Slug Tests in Site Characterization: Some Practical Considerations

James J. Butler Jr.
Kansas Geological Survey
1930 Constant Ave., Campus West
University of Kansas
Lawrence, KS   66047

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ABSTRACT

The slug test is currently the most common method for the in situ estimation of hydraulic conductivity at sites of suspected groundwater contamination. It is widely recognized, however, that the quality of the parameter estimates obtained using this technique can vary tremendously. The success of a program of slug tests critically depends on well installation and development procedures, as field data have repeatedly shown that low-permeability (low-K) well skins are the largest source of error in slug-test estimates. Theoretical analyses have demonstrated that hydraulic-conductivity estimates from slug tests in wells with low-K skins are often of limited value, regardless of the particular approach used to analyze the response data. It is therefore imperative that a low-K skin be identified through a program of repeat slug tests. Recently, a series of practical guidelines for the performance and analysis of slug tests has been developed at the Kansas Geological Survey in an attempt to improve the quality of slug-test estimates. A subset of these guidelines was presented in Butler et al. (1996). Additional guidelines of relevance to the field practitioner are described here.

INTRODUCTION

The slug test is a very commonly used technique for the in situ estimation of hydraulic conductivity at sites of suspected groundwater contamination (Chirlin, 1990; Butler et al., 1996). This approach, which is quite simple in practice, consists of measuring the recovery of head in a well after a near-instantaneous change in water level at that well. The recovery data can be used to estimate the hydraulic conductivity of the formation adjacent to the screened (open) interval of the well through comparisons with theoretical models of test responses. The widespread use of this technique in the environmental industry cannot be overemphasized, as literally tens of thousands of these tests are performed each year in the United States alone. The slug test has become so prevalent primarily as a result of its simplicity and low cost, its utility in low-permeability formations where pumping tests may not be feasible, and the fact that the approach can be configured so that no water is actually removed from or added to the well during the course of testing (e.g., Levy and Pannell, 1991).

Over the last three decades, a significant amount of work has been directed at developing theoretical models for use in the analysis of the head data collected during a slug test (see Hyder et al. (1994) and references therein). Although considerable work has also been directed at very practical aspects of the approach, relatively little of that work has actually appeared in the published literature. Standard texts on well hydraulics that discuss slug tests essentially just summarize the theoretical

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models that can be used to analyze slug-test data (e.g., Kruseman and de Ridder, 1990; Dawson and Istok, 1991). Little, if any, discussion of how the technique should be applied in practice is provided. With limited guidance from the literature, field practitioners often must resort to ad-hoc approaches, the ramifications of which may not be fully understood. The result is that the quality of parameter estimates obtained from slug tests can vary tremendously. Clearly, significantly more attention must be given to the practical aspects of the methodology before this technique can be expected to provide reliable estimates of the hydraulic conductivity of a formation on a consistent basis.

Over the last six years, the Kansas Geological Survey has carried out extensive theoretical and field research on slug tests. A major product of this work has been the definition of a series of practical guidelines. Butler et al. (1996) describe a subset of these guidelines, strongly emphasizing the need for both thorough well development and repeat slug tests. Space limitations, however, prevented those authors from discussing several guidelines of considerable relevance to the field practitioner. The purpose of this article is to briefly describe these additional guidelines of practical importance. Tests from a variety of field sites, in conjunction with numerical simulations, will be used to demonstrate the significance of the proposed guidelines.

PRACTICAL SLUG-TEST GUIDELINES

THE PRESENCE OF A LOW-PERMEABILITY SKIN MUST BE RECOGNIZED

As stated by Butler et al. (1996), the failure to recognize the existence of a low-permeability (low-K) well skin is undoubtedly the largest source of error in parameter estimates obtained from slug tests. Butler and Healey (1995b) describe two field examples that demonstrate the ubiquitous nature of low-K well skins and the magnitude of the error introduced into the hydraulic-conductivity estimate when a low-K skin is present. They speculate that the widely observed difference between hydraulic-conductivity estimates obtained from slug tests and those from pumping tests (slug-test estimates are usually less than estimates from pumping tests) is primarily a product of low-K skins produced by residual drilling debris and/or products of biochemical processes.

Although theoretical models for slug tests in wells with skins exist (e.g., Ramey et al., 1975; Moench and Hsieh, 1985; Hyder et al., 1994), these models are of quite limited use in practice. The primary reason for this is the nonuniqueness of test responses in the presence of a low-K skin, which has been theoretically demonstrated by Moench and Hsieh (1985) among others, coupled with the nonidealities (e.g., sensor noise, formation layering, poor well construction, etc.) common to field applications. This nonuniqueness of test responses is especially pronounced in wells that are screened over a limited portion of the formation, which is the usual configuration at sites of suspected groundwater

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contamination. Thus, a reliable estimate of the formation hydraulic conductivity may be virtually impossible to obtain from a slug test in a well with a low-K skin under conditions common to environmental applications.

In the petroleum industry, however, the slug test is considerably more useful in wells with low-K skins because petroleum applications commonly involve much deeper wells than those used in groundwater investigations. The head disturbance initiating a slug test is often on the order of hundreds to thousands of meters of water in petroleum applications, in contrast to the less-than-one to two meter range commonly used in the environmental industry. The much larger initial head disturbance allows the data to be analyzed using techniques that are based on large-time approximations to the theoretical models (see Sageev (1986) and references therein). These large-time techniques, most of which are some variant of the Ferris-Knowles method (Ferris and Knowles, 1963), enable quite reasonable estimates of the hydraulic conductivity of the formation to be obtained. Unfortunately, these techniques are only valid for the very small normalized heads found in the very late stages of a slug test ($H(t)/H_0 < 0.0025$, where $H(t)$ is measured deviation from static and H_0 is the size of the slug). Thus, these methods are essentially of no use in most environmental applications, where the deviations from static for which these techniques would be applicable would be on the order of a centimeter or less.

Because hydraulic-conductivity estimates from slug tests in

wells with low-K skins are of little value in shallow groundwater applications, a program of slug tests should be designed to identify the presence of a low-K skin. Butler and Healey (1996) point out that well skins may be dynamic or static in nature. If a portion of the material that is producing the skin effect is mobilized by the introduction of the slug-induced disturbance (the dynamic case), one should expect to see sizable changes in hydraulic-conductivity estimates between repeat tests at that well. If the flow during the slug test is insufficient to mobilize this material (the static case), one should expect a consistent set of conductivity estimates from repeat tests. Butler et al. (1996) recommend that at least three slug tests be performed at each well in order to identify a dynamic skin. One of these tests should be configured so that the flow of water in response to the slug-induced disturbance is opposite the flow direction of the other tests. This reversal of flow direction is analogous to the pulsing action of well development and often will mobilize a portion of the material comprising the skin. Note that the primary direction of flow during a series of slug tests should be from the formation into the well, as flow into the formation will often lead to a progressive decrease in near-well hydraulic conductivity. This decrease is primarily a result of mobilized fine material being lodged deeper in the formation.

Figures 1 and 2 illustrate the types of slug-test responses that are often observed in the field. In these figures, test responses can be compared using T_0, which is the basic time lag

(i.e., time at which a normalized head of 0.37 is obtained (Hvorslev, 1951)) and inversely proportional to hydraulic conductivity. The repeat tests shown on Figure 1 display rather typical dynamic skin effects (T_0, and thus K, varies by a factor of 1.8) and a very limited dependence on flow direction. Because T_0 increases with the later tests, one might speculate that analysis of Test #1 would produce an estimate of hydraulic conductivity that is reasonably close to that of the formation (e.g., Butler et al., 1996). However, the dynamic skin effects observed during these tests are an indication that development activities have been insufficient at this well. Therefore, when confronted with such a situation, it is best to err on the side of caution and assume that all tests have been impacted by insufficient development.

