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IMPROVING THE RELIABILITY OF PARAMETER ESTIMATES  
OBTAINED FROM SLUG TESTS

by

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## ABSTRACT

The slug test is one of the most commonly used field methods for obtaining estimates of hydraulic conductivity. Despite its prevalence, this method has received criticism from many quarters in the groundwater community. This criticism emphasizes the poor reliability of the estimated parameters, a condition that is primarily a product of the somewhat casual approach that is often employed in slug tests. Recently, the Kansas Geological Survey (KGS) has pursued research directed at improving methods for the performance and analysis of slug tests. Based on extensive theoretical and field research, a series of guidelines have been proposed that should enable the reliability of parameter estimates to be improved. The most significant of these guidelines are: 1) three or more slug tests should be performed at each well during a given test period; 2) two or more different initial heads ( $H_0$ ) should be used at each well during a test period; 3) the method used to initiate a test must enable a good estimate of  $H_0$  to be obtained; 4) data acquisition equipment that enables a large quantity of high quality data to be collected must be employed; 5) if an estimate of the storage parameter is needed, an observation well other than the test well should be employed; 6) the method chosen for analysis of the slug-test data must be appropriate for site conditions; and 7) use of pre- and post-analysis plots should be an integral component of the analysis procedure. The importance of these guidelines will be demonstrated using data from KGS field sites.

## 1. Three or more slug tests should be performed at a given well

According to conventional theory (e.g., Cooper et al., 1967), data from repeat tests at the same well should coincide when graphed in a normalized format. Figure 1 is a plot of a series of slug tests from a well in Lincoln County, Kansas in which the response data conform to conventional theory despite a variation of almost a factor of 4 in the magnitude of the initial displacement (i.e. - size of slug,  $H_0$ ). Unfortunately, however, data from repeat tests at the same well will often not plot in this ideal manner. Figure 2 displays data from a series of slug tests from another well at the same site in Lincoln County in which there was considerable variation in test responses. Since the pattern of responses shown on Figure 2 does not indicate a strong dependence on  $H_0$  (test 3 on 5/21 and test 11 on 6/26 have similar  $H_0$  but yield Cooper et al. parameter estimates that differ by a factor of 2), this behavior is probably an indication that the gravel pack or a portion of the formation in the vicinity of the well is being altered during the course of testing. One possible explanation is that some fine material is being mobilized by the introduction of the slug and is moving in a manner that produces progressive decreases in formation permeability during the course of testing. Without doing a series of tests at a given well, this behavior would not be identified and thus properties reflective of the skin could inadvertently be assigned to the formation. A minimum of three tests is suggested in order that the effects of an evolving skin can be separated from a dependence on  $H_0$  (discussed in the next section). Clearly, considerable attention must be given to well construction and development in order to minimize the possibility of skin development during the course of testing.

FIGURE 1

Lincoln County Site  
Ln-2 1991 Slug Tests

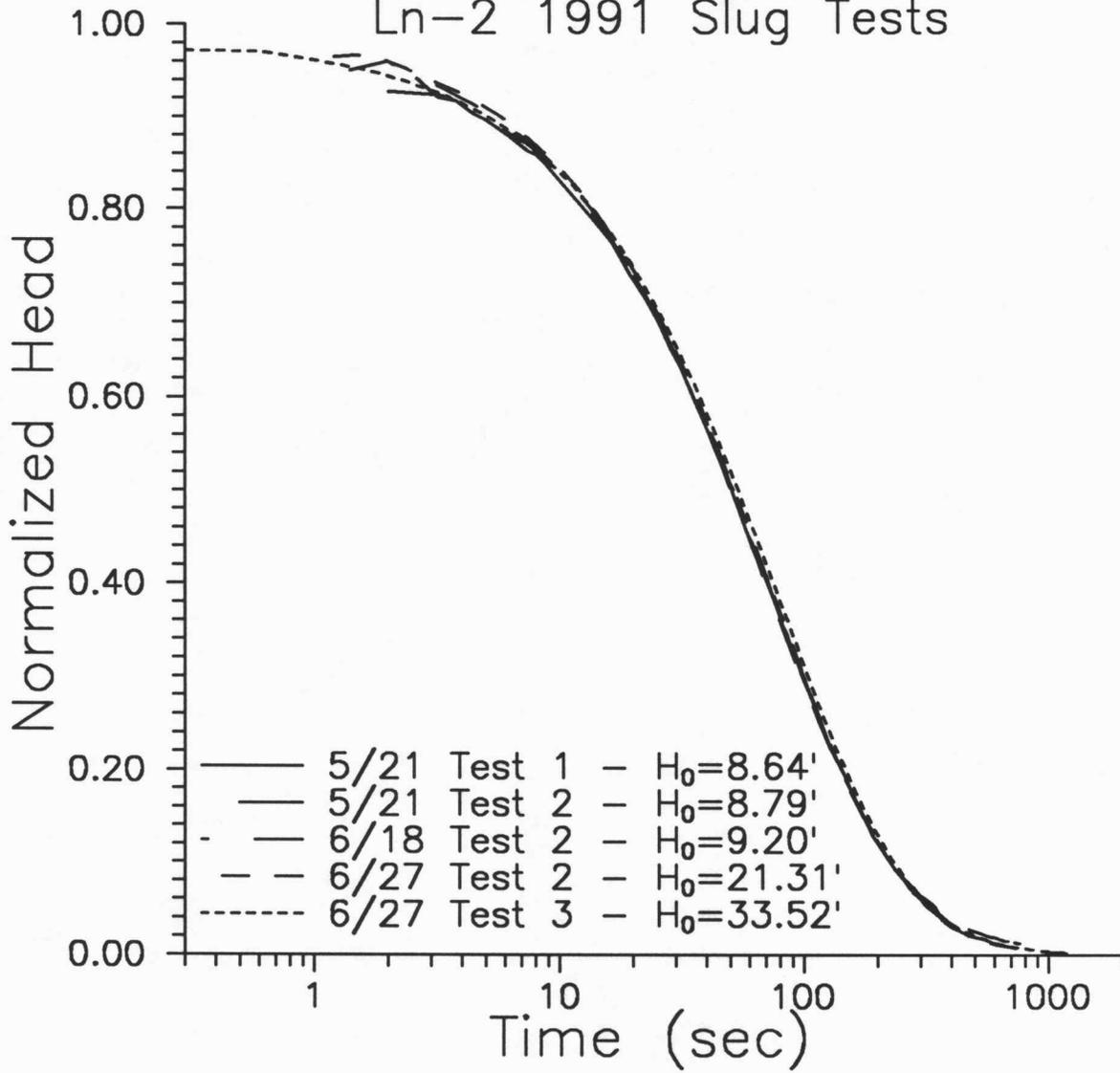
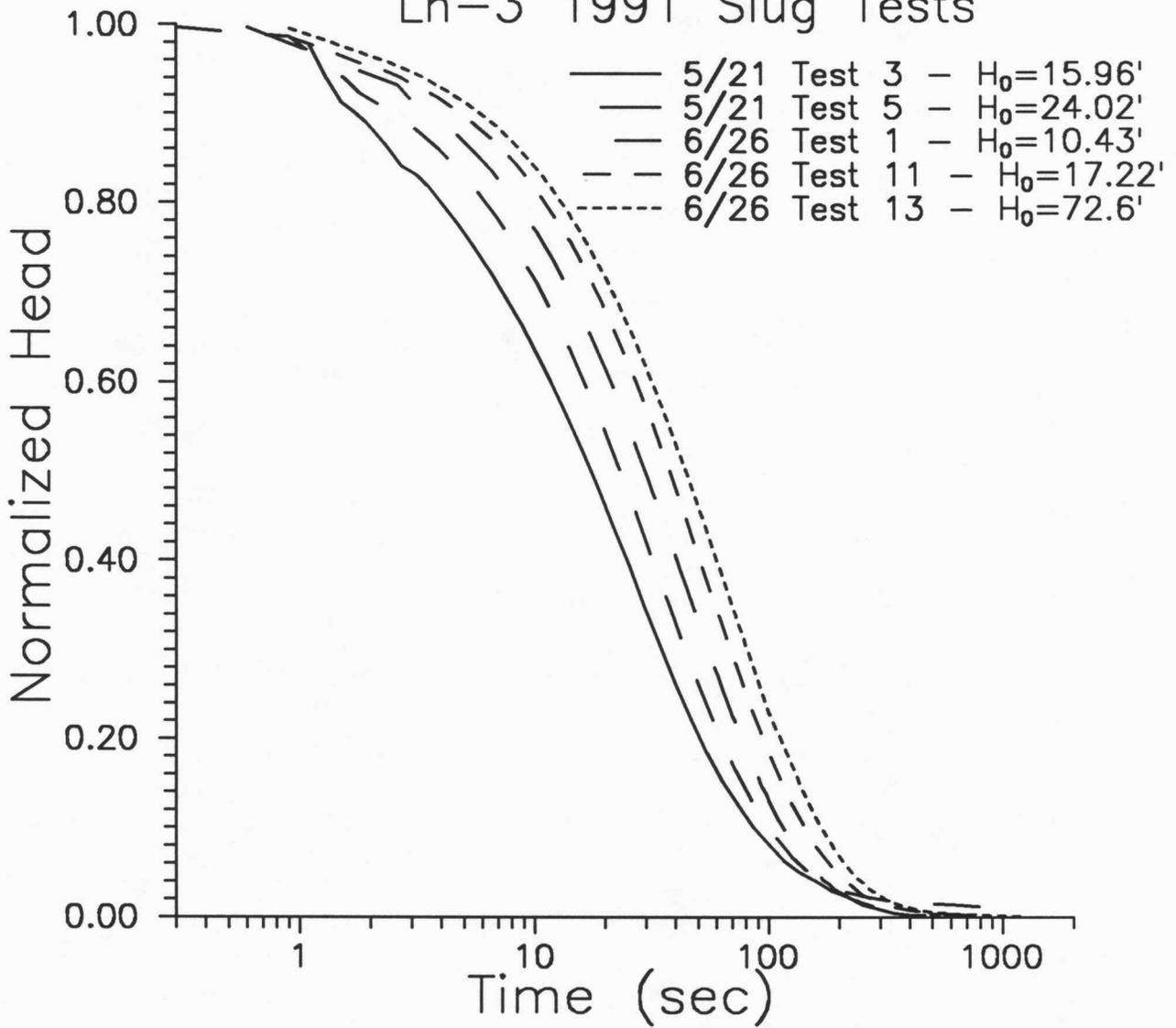


