 1.9 using the Hvorslev method). This degree of overestimation is commonly observed when oscillatory response data are analyzed with the conventional forms of the Hvorslev and Bouwer and Rice methods.

**Nonoscillatory Example.** Figure 7a displays the normalized head versus time plot for three of a series of slug tests performed in a packer-isolated interval in a monitoring well in the same aquifer as in the previous example. The near-coincidence of the normalized plots indicates that dynamic-skin effects and any dependence on the magnitude of the initial displacement can again be neglected. Figure 7b shows the type-curve fit determined using the spreadsheet-based procedure. In this case, a  $C_D^*$  value of 3.0 and time match points of 17.39 ( $t_d^*$ ) and 16.0 ( $t^*$ ) are obtained. Substituting these values and those for the well-construction parameters ( $b = 0.610$  m,  $r_c = 0.025$  m,  $r_w = 0.057$  m) into Equation 5 yields a  $K_r$  value of 38.7 m/day. A joint analysis of all three tests of Figure 7a performed with the McElwee and Zenner (1998) model coupled to an optimization routine yielded a  $K_r$  estimate ~1% lower. Analysis with the conventional form of the Hvorslev method yielded a  $K_r$  estimate ~13% higher. Additional work has shown that the conventional forms of the Hvorslev and Bouwer and Rice

BB426 - Test Series D3  
4/27/00



Analysis of Slug Test D3-6 at BB426  
4/27/00

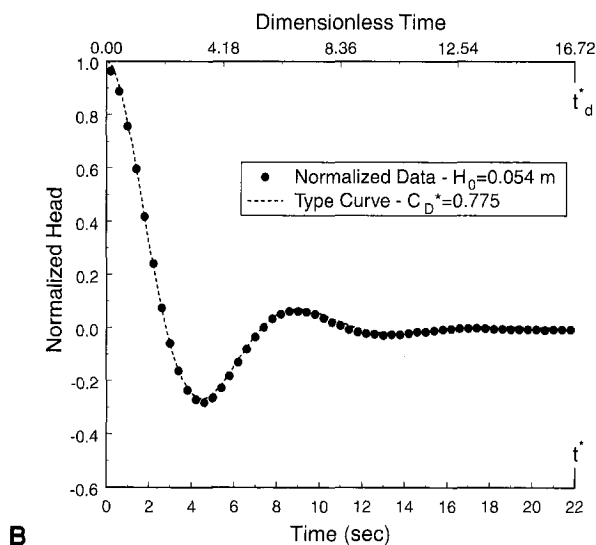


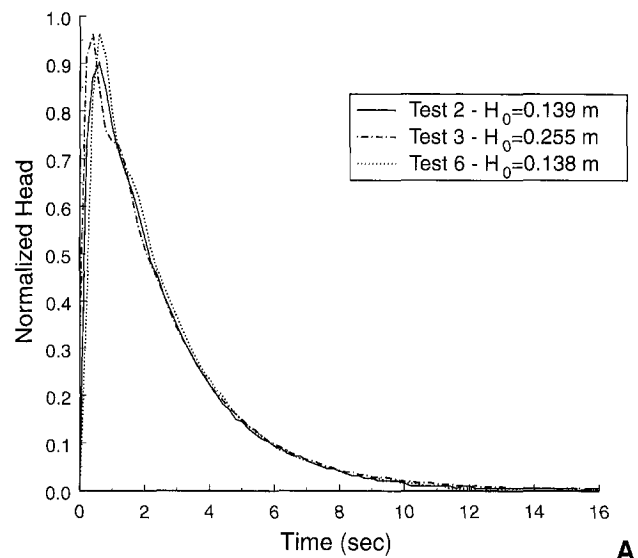
Figure 6. (A) Normalized head versus time plot for three slug tests performed in direct-push equipment at the Geohydrologic Experimental and Monitoring Site (GEMS) near Lawrence, Kansas (all tests initiated with the pneumatic method;  $H_0$  determined from air-pressure transducer); (B) superposition of normalized data and best-fit type curve for test 6 (every second data point plotted; starred (\*) quantities are match parameters; calculated  $L_e$  (16.98 m) is approximately 26% larger than nominal value).

methods will yield reasonable parameter estimates when  $C_D > 3$ .