The tests shown on Figure 2, in contrast to those of Figure 1, display a very dramatic dependence on flow direction, a clear indication of a significant low-K skin. There should be little doubt that all tests at this well, regardless of the flow direction, have been significantly impacted by insufficient well development. Slug-test estimates from wells exhibiting such behavior must be viewed with considerable skepticism.

The performance of repeat slug tests using the range of H_0 commonly employed in the environmental industry is usually sufficient to mobilize a portion of the material comprising the low-K skin and/or reveal a skin-related directional dependence. If such effects are not observed during a series of repeat slug tests, it has been our experience that theoretical models (e.g., Cooper et

al., 1967; Hyder et al., 1994) will provide very reasonable fits to the test data. However, as discussed by Butler and Healey (1995b), close agreement between T_0 values from repeat slug tests is strictly only a partial demonstration of appropriate well development, so only limited credence should be given to the resulting hydraulic conductivity estimates. For example, as discussed in the next section, the slug-induced flow may simply be constrained to a few thin, well-developed zones that pass through a relatively static low-K skin. Additional testing is required for cases where there is concern that the skin may be primarily static in nature. Butler and Healey (1996) recommend performing repeat slug tests in which the effective casing radius is varied between tests through use of a packer and standpipe arrangement. When hydraulic-conductivity estimates from a series of slug tests performed with successively smaller effective casing radii are plotted in the format shown in Figure 3, it may be possible to recognize the presence of a low-K skin. Butler and Healey (1996) describe the theoretical basis of the approach and an initial field application. As they discuss, this approach provides one tool by which to assess if well-development activities have been sufficient for slug-test purposes in formations of moderate to low hydraulic conductivity. Note that the theoretical relationships depicted in Figure 3 are for conditions similar to those often faced in shallow groundwater investigations (i.e. partially penetrating wells and moderate to small values of the storage parameter).

Static skins are of special concern in low-permeability

formations, where the slug-induced flow may be insufficient to mobilize a portion of the skin. Although the approach of Butler and Healey (1996) could be of considerable use in this situation, the permeability of the formation may be such that tests with large effective casing radii take a very long time to complete. In this case, one should consider adopting an approach analogous to the drill-stem test of the petroleum industry (Earlougher, 1977). As Karasaki (1990) points out, the drill-stem test is essentially a slug test that begins as the standard open-hole test used in groundwater investigations, and then is changed at some point to the shut-in test used for very low permeability units (Bredehoeft and Papadopulos, 1980; Neuzil, 1982). Thus, a slug test can be performed in the open-hole mode long enough to obtain an estimate of T_0 or some other criterion, and then the test can be shut in to allow more rapid recovery. The packer and standpipe arrangement described by Butler and Healey (1995a) allows such a procedure to be done quite readily, without all the specialized equipment required for the deep applications common to the petroleum industry. One should be able to use this approach to perform a series of tests over a wide enough range of effective casing radii to allow the existence of a static skin to be recognized.

If, as a result of a series of repeat slug tests, one strongly suspects that responses at a given well are being significantly influenced by a low-K skin, the parameter estimates obtained from those tests must be discounted. In this case, the only option for obtaining a reliable estimate of the hydraulic conductivity of the

formation is to perform a short-term pumping test. The exact configuration of this test (i.e., discharge versus injection, constant rate versus constant head, etc.) will depend on specific site conditions.

NOMINAL SCREEN LENGTH SHOULD BE USED AS EFFECTIVE SCREEN LENGTH

Regardless of which particular method is used to analyze the response data from a slug test, an estimate must be provided for the effective length of the screened interval (b_{ef}). The nominal length of the well screen (b_w) and the length of the gravel pack (b_{gp}) are the two most common quantities used for the effective screen length. Because the gravel pack is usually considerably more permeable than the formation, many authors (e.g., Palmer and Paul, 1987; Butler et al., 1996) have recommended using b_{gp} for the effective screen length. This recommendation, however, needs to be revised, as it is based on the often unrealistic assumption that near-well portions of the formation have been well developed along the entire length of the gravel pack (Figure 4A).

It is important to emphasize that regardless of which drilling technology is employed, a considerable amount of drilling debris (e.g., mobilized fine material, remnant drilling fluids, clay smears, etc.) will be concentrated in the near-well portions of the formation (Aller et al., 1989). Given the standard well installation and development procedures used in the environmental industry, it may be very difficult, if not impossible, to remove this debris from portions of the formation opposite the gravel pack

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but either above or below the screened interval. In reality, near-well portions of the formation will invariably only be developed in the zones of highest hydraulic conductivity intersecting the gravel pack and/or immediately adjacent to the screen, and even in those locations the development may just be partially successful. Thus, the best one can hope for are conditions similar to those shown in Figure 4B. Actual conditions, however, are undoubtedly much closer to Figure 4C. Note that in Figure 4C the zones of development are depicted as being located opposite the screened interval. Actually, the location of these zones will be a function of factors such as the hydraulic conductivity variations within the formation, the width and hydraulic conductivity of the gravel pack, and the nature of the specific method employed for development.

Unfortunately, conditions similar to those depicted in Figure 4C may be very difficult to recognize in the field. The dynamic skin effects and/or directional dependence discussed in the previous section may be present if development in the more-permeable channels through the drilling debris has been incomplete. If the developed portion of the screened interval is very small relative to b_w and the skin is essentially static in nature, then the technique described by Butler and Healey (1996) may be useful. However, in layered systems where development in the more-permeable channels through the drilling debris has been nearly complete, it may oftentimes be virtually impossible to recognize the situation depicted in Figure 4C.

The influence of well development and effective screen length

on hydraulic-conductivity estimates can be best illustrated with a series of numerical simulations performed using a cylindrical-coordinate, finite-difference model that has been developed at the Kansas Geological Survey for the simulation and analysis of well tests (Butler et al., 1994). Formation and well parameters similar to those that might be found in the field were employed in the configurations shown in Figures 4A-4C (aquifer thickness = 10 m, screen length = 2 m, gravel pack length = 7 m, distance from top of aquifer to top of screen = 4 m, casing and screen radius = 0.05 m, radius of gravel pack = 0.11 m, radius of skin zone (Figures 4B-4C) = 0.20 m, ratio of hydraulic conductivity of the formation over that of the skin (Figures 4B-4C) = 150, and developed portion of the screened interval (Figure 4C) = 1 m).

Figure 5 presents the results of the analysis of the simulated slug-test response data in the form of a plot of the ratio of the hydraulic conductivity estimated using the Hvorslev method (shape factor as in case 8 of Hvorslev (1951)) over the actual conductivity of the formation versus the simulation case, where simulation cases A, B, and C are for the conditions illustrated in Figures 4A, 4B, and 4C, respectively. Results for two different gravel pack-formation permeability contrasts and two different assumed effective screen lengths are presented. The solid and dashed lines depict conditions for a gravel pack that is two orders of magnitude more permeable than the formation, while the circles denote results for the case of a gravel pack that is 4000 times more permeable than the formation (the point labelled "1" is for

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the case where b_{ef} is assumed to equal b_{gp}, while point "2" is for the case where b_{ef} is assumed to equal b_w). The results for the two gravel pack-formation permeability contrasts are approximately equal for simulation cases B and C, so results are only presented for the smaller contrast ($K_{gp} = 100K_{fm}$) in those cases. Note that the relationships displayed in this figure are independent of the value of formation hydraulic conductivity and apply for the range of storage parameters common in groundwater investigations.

The major conclusion that can be drawn from Figure 5 is that the nominal length of the well screen (b_w) is a much better estimate of b_{ef} than the length of the gravel pack (b_{gp}) for conditions commonly found in the field. Only when the formation has been well developed along the entire length of the gravel pack and the gravel pack-formation permeability contrast is greater than two orders of magnitude will b_{gp} be a significantly better estimate. Given the rarity of such ideal conditions with respect to well development, the nominal length of the well screen should be used for the effective screen length in virtually all cases.