FIGURE 2  
Lincoln County Site  
Ln-3 1991 Slug Tests



## 2. Two or more different slug sizes should be used during testing at a given well

Conventional theory maintains that slug-test responses should be independent of the magnitude of the initial displacement ( $H_0$ ). In systems of moderate to low permeability (e.g., Figure 1), this assumption appears quite sound. In very permeable systems, however, a dependence on  $H_0$  is often seen. Figure 3 is a plot from a series of tests in the alluvial aquifer underlying the Geohydrologic Experimental and Monitoring Site (GEMS) in Douglas County, Kansas. A very strong dependence on  $H_0$  is seen in these data, producing an inverse relationship between  $H_0$  and hydraulic conductivity estimates obtained using conventional methods (i.e. Hvorslev (1951) and Cooper et al. (1967)). Note that the tests displayed on Figure 3 were done in a cyclic fashion from low to high  $H_0$ . As shown in the figure, repeat tests with the same approximate  $H_0$  from different cycles coincided, verifying that the observed behavior is a function of  $H_0$  and not a result of an evolving skin. In order to identify a dependence on  $H_0$ , a series of tests in which  $H_0$  varies between tests should be performed. The first and last tests should use the same  $H_0$  so that the effects of an evolving skin can be separated from the  $H_0$  dependence. Figures 4A and 4B display response data from such a test series. The coincidence of the normalized plots on Figure 4B indicates that the test responses are independent of  $H_0$ , the formation is not being altered during testing, and that the responses are independent of whether the slug was induced by raising or lowering the water level in the well. It is strongly recommended that such a series of tests always be performed. Failure to do so can potentially introduce considerable error into the hydraulic conductivity estimates obtained from a program of slug tests.