### Recommended Field Guidelines

The procedure described in the preceding sections is considerably simpler than recently proposed approaches for analysis of slug tests in highly permeable aquifers (McElwee and Zenner 1998; Zurbuchen et al. 2002). Although the simplifications required for this procedure can introduce

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14.63 m Below TOC - 7/20/99



Gems4S - Multilevel Slug Tests  
Analysis of Slug Test #3  
14.63 m Below TOC - 7/20/99

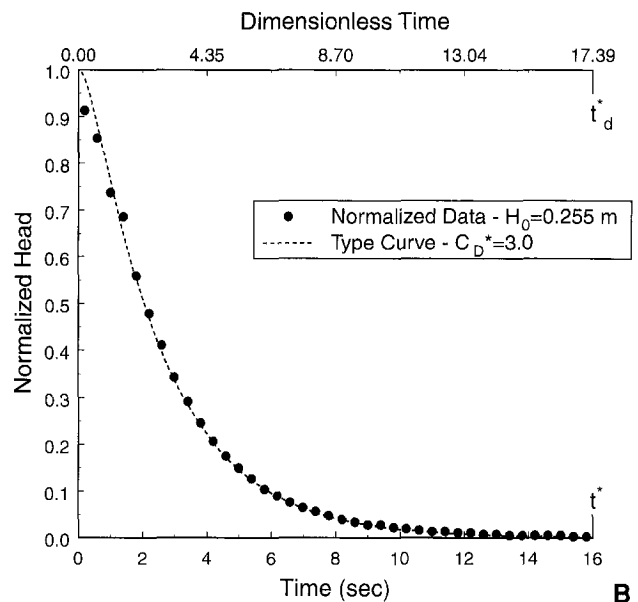
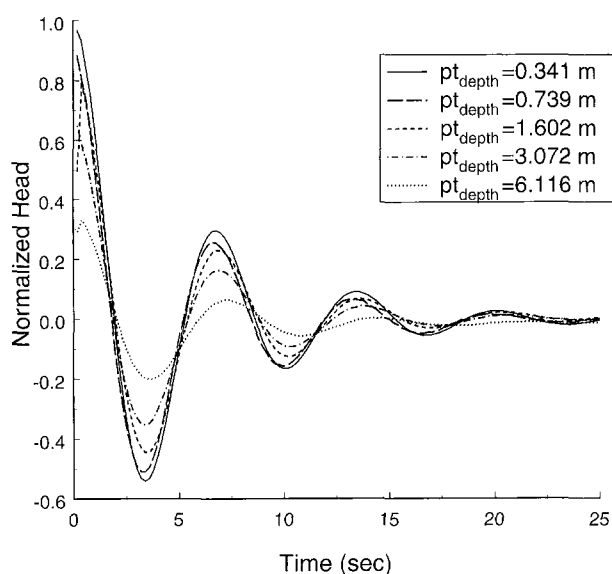


Figure 7. (A) Normalized head versus time plot for three slug tests performed in a monitoring well at GEMS (all tests initiated with the pneumatic method;  $H_0$  determined from air-pressure transducer); (B) superposition of normalized data and best-fit type curve for test 3 (every second data point plotted; starred (\*) quantities are match parameters; calculated  $L_e$  (8.31 m) is within 14% of nominal value).

error into  $K_r$  estimates, the results of the comparisons presented in the previous section show that this error is negligible when appropriate measures are taken in the field. These field measures can be encapsulated in the following three guidelines for slug tests in formations of high hydraulic conductivity.