It is important to emphasize that use of b_w will, as illustrated by case C in Figure 5, virtually always lead to an underestimation of the hydraulic conductivity of the formation, because the actual effective screen length is undoubtedly less than b_w. Use of relatively vigorous well-development procedures that stress (preferably via a pulsing action) discrete intervals along the screen (Kill, 1990; ASTM, 1996) are therefore recommended prior to testing in order to obtain the most reasonable estimate of the

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hydraulic conductivity of the formation.

GRAVEL-PACK RADIUS SHOULD BE USED AS EFFECTIVE SCREEN RADIUS IN MOST CASES

In addition to an estimate of the effective screen length, all methods for the analysis of slug-test response data require an estimate for the effective radius of the well screen (r_{ef}). The nominal radius of the well screen (r_w) and the radius of the gravel pack (r_{gp}) are the two quantities commonly used for r_{ef}. Again, because the gravel pack is usually considerably more permeable than the formation, many authors (e.g., Palmer and Paul, 1987; Butler et al., 1996) have recommended using r_{gp} for the estimate of r_{ef}. Although intuitively this proposal seems appropriate, numerical simulation can play a useful role in verifying the soundness of this recommendation.

Figure 6 presents the results of the analysis of a series of hypothetical slug tests simulated using the numerical model of the previous section and the same formation and well parameters as in Figure 4B. The results are presented in the form of a plot of the hydraulic conductivity ratio versus the gravel pack-formation permeability contrast. Two conclusions can be drawn from the relationships depicted in this figure. First, in cases where the permeability of the gravel pack is approximately a factor of 1.5 or greater than that of the formation, r_{gp} is the most appropriate estimate of r_{ef}. Thus, r_{gp} should be used in virtually all cases where an artificial gravel pack (gravel pack consists of material

introduced from the surface) is employed. Second, in cases where a natural gravel pack is used (gravel pack consists of collapsed formation materials), r_w is often the most appropriate quantity. Note that in certain situations, r_{ef} may actually be larger than r_{gp} as a result of a relatively high rate of pumping producing a zone of intensive development that extends a small distance into the formation. However, the extent of this zone beyond the gravel pack is probably very limited in most monitoring wells used for environmental applications because the stresses applied during well development tend to be rather small in such situations. As with Figure 5, the relationships given in Figure 6 are independent of formation hydraulic conductivity and apply for the range of storage parameters common in groundwater investigations.

THE DOUBLE STRAIGHT LINE ANALYSIS SHOULD BE USED FOR CONCAVE-UPWARD RESPONSE DATA

Most field practitioners use the techniques of Hvorslev (1951) or Bouwer and Rice (1976) to analyze response data from slug tests. Both approaches are based on the assumption that a plot of the log of the deviation of head from static conditions versus time will be linear in form. It is not uncommon, however, for slug-test responses to display a concave-upward curvature when plotted in this format (e.g., Figure 7). Bouwer (1989) speculated that concave-upward responses, which he termed the double straight line effect, are a result of a rapid draining of the gravel pack (represented by interval A-B in Figure 8 according to his

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hypothesis) followed by a much slower response controlled by the hydraulic conductivity of the formation (represented by interval B-C in Figure 8). Bouwer carefully qualified his hypothesis by stating that such behavior should only be seen in cases where the well screen or gravel pack intersects the water table, and where the gravel pack is more permeable than the formation. He recommended that the Bouwer and Rice method be modified in such situations by using initial head and slope estimates obtained from a straight line fit to the second linear segment (interval B-C of Figure 8; H_0^* is initial head estimate for second linear segment).

How common the conditions hypothesized by Bouwer (1989) actually are in the field is unclear. In the case of a well screened across the water table, a very rapid dewatering of the gravel pack (slug tests in such wells are virtually always configured so that the direction of flow is into the well) is often observed immediately after test initiation. This dewatering is frequently so rapid with respect to the timing of the formation response that it is not observable past the origin on a linear time plot of the response data. As the contrast between the permeability of the gravel pack and that of the formation decreases, one might expect to find a range of conditions over which the behavior hypothesized by Bouwer would occur. Unfortunately, there has been little reported field experimentation or theoretical modeling to assess the frequency of occurrence of these conditions. Despite this, the recommendation of Bouwer to base analyses on the second interval of the response plot (the

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double straight line analysis) has been widely adopted in the environmental industry. In cases where the screen or gravel pack does not intersect the water table, a leaky annular seal is frequently invoked as the mechanism responsible for the observed curvature.

Actually, slug-test responses that display a concave-upward curvature are not at all uncommon in either confined or unconfined systems, and often have nothing to do with the gravel pack (e.g., Figure 7). Chirlin (1989) provides a theoretical explanation for this behavior in the case of a fully penetrating well in a confined aquifer. He shows that concave-upward responses are primarily a product of a large storage parameter, α, which is defined as $(bS_s r_w^2/r_c^2)$, where b is the effective screen length, S_s is the specific storage, and r_w and r_c are the effective screen radius and casing radius, respectively. Although the degree of curvature of the response data changes, his explanation is equally valid for partially penetrating wells in confined or unconfined formations. Thus, it appears that the double straight line analysis may be frequently being applied to conditions outside of the range for which it was originally proposed. It is therefore important to assess the error that is being introduced into hydraulic-conductivity estimates through this practice.

Figure 9 displays responses for a hypothetical slug test simulated using the KGS Model for slug tests in partially penetrating wells (Hyder et al., 1994; Liu and Butler, 1995). The

α value (0.0125) employed in this simulation was the same as that estimated from the analysis of the test shown in Figure 7 (Butler et al., 1996). The simulated test responses of Figure 9 have a distinct concave-upward curvature. An important issue regarding the double straight line approach is which interval to use in the analysis. In order to address this issue, the simulated response plot on Figure 9 was divided into five separate intervals (AB, BC, CD, DE, and EF), and the double straight line approach was employed to obtain a hydraulic-conductivity estimate for each interval. The ratio of that estimate over the hydraulic conductivity used in the model is shown in Figure 9 for both the Hvorslev (Hv) and Bouwer and Rice (BR) methods. The difference between the ratios for the two methods is a result of the tendency for the Hvorslev method to slightly overpredict and the Bouwer and Rice method to slightly underpredict hydraulic conductivity in homogeneous, isotropic formations (Hyder et al., 1994; Hyder and Butler, 1995). Most field practitioners would have applied the double straight line analysis to data lying between B and D. Fortunately, this practice appears to produce a reasonable estimate of the hydraulic conductivity of the formation. As α increases, the interval for which a reasonable estimate of hydraulic conductivity can be obtained shrinks. A considerable number of numerical simulations, however, have shown that a very reasonable estimate of hydraulic conductivity can virtually always be obtained if the double straight line method is applied using normalized heads in the range of 0.25-0.15 and 0.30-0.20 for the Hvorslev and Bouwer and Rice

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approaches, respectively.

The double straight line method recommended by Bouwer (1989) appears to be a reasonable approach for the analysis of data with a pronounced concave-upward curvature, regardless of the mechanism producing the concave-upward behavior. Clearly, however, the approach must be used with care. In cases where the water table is not impacting slug-test responses, normalized heads in the ranges recommended in the previous paragraph should be employed in the analysis. In cases where the mechanism hypothesized by Bouwer may be impacting responses, consideration of the volume of water involved in the initial slug-induced disturbance and the gravel-pack dimensions should help identify the appropriate range of normalized heads to use in the analysis. Given the uncertainty about whether the drainage mechanism hypothesized by Bouwer is actually occurring, it is strongly recommended that the ranges of normalized heads proposed here be employed in the analysis unless there is very convincing evidence to support use of a different range. As shown by Figure 9, one particularly wants to avoid use of very small normalized heads because of the strong likelihood that the resulting hydraulic conductivity estimate will significantly underpredict the actual conductivity of the formation.