FIGURE 3

GEMS Well 2-5  
11/2/90 Slug Tests

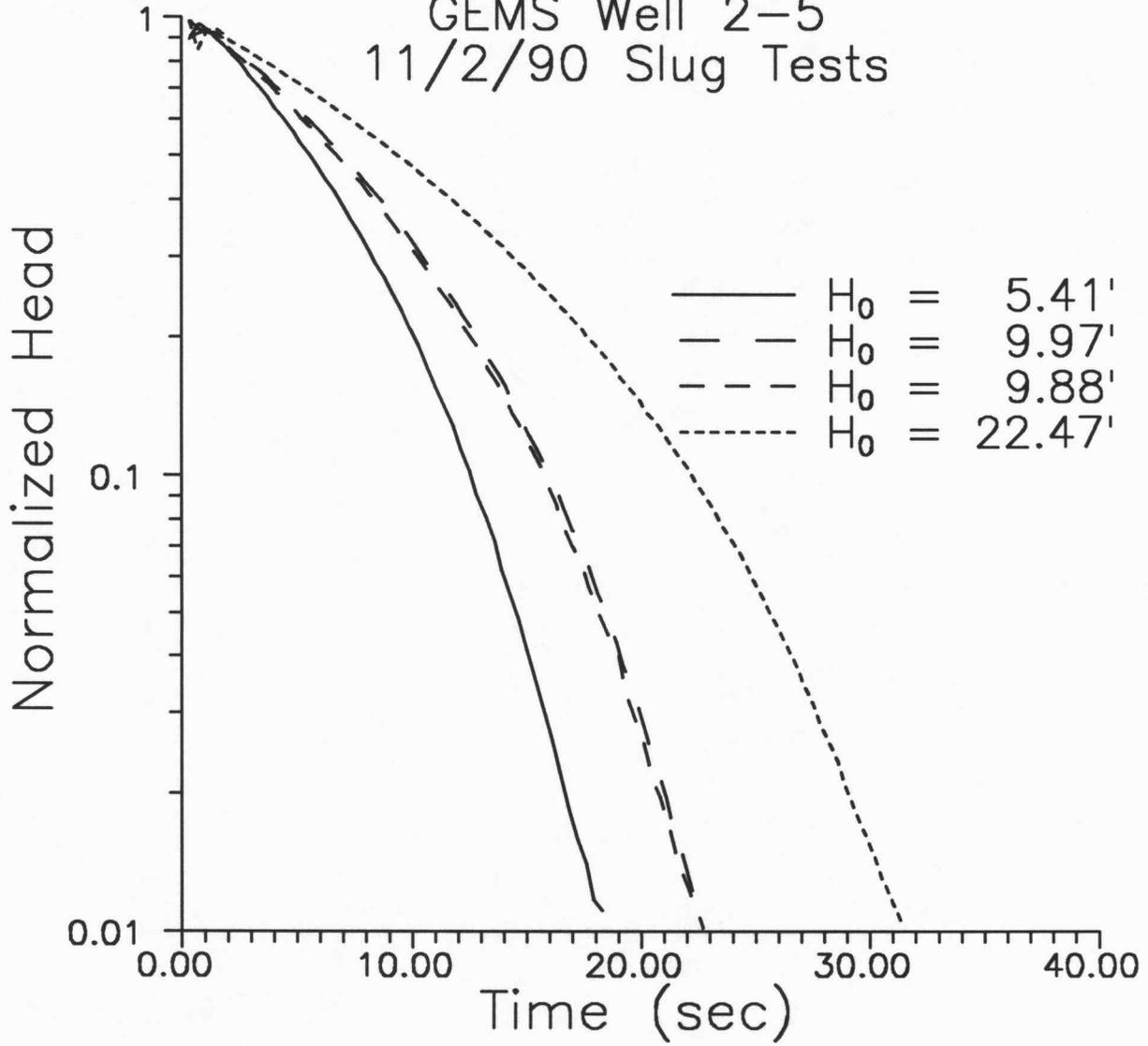


FIGURE 4A

Stafford County Site 16, Well #3  
10/15/93 Slug Tests

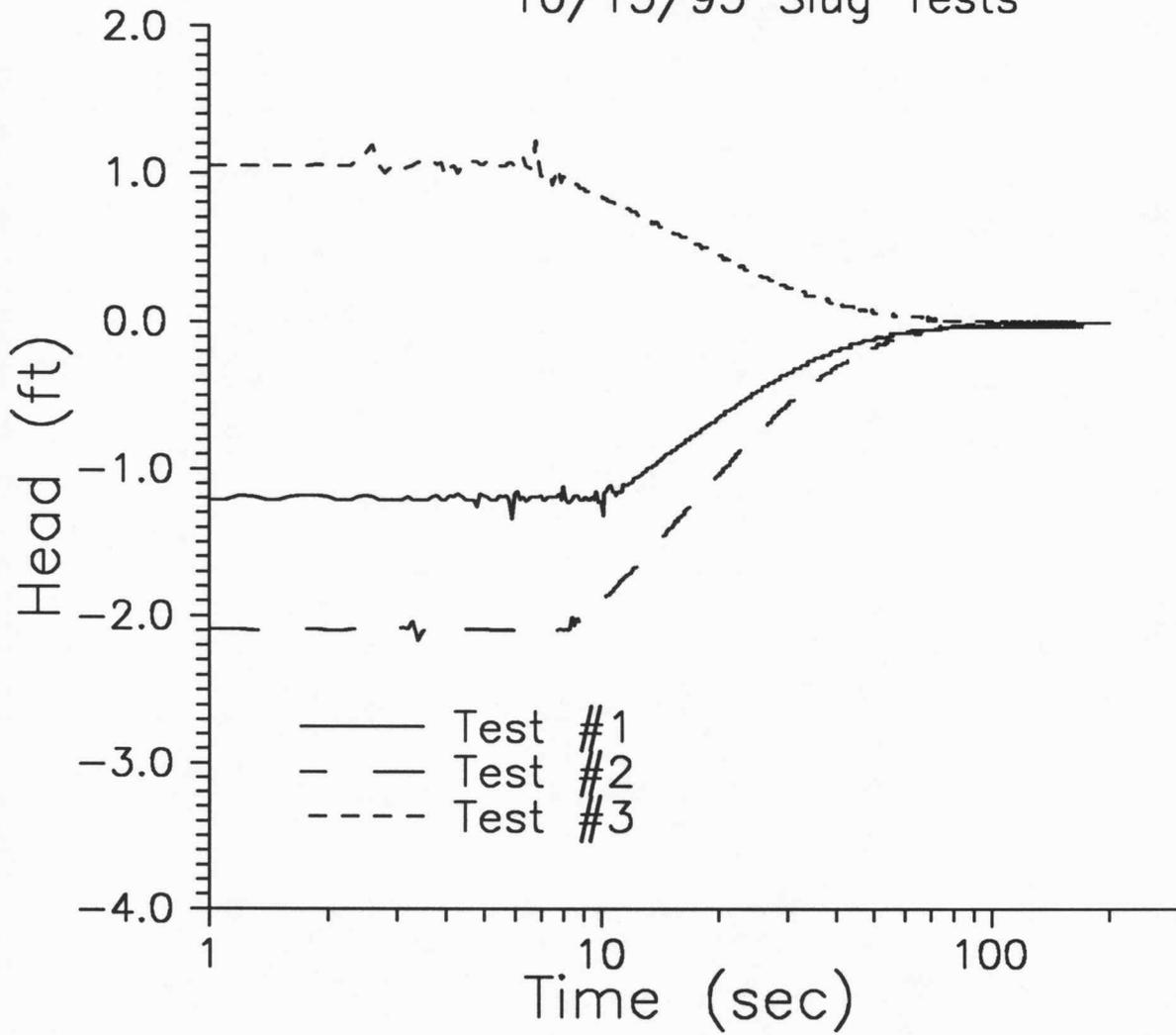
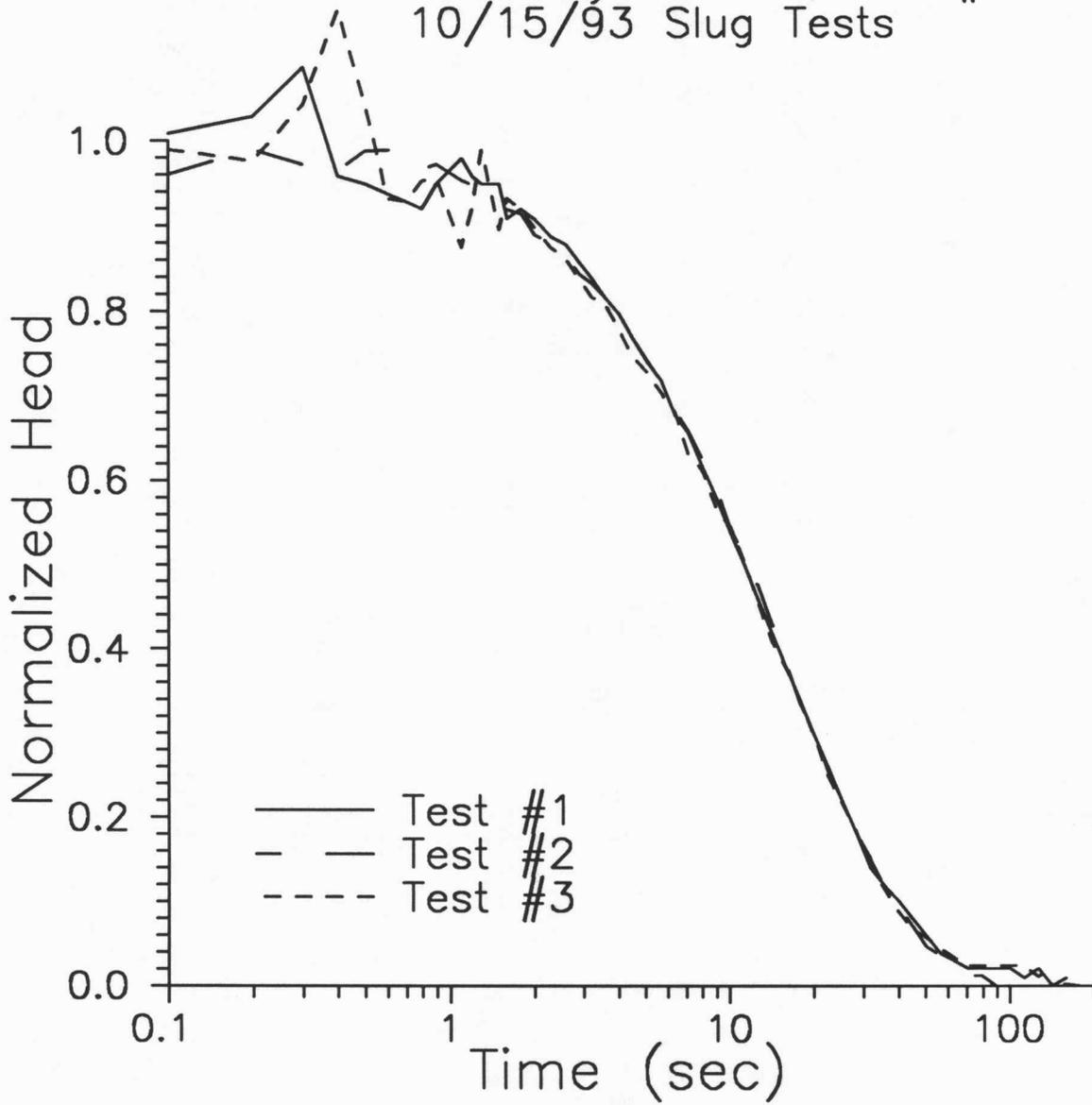


FIGURE 4B

Stafford County Site 16, Well #3  
10/15/93 Slug Tests

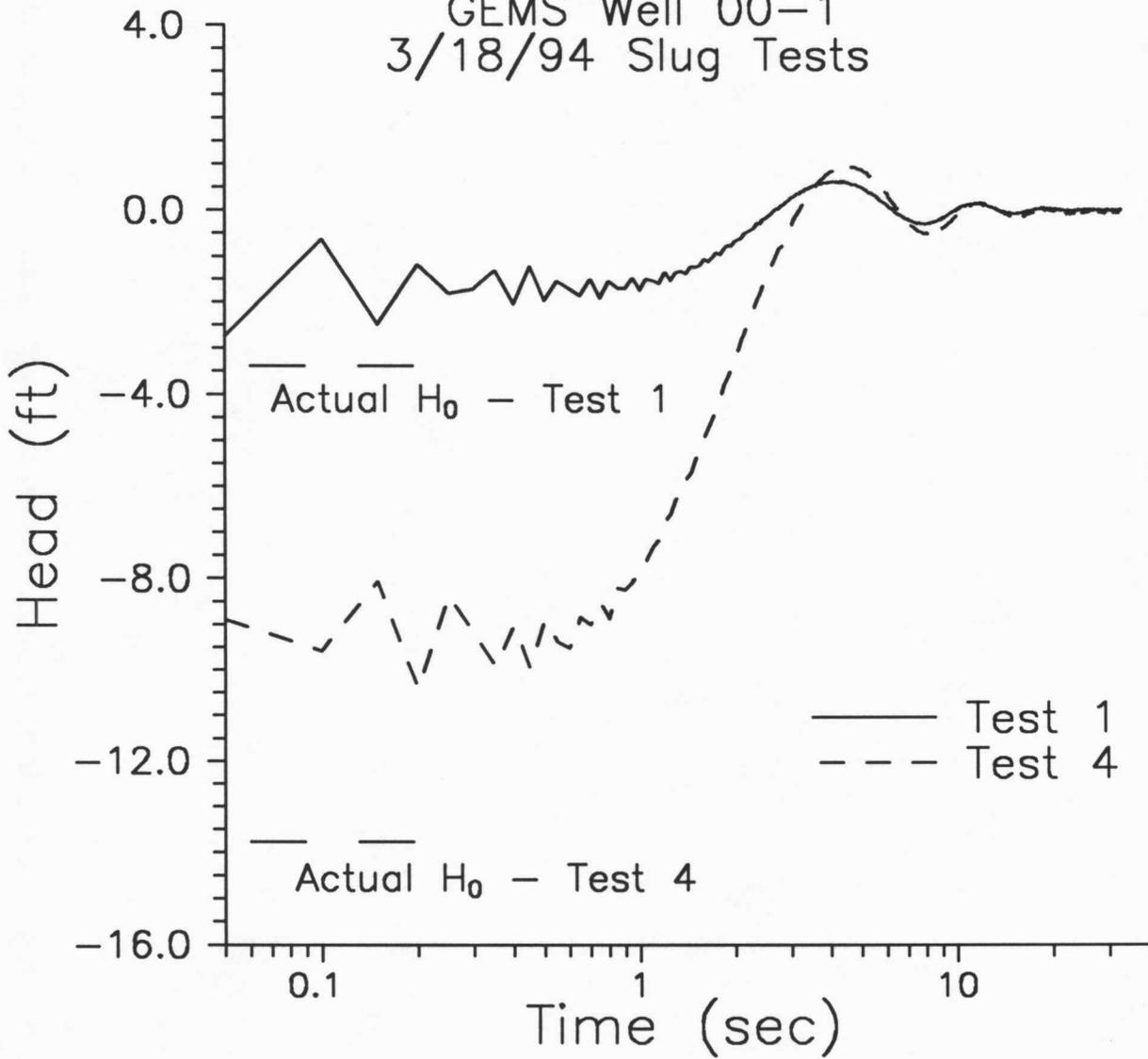


### 3. A good estimate of the initial displacement should be obtained

Conventional methodology for the analysis of slug-test data requires that the magnitude of the initial displacement ( $H_0$ ) be known. Therefore, the method used to initiate a slug test must enable a good estimate of  $H_0$  to be obtained. In systems of moderate to low permeability, measurements taken immediately after test initiation should yield a very good estimate of  $H_0$ . In rapidly responding systems, however, such measurements may not be sufficient. Figure 5 displays data from a series of tests in which the slug was introduced by pneumatic means (i.e. pressurizing the air column in the well casing (producing a depression of the water level) followed by a near-instantaneous depressurization). The actual  $H_0$  values shown in Figure 5 (3.39' and 13.78' for tests 1 and 4, respectively) are based on measurements of the air pressure in the well casing using a high-accuracy gas pressure transducer, while the head readings were taken using submersible pressure transducers. The difference between the  $H_0$  readings taken with the gas pressure transducer and the submersible pressure transducers (0.64' and 3.37' for tests 1 and 4, respectively) leads to a lower-than-actual estimate of hydraulic conductivity when only the submersible transducer readings are used. Further testing at the same site showed that the difference between the  $H_0$  readings did not exist at wells screened in material of moderate to low permeability. Although the example displayed in Figure 5 was from a pneumatic slug test, similar uncertainty regarding  $H_0$  will arise in tests initiated by the addition or removal of a solid slug. Packer-based systems, in which the slug is introduced by opening the central pipe upon which the packer is mounted, provide one means of obtaining good estimates of  $H_0$  in very permeable systems.