**1. Slug tests should be initiated very rapidly relative to the formation response, so that details of the ini-**

### Dependence on Transducer Position GP43C - 4/4/00 - $H_0 < 0.26$ m

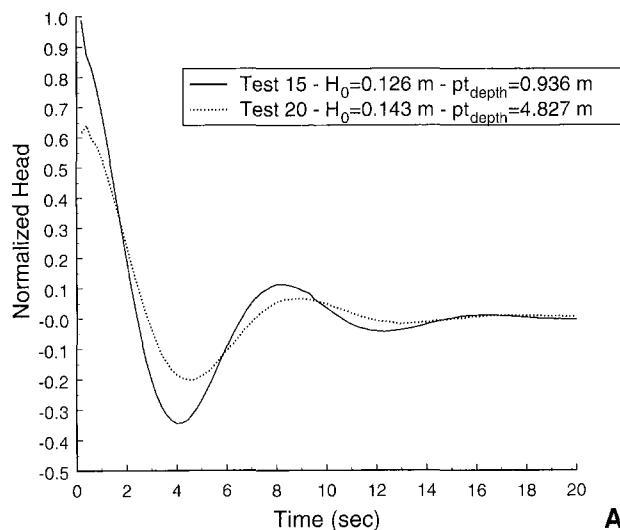


**Figure 8.** Normalized head versus time plot displaying a dependence on the depth ( $pt_{depth}$ ) of the transducer below the static water level ( $r_c = 0.007$  m,  $r_w = 0.013$  m,  $b = 0.156$  m; all tests initiated with the pneumatic method;  $H_0$  dependence and dynamic-skin effects (Butler 1998) negligible;  $H_0$  determined from air-pressure transducer; tests performed in direct-push pipe in the same aquifer as in Figures 6 and 7).

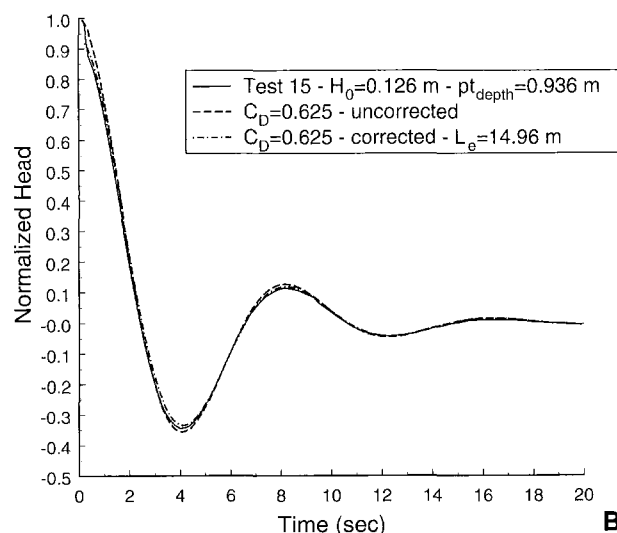
tiation process can be ignored in the analysis. The analysis procedure described here is based on the assumption that the initiation process has a negligible impact on the response data. As recommended by Butler (1998) and Zurbuchen et al. (2002), the pneumatic method should be used for test initiation whenever possible (i.e., in wells not screened across the water table) in order to avoid the error introduced into the  $K_r$  estimate by shifts in phase and magnitude of the response data produced by slower initiation methods. Although Butler (1998) and others have suggested using truncated data sets when test initiation is relatively slow, Zurbuchen et al. (2002) have recently demonstrated that this approach may often be inappropriate in highly permeable systems and can lead to an underprediction in hydraulic conductivity as large as 30%.

2. A series of tests should be performed at each well using a range of initial displacements to demonstrate that any dependence on  $H_0$  can be justifiably neglected in the analysis. Butler et al. (1996) and others have noted that response data can be dependent on the magnitude of the initial water-level change ( $H_0$ ). The analysis method described here is based on the assumption that any dependence on  $H_0$  is negligible. To ascertain the range of  $H_0$  for which that assumption is valid, Butler et al. (1996) recommend that a series of slug tests be performed in which  $H_0$  is changed in a systematic fashion between tests (e.g., 0.06, 0.12, 0.18, 0.12, and 0.06 m). If the plot of a series of tests demonstrates that dependence on  $H_0$  is negligible for a certain range of  $H_0$ , then the method presented here can be used with confidence. When such conditions cannot be demonstrated, more involved approaches must be consid-

### Dependence on Transducer Position 4SGP2900 - Lv2 - 2/10/00



### Dependence on Transducer Position 4SGP2900 - Lv2 - 2/10/00



**Figure 9.** (A) Normalized head versus time plot displaying a dependence on the depth ( $pt_{depth}$ ) of the transducer below the static water level ( $r_c = 0.007$  m,  $r_w = 0.013$  m,  $b = 0.076$  m; both tests initiated with the pneumatic method;  $H_0$  dependence and dynamic-skin effects (Butler 1998) negligible;  $H_0$  determined from air-pressure transducer; tests performed in direct-push pipe in the same aquifer as in Figures 6 and 7); (B) superposition of normalized head plot and best-fit uncorrected and corrected type curves (type curve corrected according to Equation 7).