CASES OF NONINSTANTANEOUS SLUG INTRODUCTION REQUIRE SPECIAL CARE

In formations of moderate to high permeability, response data from slug tests that are initiated by the removal or introduction

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of a solid slug are often quite "noisy" as a result of a number of factors related to the nature of the test initiation (e.g., Figure 10). A significant difference between the expected initial head (H_0) and the apparent initial head (H_0^*), such as that shown in Figure 10, may be an indication that the slug-induced disturbance is being introduced in a noninstantaneous fashion relative to the timing of the formation response (other possibilities include rapid drainage of the gravel pack, as discussed in the previous section, and entrapped air in the gravel pack (Keller and Van der Kamp, 1992)). There are three common approaches for dealing with response data that are impacted by noninstantaneous slug introduction. One approach (henceforth designated as the translation method following the terminology of Pandit and Miner (1986)) is to ignore the noisy early-time portions of the record and assume that the test started at point A on Figure 10. The head (H_0^*) and time (t_i) of point A are then used for the initial head and start time of the test, respectively. A second approach (henceforth designated as the conventional approach) is to use the expected initial head (H_0) and the actual start time (t_0) but just ignore the early-time portions of the record. A final approach (henceforth designated as the worst-case approach) is to use H_0^* and t_0 but again ignore the early-time portions of the record. Given the frequency with which all three approaches are employed, assessing which method is the most appropriate for general use is important.

The error introduced into parameter estimates through non-

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instantaneous slug introduction was assessed for each of these approaches through a series of simulations using the cylindrical-coordinate, finite-difference model described previously. In these simulations, the rate at which the slug was introduced was assumed to be constant over the total time required for slug introduction (t_i of Figure 10). Figure 11 displays the results of this assessment for the configuration given in Figure 4B. These results, which are valid for partially penetrating wells and moderate to small values of the storage parameter (α), indicate that the translation method can produce very reasonable hydraulic-conductivity estimates, even in the case of a large difference between the expected and apparent initial heads. This is not surprising because test data from a partially penetrating well will be quite linear in form when plotted on a semilog head versus time plot for the case of moderate to small values of α. If a hydraulic-conductivity ratio of between 0.8 and 1.2 is deemed acceptable, then Figure 11 indicates that the worst-case and conventional methods should not be used when H_0^*/H_0 is less than about 0.9 and 0.8, respectively. In cases where there is considerable uncertainty about H_0, the translation method is clearly the method of choice.

The above recommendations are for nonoscillating responses and moderate to small values of α (i.e., the case of linear log head versus time plots). At large α values, the translation approach can potentially introduce considerable error as a result of the concave-upward curvature of the response data. In very permeable

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formations, test responses may be oscillatory in nature (Van der Kamp, 1976). In this case, the translation method can potentially introduce significant error because the amplitude of the oscillations relative to the initial head are the basis of most conventional analysis approaches (e.g., Kipp, 1985; Springer and Gelhar, 1991). Thus, the translation method should not be employed when α is large or responses are oscillatory in nature. Instead, in those conditions, a considerable effort should be made to ensure that the slug is introduced in a near-instantaneous fashion (Butler et al., 1996). An assessment of the linearity of test responses when plotted in a log head versus time format is clearly the best way to determine if the translation method is appropriate for any particular test.

CONCLUSIONS

The slug test is currently the most common technique for in situ estimation of hydraulic conductivity at sites of suspected groundwater contamination. A series of practical guidelines for the performance and analysis of slug tests was presented here. These guidelines, when considered in conjunction with those given earlier by Butler et al. (1996), should enable the field practitioner to better understand the conditions under which this technique can yield a reasonable estimate of the hydraulic conductivity of a formation.

This article has touched on several factors that may introduce error into slug-test estimates. Inattention to most of the issues

discussed here will lead to an estimation error on the order of a factor of two or less, a magnitude that should not be considered large given the uncertainty inherent in most hydrogeologic investigations. Clearly, the primary source of large errors (i.e., those considerably greater than a factor of two) in slug-test estimates is the failure to recognize the existence of a low-permeability (low-K) well skin. Thus, considerable effort should be expended to assess whether a low-K skin exists at a well at which a series of slug tests are being performed. One cannot overemphasize the fact that the success of a program of slug tests critically depends on well installation and development procedures. Unfortunately, these are the very phases of the field investigation that often receive rather limited attention in environmental applications. Unless relatively aggressive well-development procedures are employed to stress discrete intervals of the well screen, the resulting hydraulic-conductivity estimate obtained from a slug test will be, at best, a very conservative lower bound on the hydraulic conductivity of the formation in the vicinity of the well. Although use of more intensive well-development procedures will certainly increase the cost of a site investigation, this action also will clearly result in parameter estimates that are more representative of reality. It will be a rare case when that benefit does not considerably outweigh the accompanying increase in cost.

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FIGURE CAPTIONS

Figure 1 - Normalized head ($H(t)/H_0$, where $H(t)$ is measured deviation from static and H_0 is magnitude of the initial displacement) versus log time plot of a series of slug tests performed during October 1993 in well 1 at site 36 in Pratt County, Kansas (T_0 defined in text, negative H_0 indicates direction of slug-induced flow was into the well).

Figure 2 - Normalized head versus log time plot of a series of slug tests performed during October and November 1995 in a monitoring well in Trego County, Kansas (T_0 defined in text, negative H_0 indicates direction of slug-induced flow was into the well).

Figure 3 - Plot of hydraulic conductivity ratio versus the log of the square of the ratio of the casing radii (subscripts 1 and i refer to tests performed with the original casing radius (r_{c1}) and casing radius r_{ci}, respectively; hydraulic conductivity estimates obtained using either the Hvorslev (1951) or Bouwer and Rice (1976) techniques).

Figure 4 - Cross sectional view of three possible conditions of well development in a partially penetrating well (K_{fm} and $S_{s_{fm}}$ denote the hydraulic conductivity and specific storage of the formation, respectively; figure not to scale).

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Figure 5 - Plot of conductivity ratio (K_{est}/K_{fm}, where K_{est} is hydraulic conductivity estimate provided by the Hvorslev technique and K_{fm} is the actual hydraulic conductivity of the formation) versus simulation case for a well with a high-permeability gravel pack (K_{gp} is the hydraulic conductivity of the gravel pack; remaining notation defined in text).

Figure 6 - Plot of conductivity ratio versus the ratio of the hydraulic conductivity of the gravel pack (K_{gp}) over that of the formation (remaining notation defined in text).

Figure 7 - Log normalized head versus time plot of a slug test performed during June 1991 in well Ln-1 at a monitoring site in Lincoln County, Kansas (H_0 = 10.35 m; see Butler et al. (1996) for test details).

Figure 8 - Log normalized head versus time plot illustrating the double straight line effect described by Bouwer (1989) (notation defined in text).

Figure 9 - Log normalized head versus time plot of a slug test simulated in a well-aquifer configuration similar to that of Figure 7 (α=0.0125, b_{ef}/r_{ef}=40; normalized heads for points B, C, D, and E are 0.51, 0.21, 0.08, and 0.03, respectively).

Figure 10 - Normalized head versus log time plot of a slug test

initiated by removal of a solid slug from the water column (notation defined in text).

Figure 11 - Plot of conductivity ratio (K_{est}/K_{inst}, where K_{est} is the hydraulic conductivity estimate provided by the Hvorslev technique and K_{inst} is the Hvorslev estimate obtained if the slug is introduced in an instantaneous manner) versus one minus the ratio of apparent (H_0^*) to expected (H_0) initial head (legend notation defined in text).