FIGURE 5

GEMS Well 00-1  
3/18/94 Slug Tests



#### **4. Appropriate data acquisition equipment should be employed**

Responses to a slug-induced disturbance can be measured either manually (electric tape, plopper, etc.) or electronically (pressure transducers connected to a data logger). For tests in wells screened in formations of moderate to low permeability, such as shown in Figure 1, manual methods can provide measurements of sufficient quality as long as a good estimate of  $H_0$  is available. However, for tests in more permeable systems, such as shown in Figures 3-5, electronic methods must be employed, as manual methods will not provide measurements of sufficient density or accuracy. Earlier theoretical work (McElwee et al., 1989) has shown that the reliability of parameter estimates is closely tied to the density and accuracy of measurements. In very rapidly responding wells (e.g., Figures 3 and 5), data acquisition rates of at least several hertz are needed in order to clearly define the nature of the responses. Note that the need for rapid acquisition rates is of special concern in oscillating systems where slow collection rates will produce aliasing and other effects that may make data interpretation and analysis difficult.

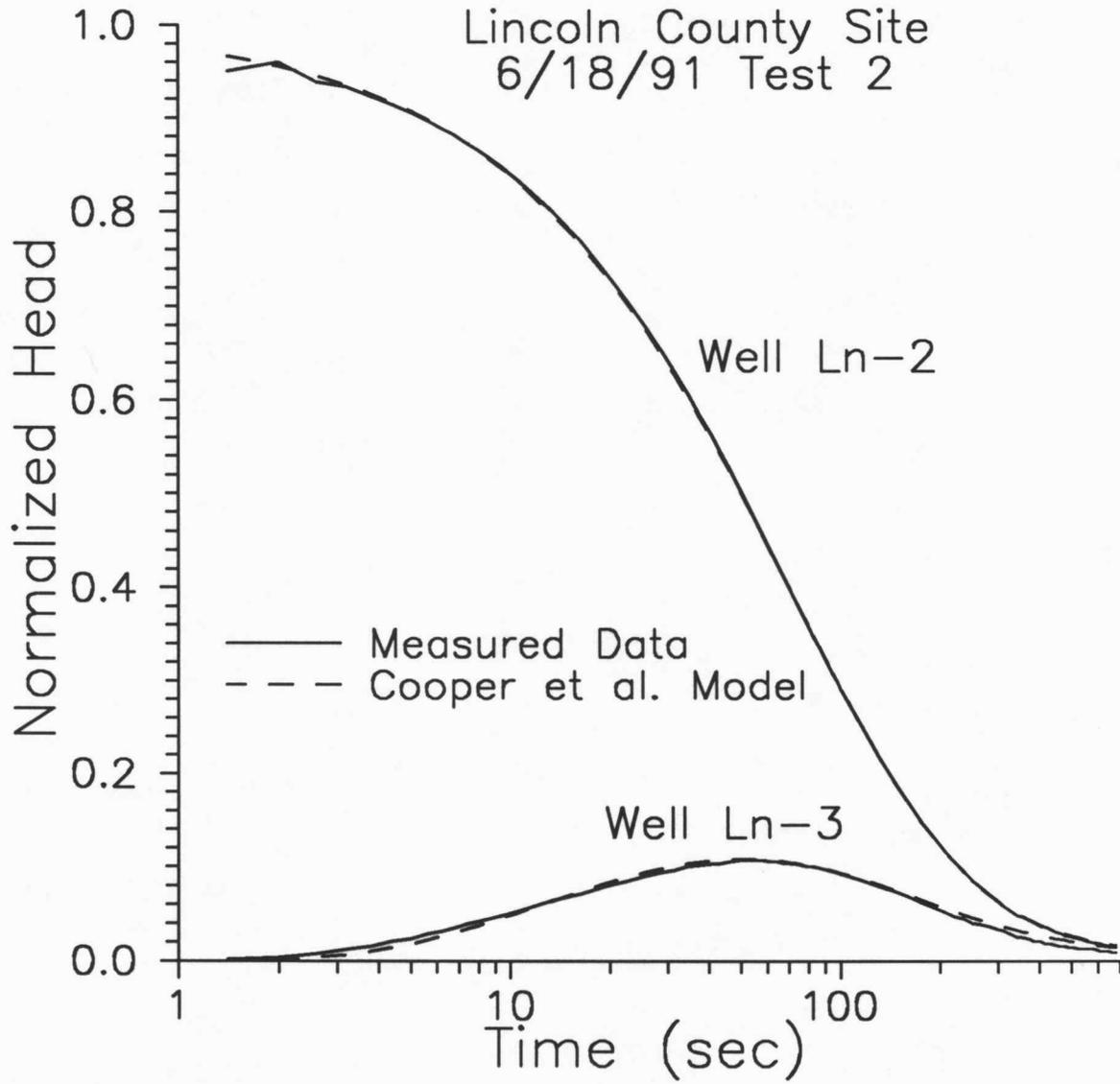
#### **5. An observation well should be employed for estimation of the storage parameter**

It has been frequently observed that slug-test responses are relatively insensitive to the value of the storage parameter (e.g., Cooper et al., 1967). McElwee et al. (1989) have used sensitivity analysis to demonstrate that reliable estimates of the storage parameter will be difficult to obtain using the density and quality of data that are normally collected during a single-well slug test. A primary reason for this condition is that the measured responses at the test well are much more sensitive to

transmissivity than to the storage parameter. The limited sensitivity to storage that does exist is highly correlated with the sensitivity to transmissivity. In addition, any uncertainties about the effective screen radius (nominal screen radius or radius of gravel pack or radius of developed zone) will have a much larger effect on storage estimates than on transmissivity estimates. Use of an observation well during a slug test can greatly improve this situation as the insensitivity and correlation effects are dramatically lessened (McElwee et al., 1991). Uncertainties about the effective screen radius also have much less of an effect when data from an observation well are used. Figure 6 displays data from a multi-well slug test at the same site as in Figure 1. The two wells, which are screened over similar intervals, are 21.17' apart. Owing primarily to uncertainty about the effective screen radius, the estimate of specific storage obtained using data from Ln-2 alone is too large by a factor of 4. When the analysis is performed using data from both wells, a specific storage estimate in keeping with other information is obtained. Note that measurements from the observation well were taken using a transducer placed below a packer located just above the screen. The observation well was packed off in order to remove the lagging and damping of responses that occurs due to wellbore storage at the observation well. Although it may not be practical to install observation wells solely for use in slug tests, the density of pre-existing monitoring wells is often such that this technique can be readily employed. Generally, the observation well must be fairly close (within 30-40') to the test well in order that the signal can be discerned from background noise.

FIGURE 6

Lincoln County Site  
6/18/91 Test 2



## 6. Method chosen for data analysis must be appropriate for site conditions

Most analyses of slug-test data are performed using one of four techniques: 1) the method of Hvorslev (1951) for fully and partially penetrating wells in confined aquifers; 2) the method of Bouwer and Rice (1976) for wells in unconfined aquifers screened below the water table; 3) the method of Cooper et al. (1967) for fully penetrating wells in confined aquifers; and 4) the method of Nguyen and Pinder (1984) for partially penetrating wells in confined aquifers. Recent theoretical work at the KGS has focussed on the quality of the estimates provided by these techniques. Figure 7 displays the results of a theoretical analysis of the error introduced into parameter estimates when applying the Cooper et al. model to data from a partially penetrating well. The  $\psi$  quantity plotted on the x axis is the square root of the anisotropy ratio ( $K_v/K_r$ ) over the aspect ratio ( $b/r_w$  where  $b$  is the screen length). The quantity plotted on the y axis is the hydraulic conductivity estimate provided by the Cooper et al. model over the actual conductivity value. This plot indicates that Cooper et al. estimates improve as  $\psi$  decreases, i.e. the proportion of vertical flow decreases. Figure 8 displays results of a similar analysis for the Hvorslev technique. In this case, an anisotropy ratio must be assumed, producing a  $\psi^*$  value (square root of assumed anisotropy ratio over the aspect ratio) that is used in the analysis. Hyder et al. (in review) and Hyder and Butler (in press) further describe theoretical analyses of the Cooper et al., Hvorslev, and Bouwer and Rice techniques. Note that Butler and Hyder (1993) have shown that parameter estimates obtained using the Nguyen and Pinder method must be viewed with skepticism owing to an error in the analytical solution upon which that model is based.

FIGURE 7

Error Introduced by Cooper et al. Model  
When Applied to Case of Partially  
Penetrating Well