ered (e.g., McElwee and Zenner 1998; McElwee 2001). Zurbuchen et al. (2002) have recently demonstrated that neglect of the dependence on  $H_0$  and initiation of tests with relatively large displacements (1.5 m) can lead to an underestimation in  $K_r$  approaching a factor of two. Note that the radius of influence of a slug test is independent of the magnitude of the initial displacement, so there is little reason to use a large displacement if a reasonable signal-to-noise ratio can be obtained with smaller displacements (Figure 6a).

**3. The pressure transducer in the water column should be placed close to the static water level, so that a type-curve correction for water-column acceleration is not necessary.** As stated earlier, the record of pressure head versus time obtained from a transducer in a well in a highly permeable aquifer is a function of the depth of the transducer below static. Figures 8 and 9a present the results of two series of slug tests in which the depth of the transducer was systematically varied between tests to reveal a very pronounced dependence on transducer position. These figures indicate that the correction defined in Equation 7 is not necessary when the pressure transducer is close to static. This was verified by analyzing test 15 of Figure 9a and using the analysis-calculated  $L_c$  (14.96 m) to compute a type curve corrected for water-column acceleration. Figure 9b demonstrates that the correction is not of practical significance when the transducer is close to static. The definition of “close” will be a function of the well-formation configuration. For example, “close” would be within 0.7 m of static for the configuration of Figure 8. Results of a large number of tests indicate that placing the transducer within 0.5 m of static is sufficiently “close” for the vast majority of practical applications. In all cases, the need for the type-curve correction can be readily assessed by considering the maximum normalized head observed during a test. A maximum normalized head greater than 0.9 (Figures 6a, 7a, 8 [ $pt_{\text{depth}} = 0.341$  m], and 9a [ $pt_{\text{depth}} = 0.936$  m]) is an indication that the transducer is close enough to static to make a type-curve correction unnecessary. However, if the maximum normalized head is below 0.9 (Figures 8 [ $pt_{\text{depth}} > 0.341$  m] and 9a [ $pt_{\text{depth}} = 4.827$  m]), the tests should be repeated with the transducer closer to the static level or the type curves must be corrected using Equation 7. If the transducer is not repositioned or the type-curve correction is not applied, the underestimation in hydraulic conductivity can exceed a factor of two when the transducer is at a considerable distance below static (e.g., factor of 2.03 for test with transducer at a depth of 6.116 m in Figure 8). Note that the maximum normalized head criterion of 0.9 proposed here is a conservative threshold determined from field experiments (Figure 8) and simulations of hypothetical tests. When the maximum normalized head is above this threshold, the error introduced into the  $K_r$  estimate through neglect of the type-curve correction will be much less than 10%.

## Summary and Conclusions

A simple, spreadsheet-based procedure was presented for the analysis of slug tests performed in partially penetrating wells in formations of high hydraulic conductivity. In this procedure, theoretical type curves are graphically fit to normalized plots of slug-test response data to obtain estimates of the hydraulic conductivity of the near-well portions of the formation. Field examples were used to illustrate the approach for the range of conditions common in highly permeable aquifers. Although the procedure is considerably simpler than previously proposed methods, example analyses demonstrated that the error introduced into  $K_r$  estimates by the simplicity of the approach is negligible when appropriate measures are taken in the field.

These measures can be summarized in the following set of practical field guidelines. First, slug tests in highly permeable aquifers should be initiated very rapidly relative to the formation response to ensure that details of the test initiation process can be justifiably ignored in the analysis. Except in wells screened across the water table, the pneumatic method is the preferred approach for test initiation. Second, a series of tests should be performed at each well using a range of initial displacements to demonstrate that any dependence on  $H_0$  can be assumed negligible. Finally, the pressure transducer in the water column should be placed close to the static level ( $< 0.5$  m), so that type curves do not have to be corrected for water-column acceleration. When these guidelines are followed, the spreadsheet procedure presented here should yield  $K_r$  estimates that are reasonable representations of the hydraulic conductivity of the formation in the vicinity of the test interval.

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