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

1—T_0=79 sec, H_0=−1.12 m
2—T_0=139 sec, H_0= 1.06 m
3—T_0=131 sec, H_0=−0.30 m
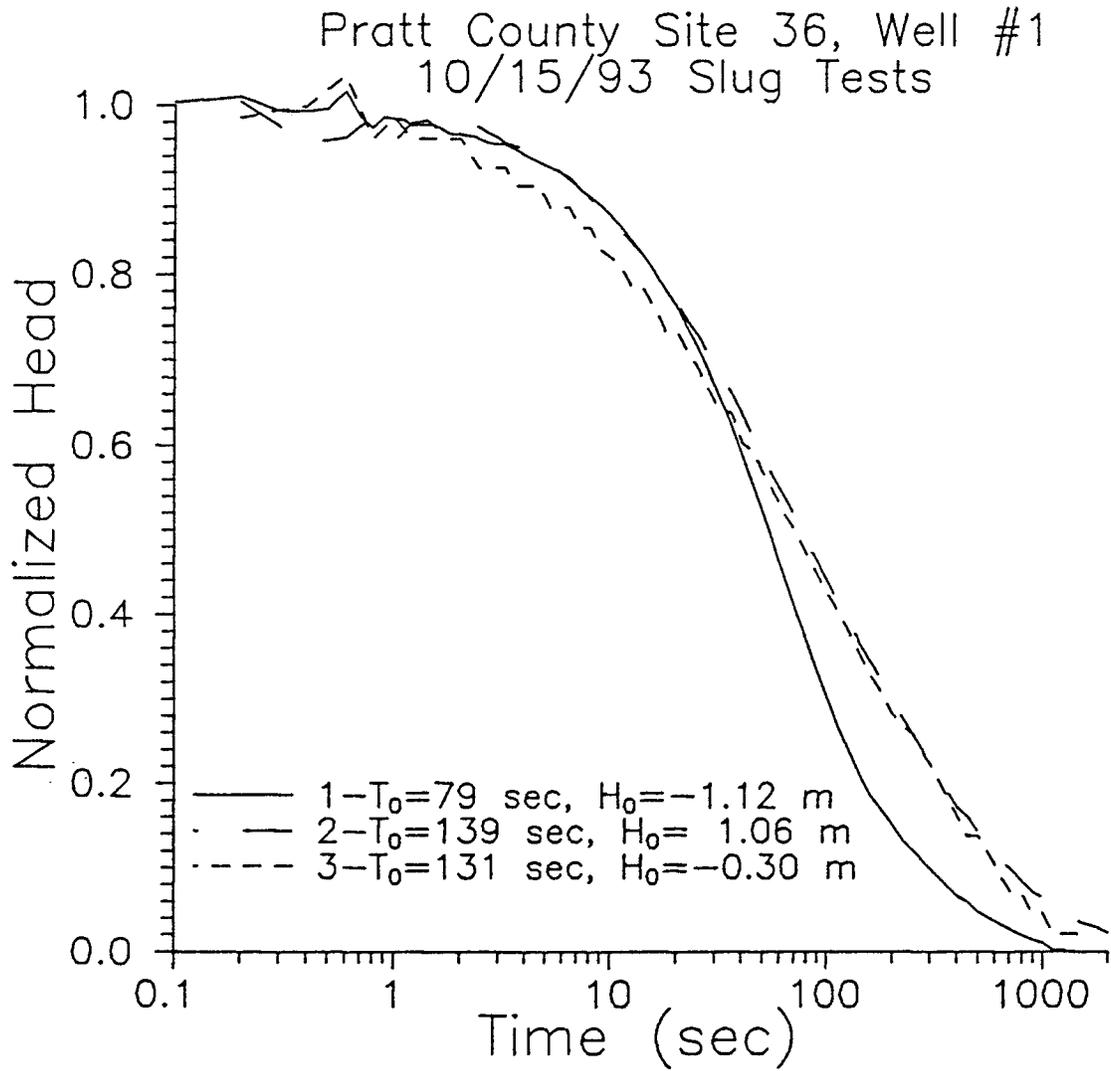
Trego County Site
Oct.–Nov. 1995 Slug Tests

——— 10/25 1-T_0=21.7 sec, H_0=-1.56 m
——— 10/26 1-T_0=39.7 sec, H_0=-0.71 m
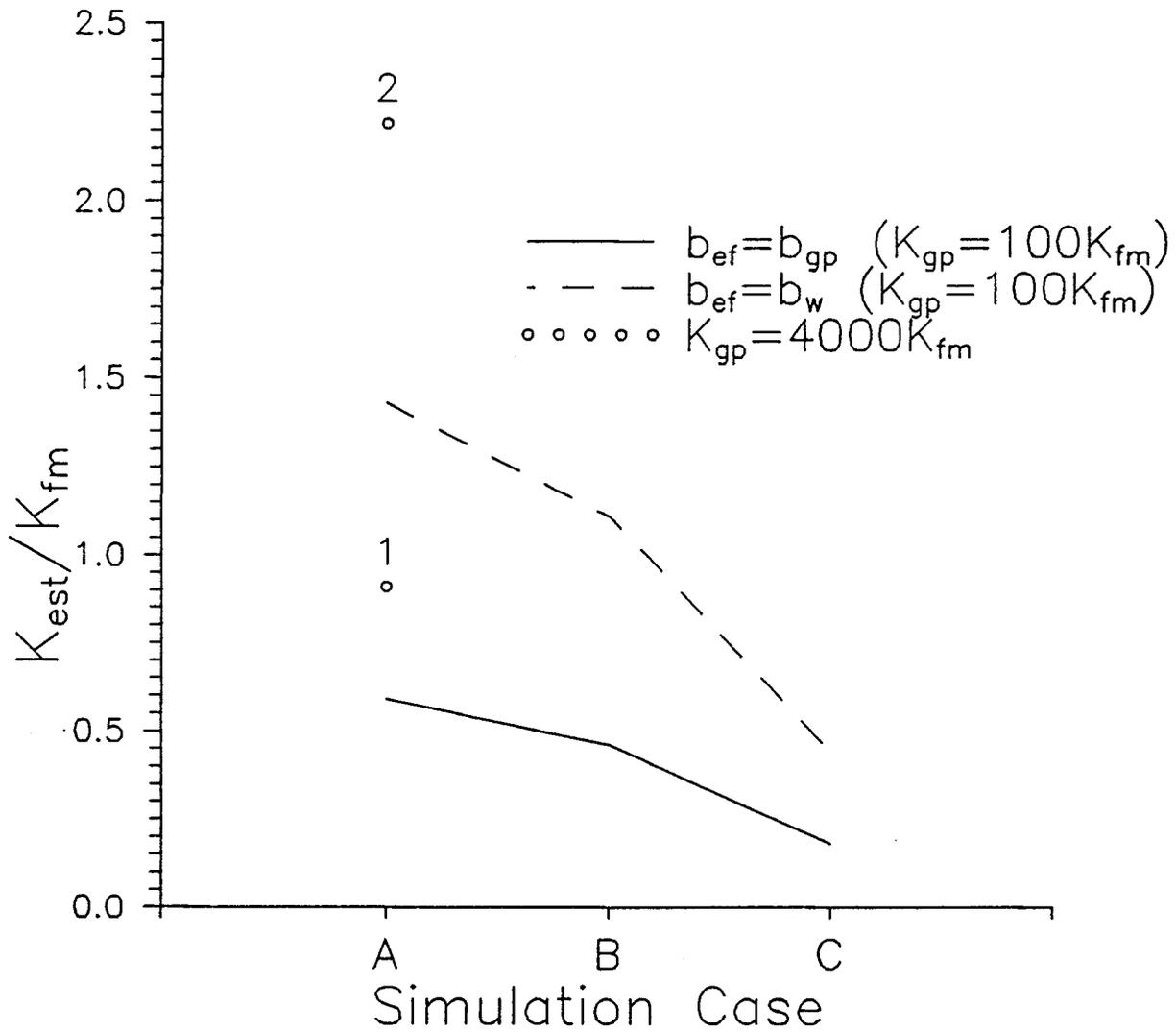•••• 11/16 2a-T_0=2112 sec, H_0= 1.82 m
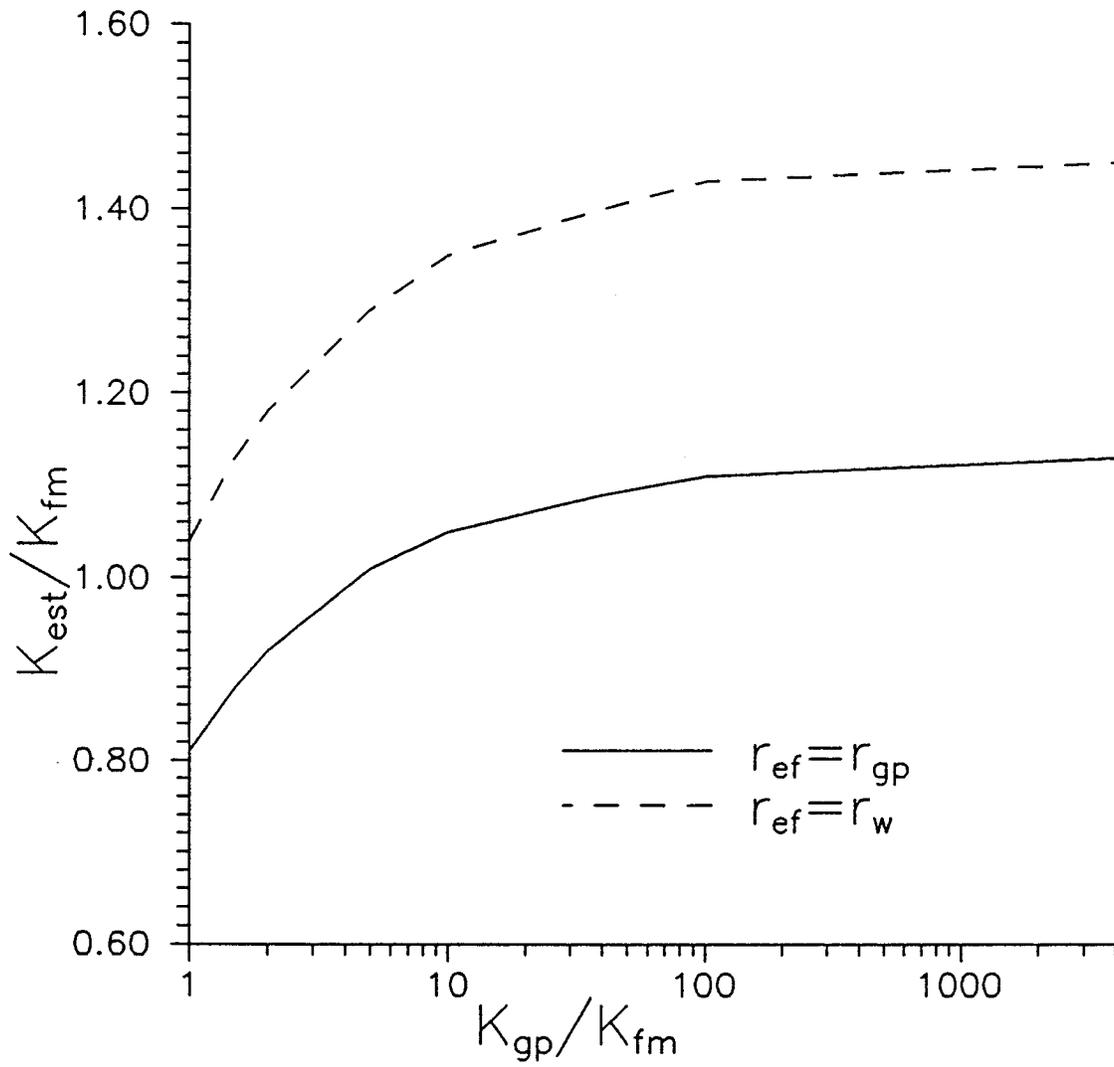- - - - 11/16 2b-T_0=41.4 sec, H_0=-1.79 m