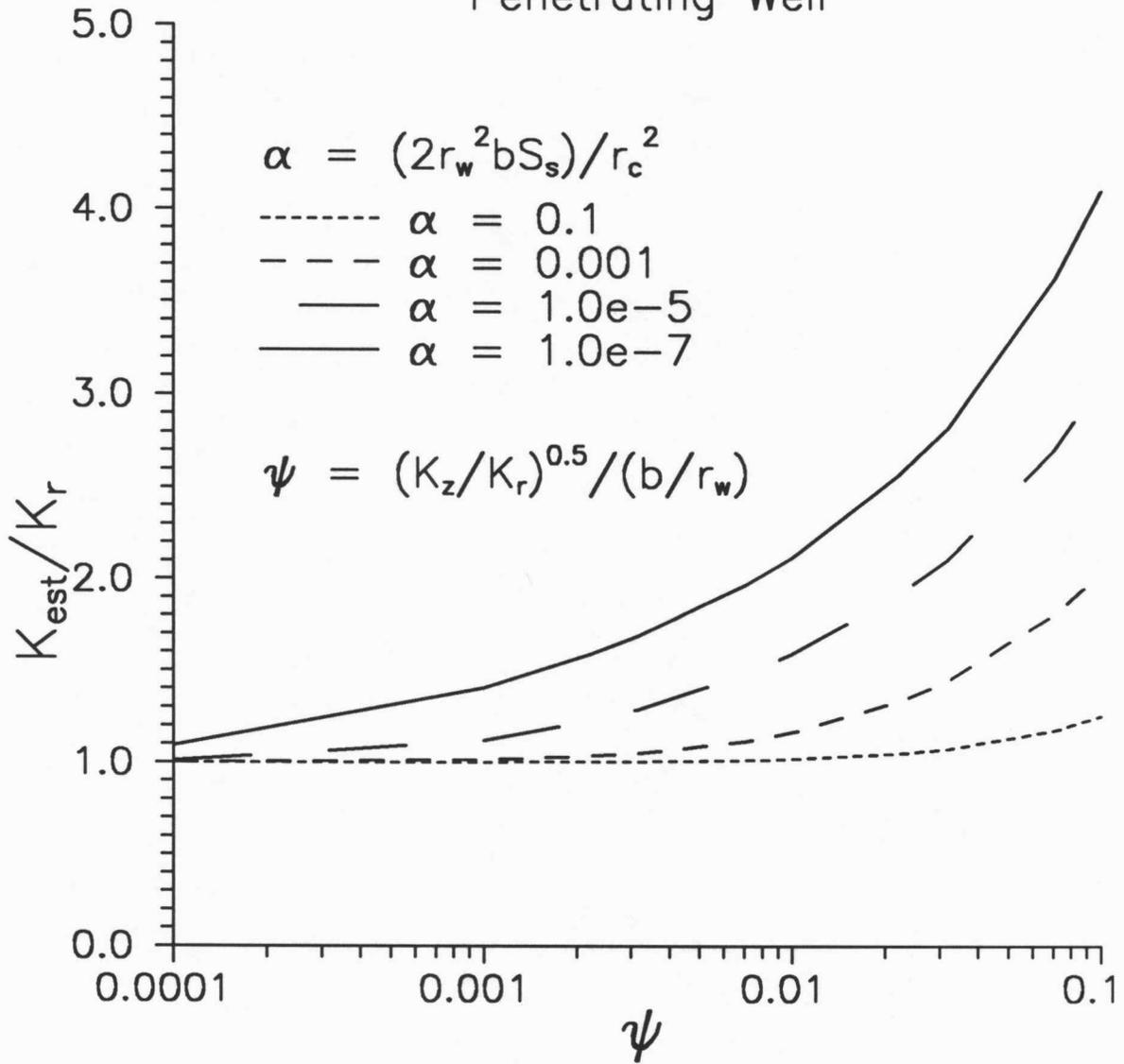
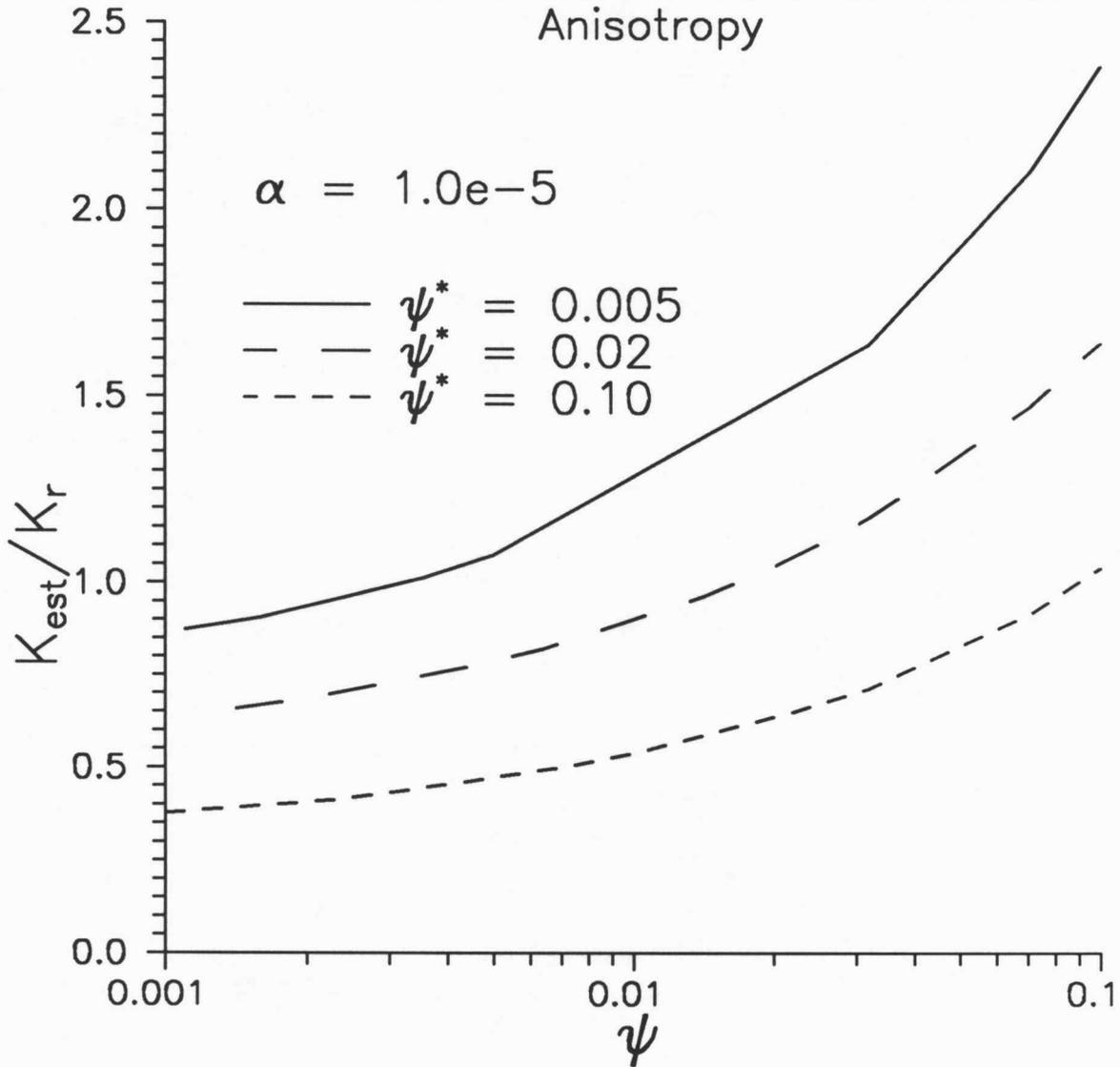


FIGURE 8

Error Introduced by Partially Penetrating  
Hvorslev Model in Case of Unknown  
Anisotropy



## 7. Use of pre- and post-analysis plots should be an integral component of the analysis

Currently, the vast majority of analyses of slug-test data are performed using automated fitting programs or procedures involving manual fitting of straight lines to test data. Unfortunately, all too often, the analysis is performed by rote with little attention paid to the form of the plots and the nature of the fit of the theoretical model to the test data. If the reliability of parameter estimates from slug tests is to be improved, more attention must be paid to all aspects of the analysis. Three examples are briefly given here in support of these statements.

Figure 9 displays data and the best-fit Cooper et al. model from a test at the Lincoln County site ( $r_w=.23'$ ,  $r_c=.08'$ ,  $b=13'$ ). Note that a constant specific storage of  $1.0e-6 \text{ ft}^{-1}$  was assumed for this analysis based on an estimate obtained from a test at a higher interval at this site (Fig. 6). The model fit in this case must be considered quite poor. The systematic deviation between fitted model and test data can be readily explained by an assumed specific storage that is too low. Justification for a higher specific storage can be found in Figure 10, which is a data plot in a semilog Hvorslev format. The distinct concave upward curvature seen on this plot is strong evidence (for a well of this aspect ratio) that the specific storage for the test interval is quite large. Therefore, the analysis was repeated without constraining the value of specific storage. Figure 11 displays the very good fit that was then obtained (estimated specific storage =  $.000125 \text{ ft}^{-1}$  corresponding to an  $\alpha$  value of 0.013). Note that the hydraulic conductivity estimate decreased by over a factor of 2 between the analyses of Figures 9 and 11, a further indication of the importance that must be paid to deviations between the

fitted theoretical model and the test data. Also note that the good match shown in Figure 11 between the Cooper et al. model and the test data would be predicted from Figure 7 for a well of this aspect ratio ( $b/r_w=56$ ), given the large  $\alpha$  value.

Figure 12 displays data and the best-fit Cooper et al. model from a test at a site in Pratt County, Kansas ( $r_w=.41'$ ,  $r_c=.21'$ ,  $b=5'$ ). Again, a systematic deviation between the measured data and the Cooper et al. model is shown. This type of deviation is often seen when applying a fully penetrating model to partially penetrating data. Given the small aspect ratio of this well (12.2), the data were reanalyzed using a partially penetrating slug-test model that has been developed at the KGS (Hyder et al., in review). This model, which is equivalent to that of Dougherty and Babu (1984) in the isotropic case, has been thoroughly tested using analytical and numerical approaches. Figure 13 displays the fit resulting from an analysis with the isotropic version of the KGS model. Note that the dramatic improvement in model fit between Figures 12 and 13 was not accompanied by an increase in the number of estimated parameters. Also note that the hydraulic conductivity estimate provided by the Cooper et al. model is 2.4 times larger than the KGS conductivity estimate, an overprediction by the Cooper et al. model very close to what would be theoretically predicted from Figure 7 for a well of this aspect ratio in an isotropic formation, given the assumed  $\alpha$  of  $4.0e-5$ .

A final example illustrates the effect of a low-conductivity skin. Figure 14 displays data in a semilog Hvorslev format from two tests in the series shown on Figure 2. Note that the degree of curvature of the plotted data is significantly smaller in test 11 than in test 3, very strong evidence of an evolving low-permeability skin. Figure 15 is a

plot of the test data and the best-fit Cooper et al. models. Note that the nature of the deviation between the test data and the best-fit models changes between the two tests. The decrease in the degree of curvature on Figure 14 and the change in the nature of the deviation seen on Figure 15 are very strong evidence of a developing low-permeability skin. Considerable more well development is required before parameter estimates of much reliability can be obtained from this well.