Figure 3
Butler

Figure 3

Figure 4
Butler

A   B   C

CENTER LINE OF WELL

Confining Bed

K_{fm}, Ss_{fm}

Confining Bed
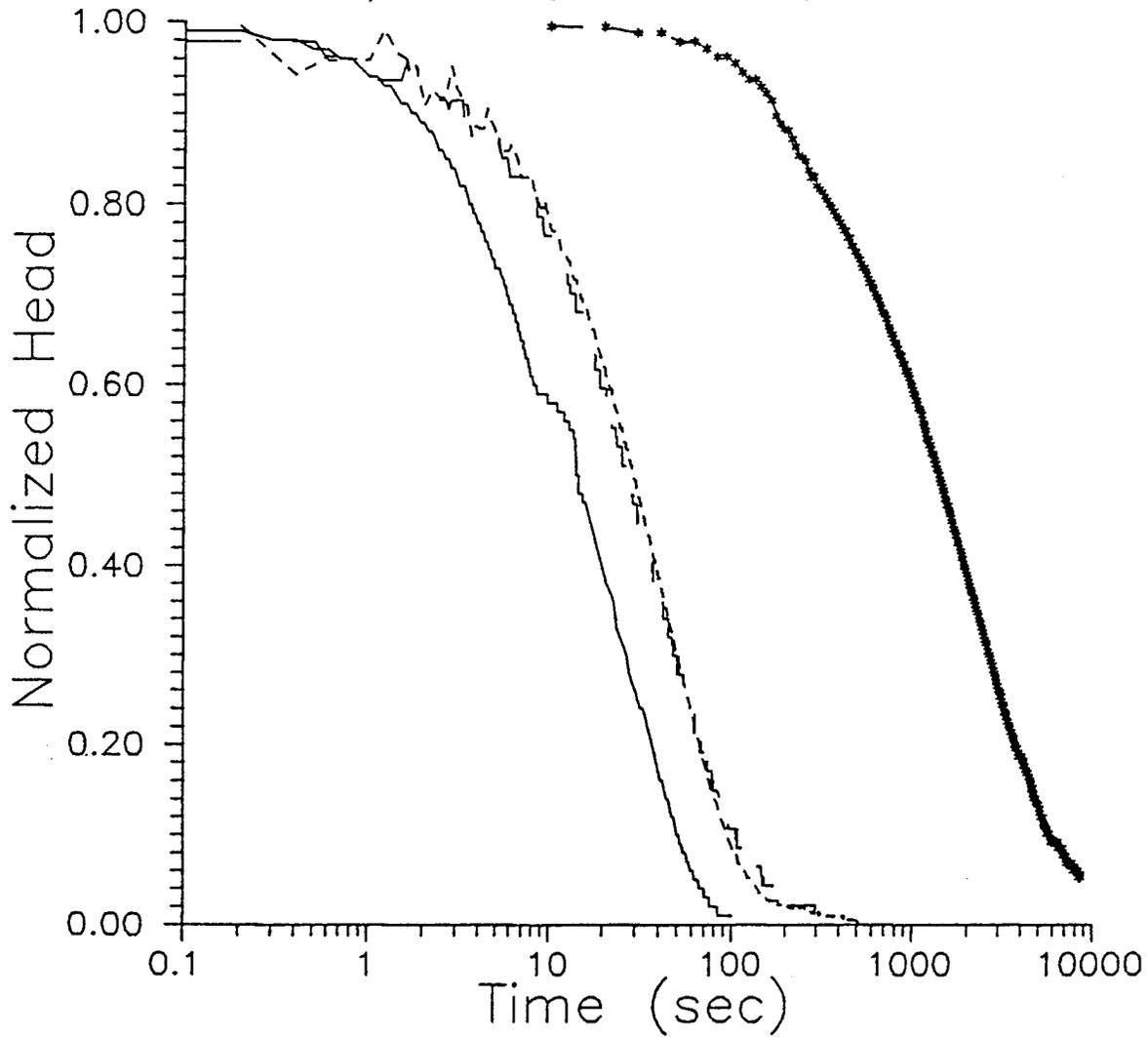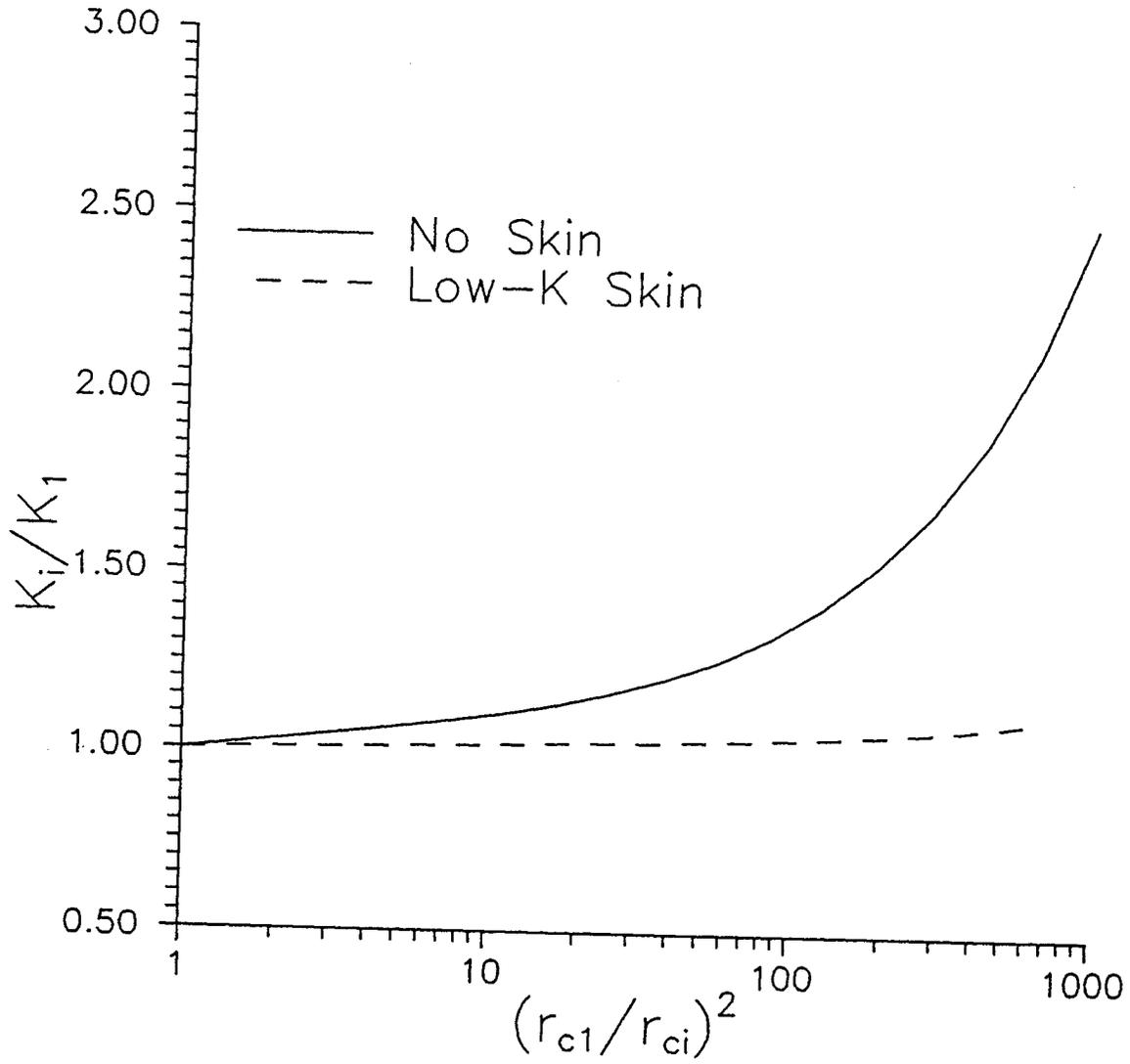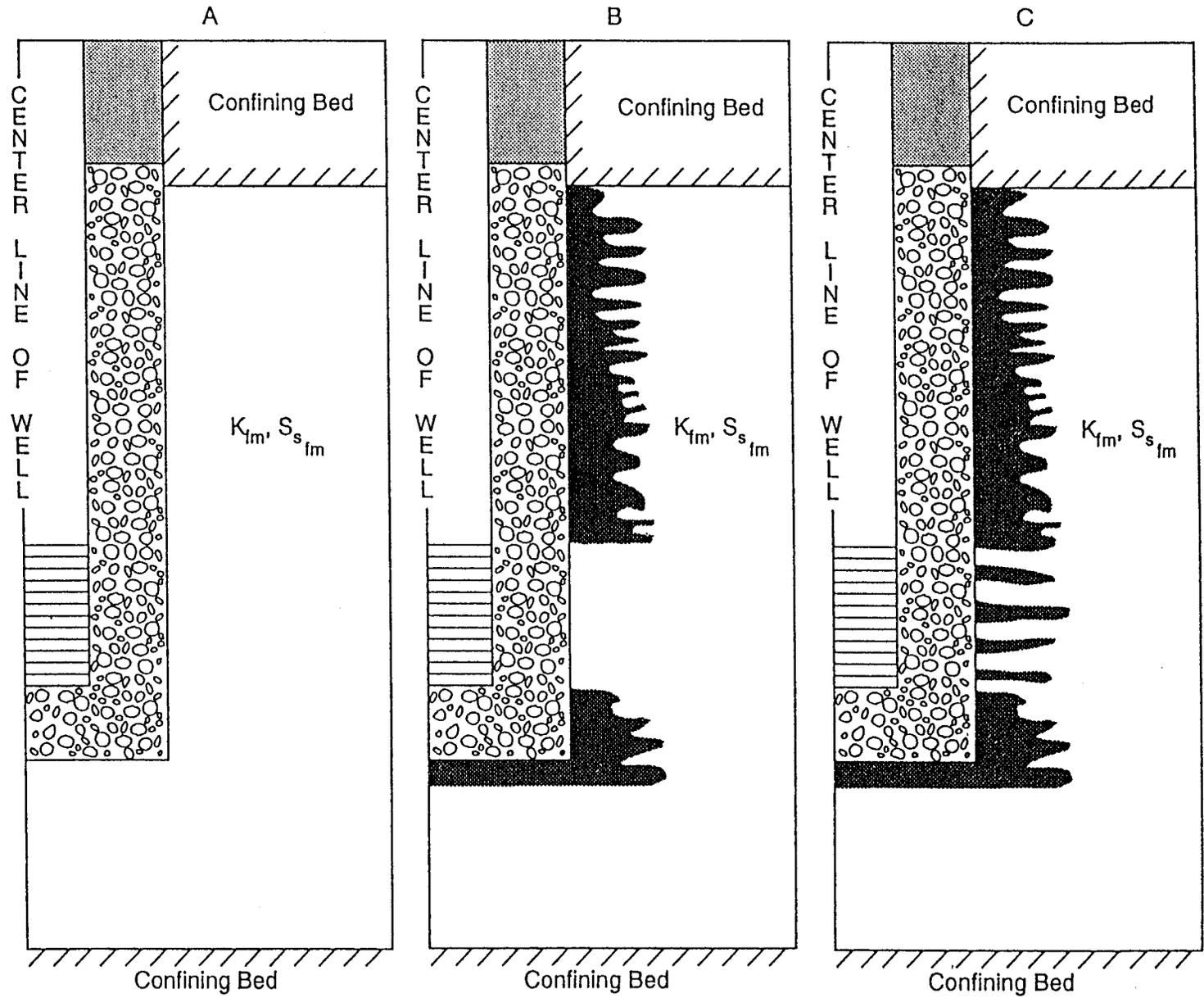
■ drilling debris ▨ grout ▨ gravel pack ≡ screened interval

Figure 5
Butler

Influence of Effective Length Estimate

Legend:
- $b_{ef}=b_{gp}$ $(K_{gp}=100K_{fm})$ — solid line
- $b_{ef}=b_w$ $(K_{gp}=100K_{fm})$ — dashed line
- $K_{gp}=4000K_{fm}$ — circles

Y-axis: K_{est}/K_{fm} (0.0 to 2.5)