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FIGURE 9  
Lincoln County Site  
Ln-1 Slug Test - 6/14/91

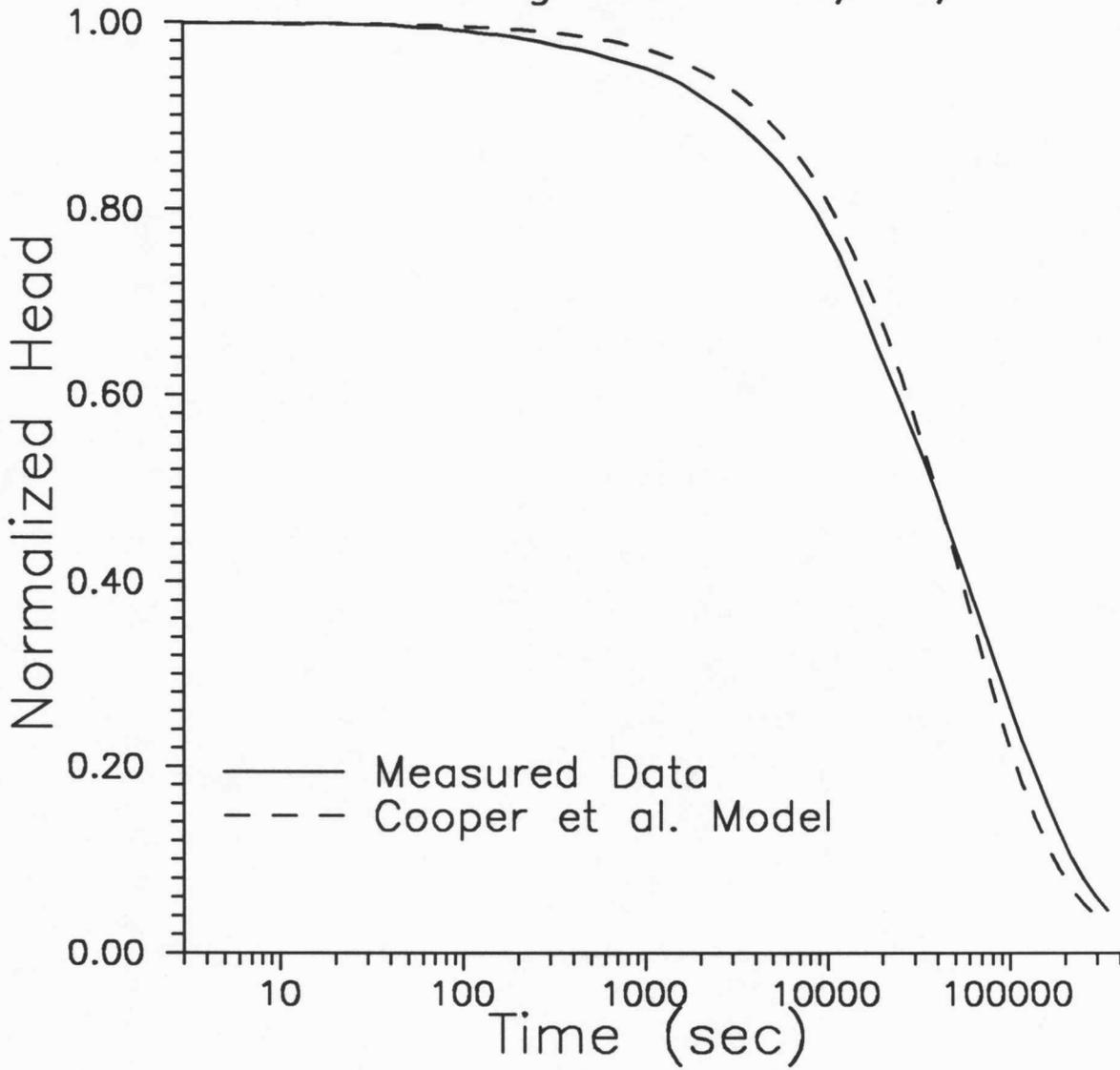


FIGURE 10  
Lincoln County Site  
Ln-1 Slug Test - 6/14/91

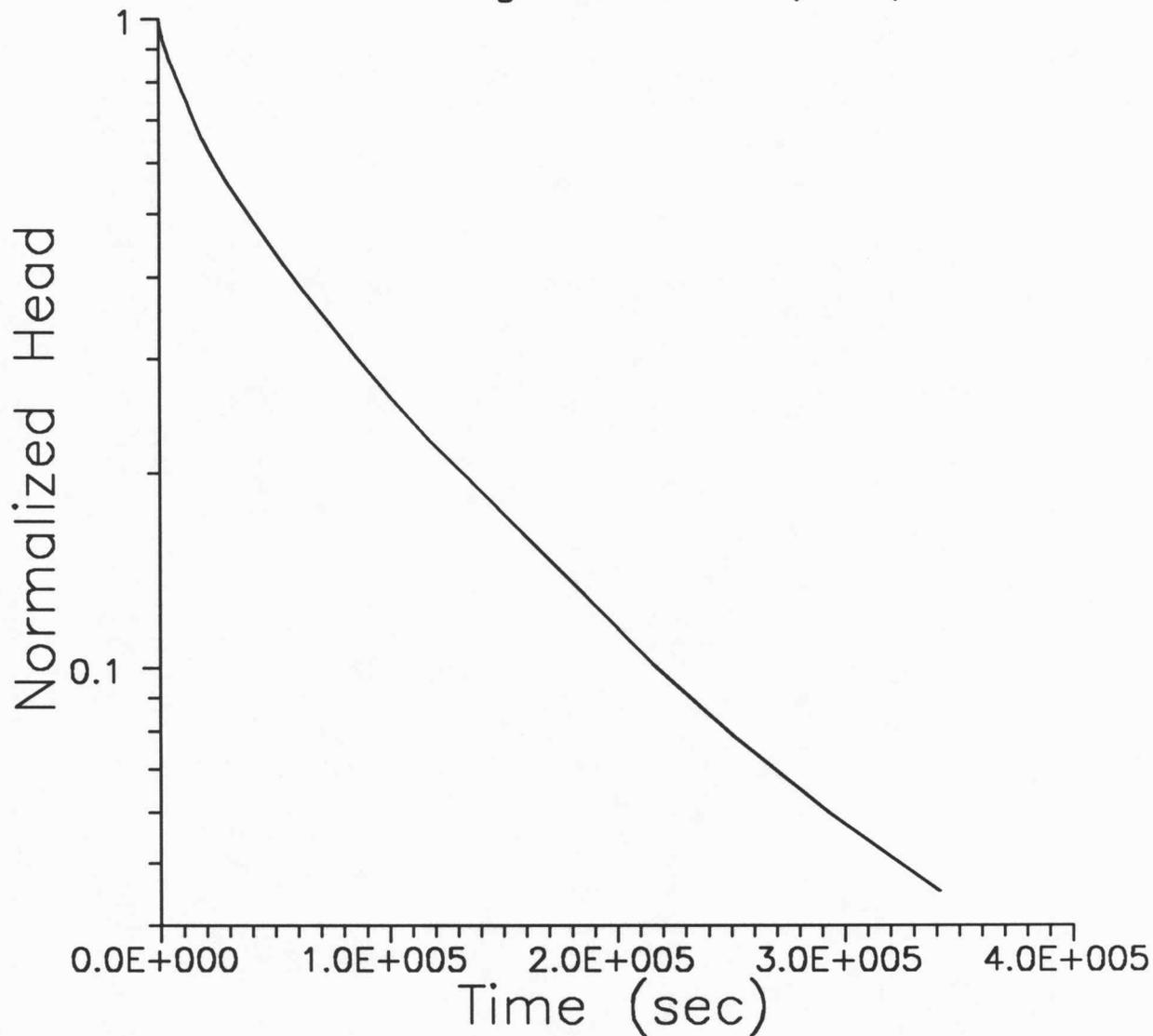


FIGURE 11  
Lincoln County Site  
Ln-1 Slug Test - 6/14/91

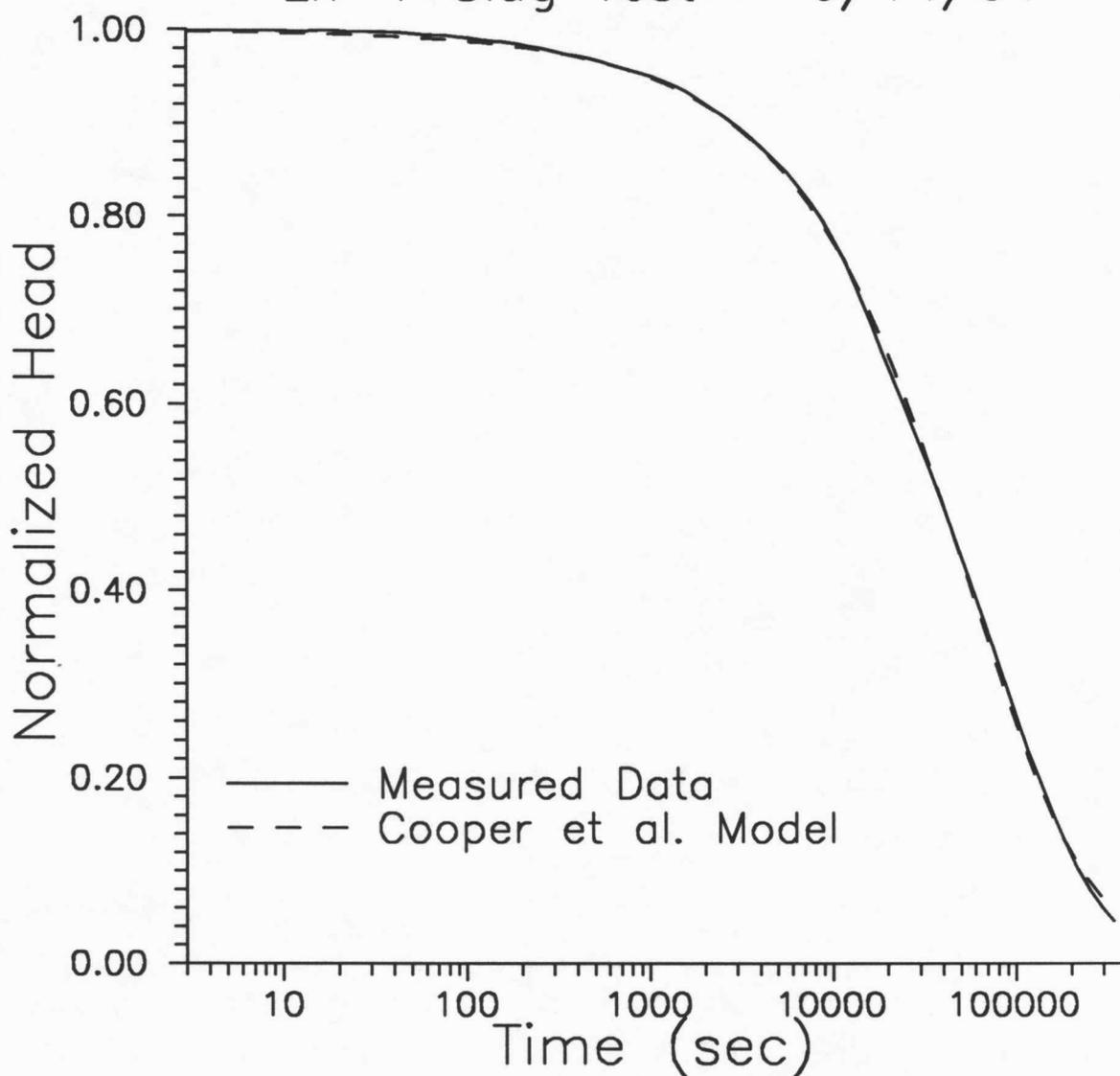


FIGURE 12

Pratt County Site 36, Well #3  
10/15/93 Slug Test #1

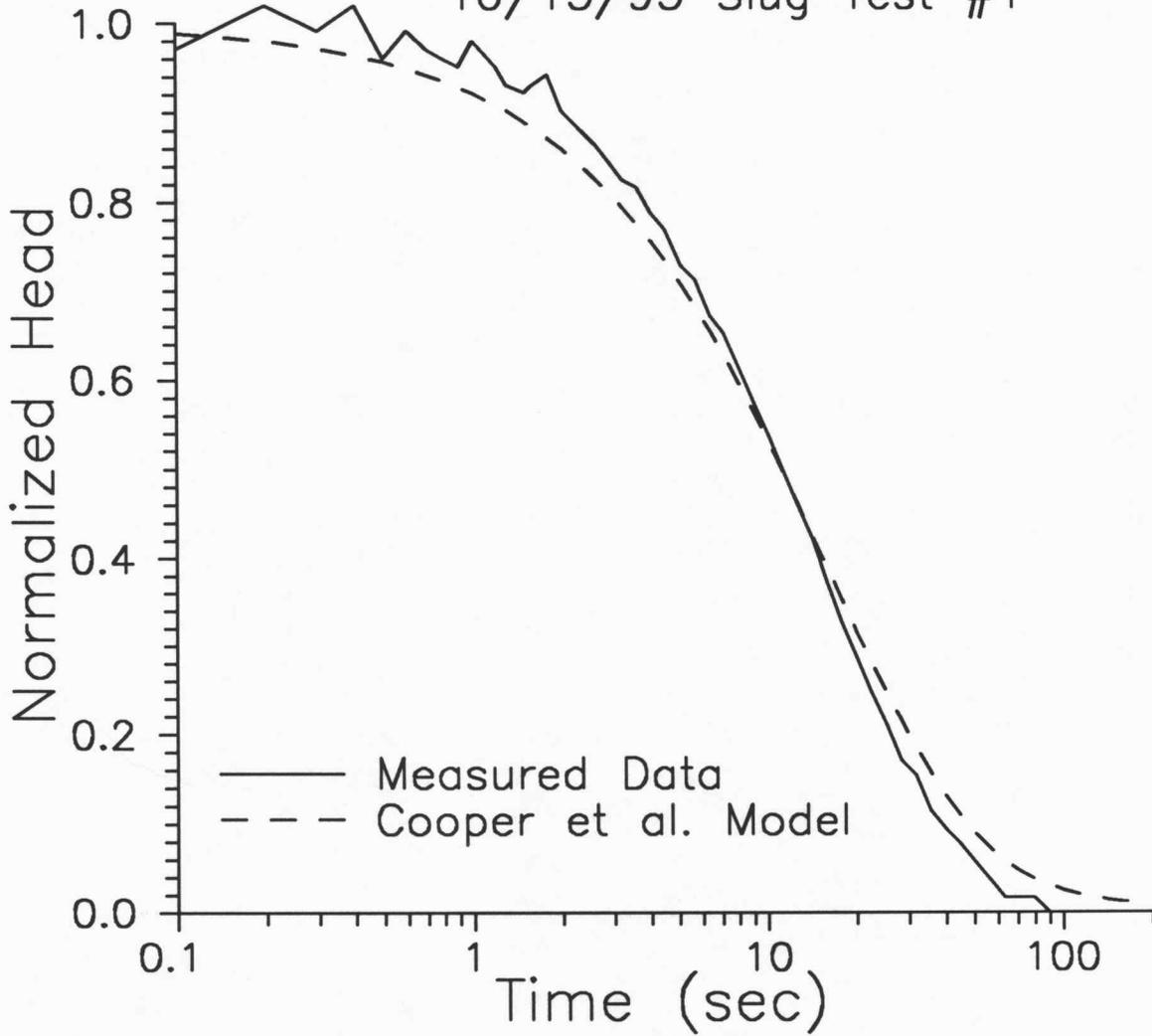


FIGURE 13

Pratt County Site 36, Well #3  
10/15/93 Slug Test #1

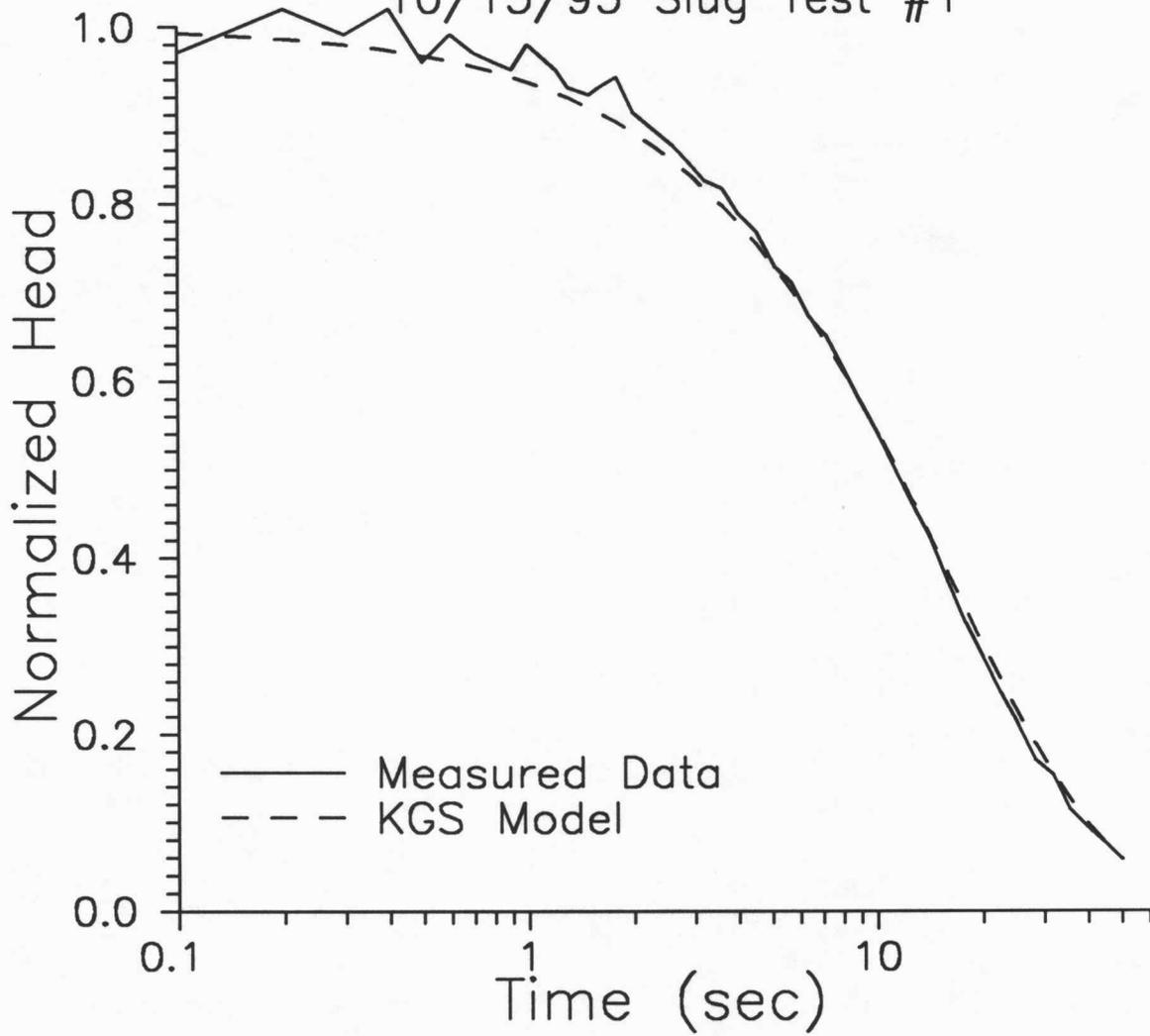


FIGURE 14  
Lincoln County Site  
Ln-3 Slug Tests

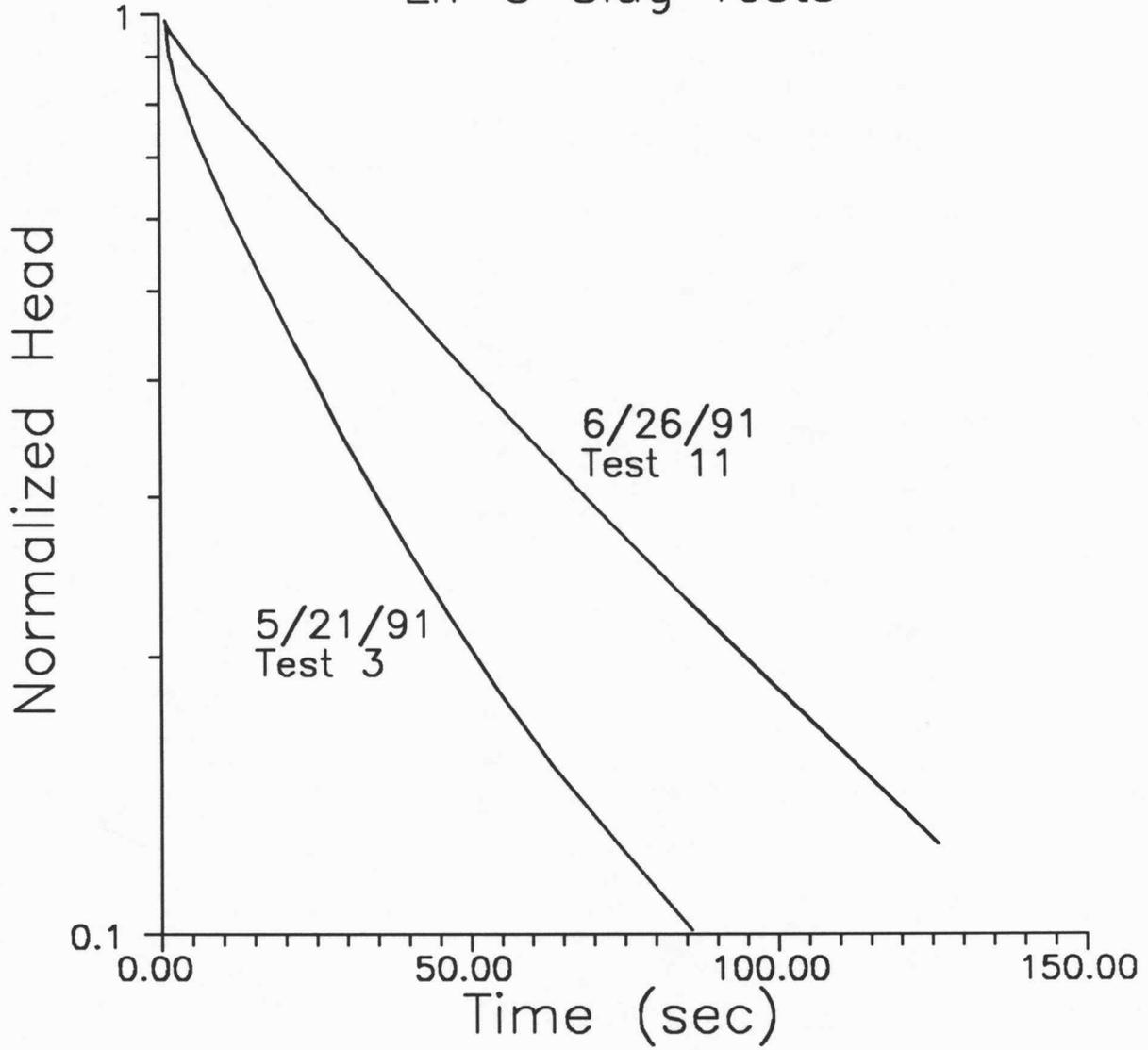
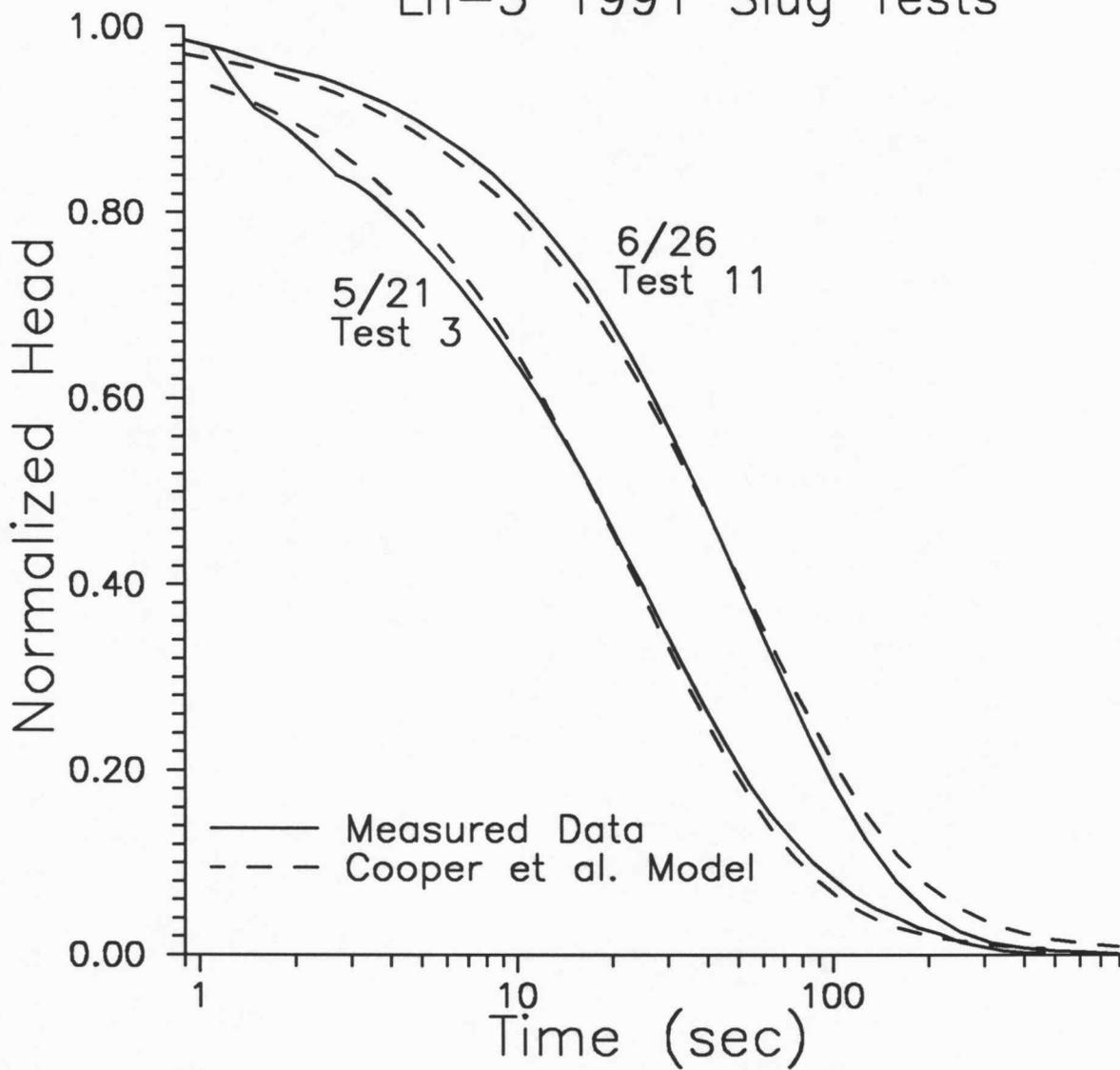


FIGURE 15  
Lincoln County Site  
Ln-3 1991 Slug Tests



## REFERENCES

- Bouwer, H., and R.C. Rice, A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resour. Res.*, 12(3), 423-428, 1976.
- Butler, J.J., Jr., and Z. Hyder, An assessment of the Nguyen and Pinder method for slug test analysis, KGS Open-File Rept.#93-46, Kansas Geological Survey, 25 pp., 1993.
- Cooper, H.H., Jr., J.D. Bredehoeft, and I.S. Papadopoulos, Response of a finite-diameter well to an instantaneous charge of water, *Water Resour. Res.*, 3(1), 263-269, 1967.
- Dougherty, D.E., and D.K. Babu, Flow to a partially penetrating well in a double-porosity reservoir, *Water Resour. Res.*, 20(8), 1116-1122, 1984.
- Hvorslev, M.J., Time lag and soil permeability in ground-water observations, Bull no. 36, *Waterways Exper. Sta., Corps of Engrs., U.S. Army*, 50 pp., 1951.
- Hyder, Z., and J.J. Butler, Jr., Slug tests in unconfined formations: An assessment of the Bouwer and Rice technique, *Ground Water*, in press.
- Hyder, Z., J.J. Butler, Jr., C.D. McElwee, and W.Z. Liu, Slug tests in partially penetrating wells, *Water Resour. Res.*, in review.
- McElwee, C. D., Bohling, G. C., and J. J. Butler, Jr., Sensitivity analysis of slug tests, KGS Open-File Report 89-33, 29 pp., 1989.
- McElwee, C.D., Butler, J.J., Jr., Bohling, G.C., and W.Z. Liu, The use of observation wells with slug tests, KGS Open-File Report 91-63, 32 pp., 1991.
- Nguyen, V., and G.F. Pinder, Direct calculation of aquifer parameters in slug test analysis, in *Groundwater Hydraulics*, AGU Water Resour. Monogr. No. 9, edited by J. Rosenshein and G.D. Bennett, American Geophysical Union, Washington, D.C., 222-239, 1984.