X-axis: Simulation Case (A, B, C)

Figure 6
Butler

Influence of Effective Radius Estimate

Figure 7
Butler
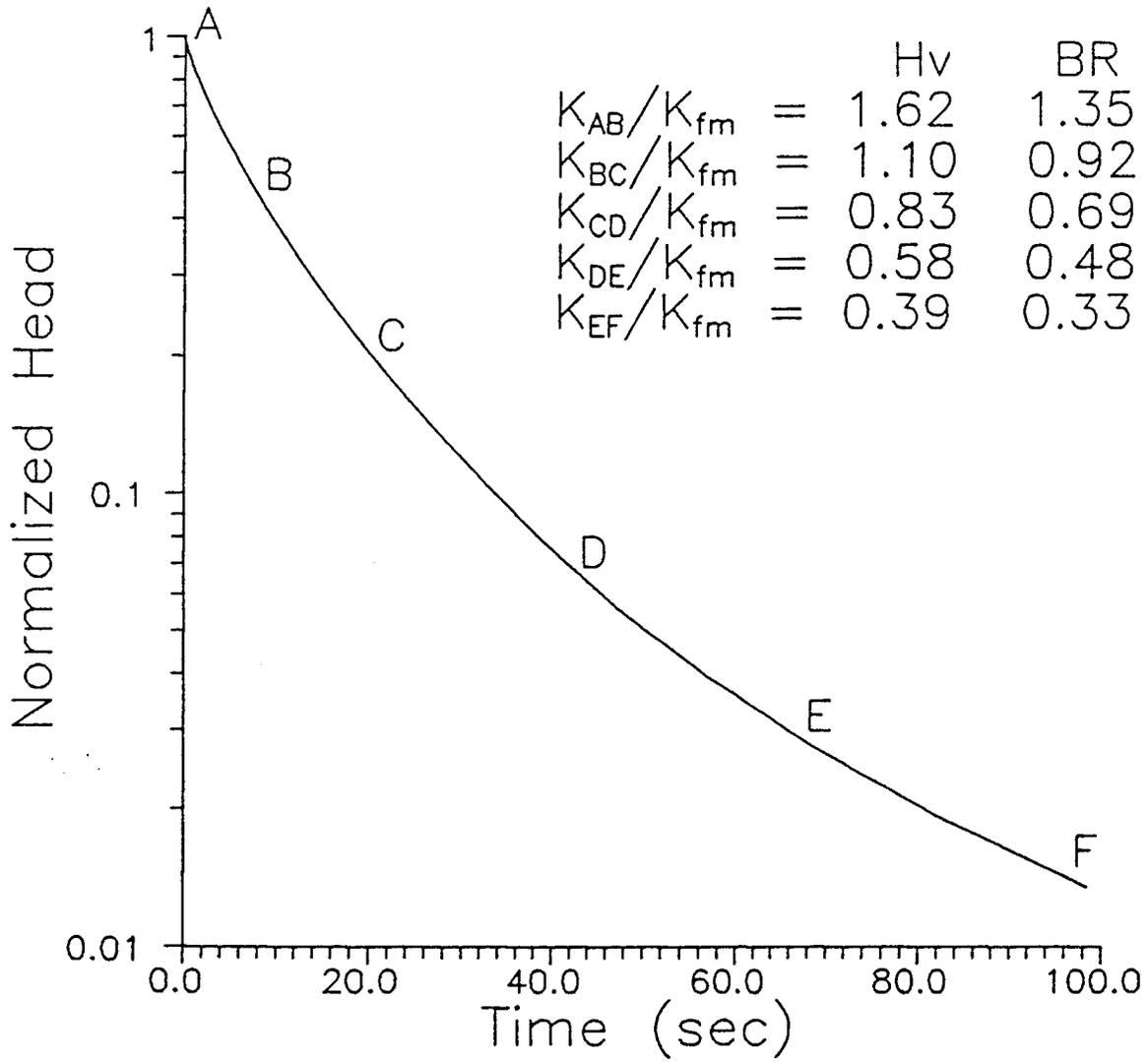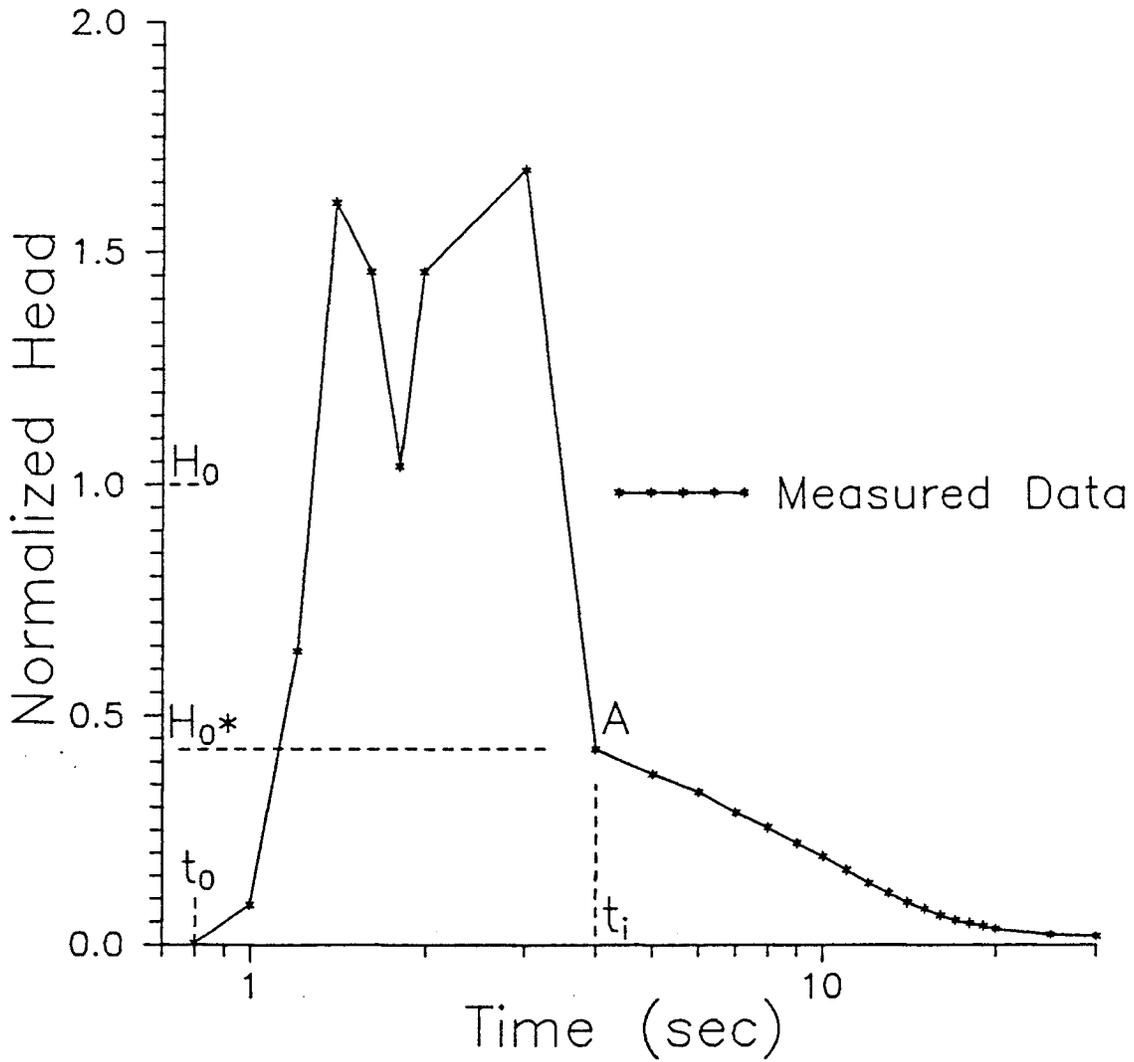
Lincoln County Site, Well Ln-1
6/14-6/18/91 Slug Test
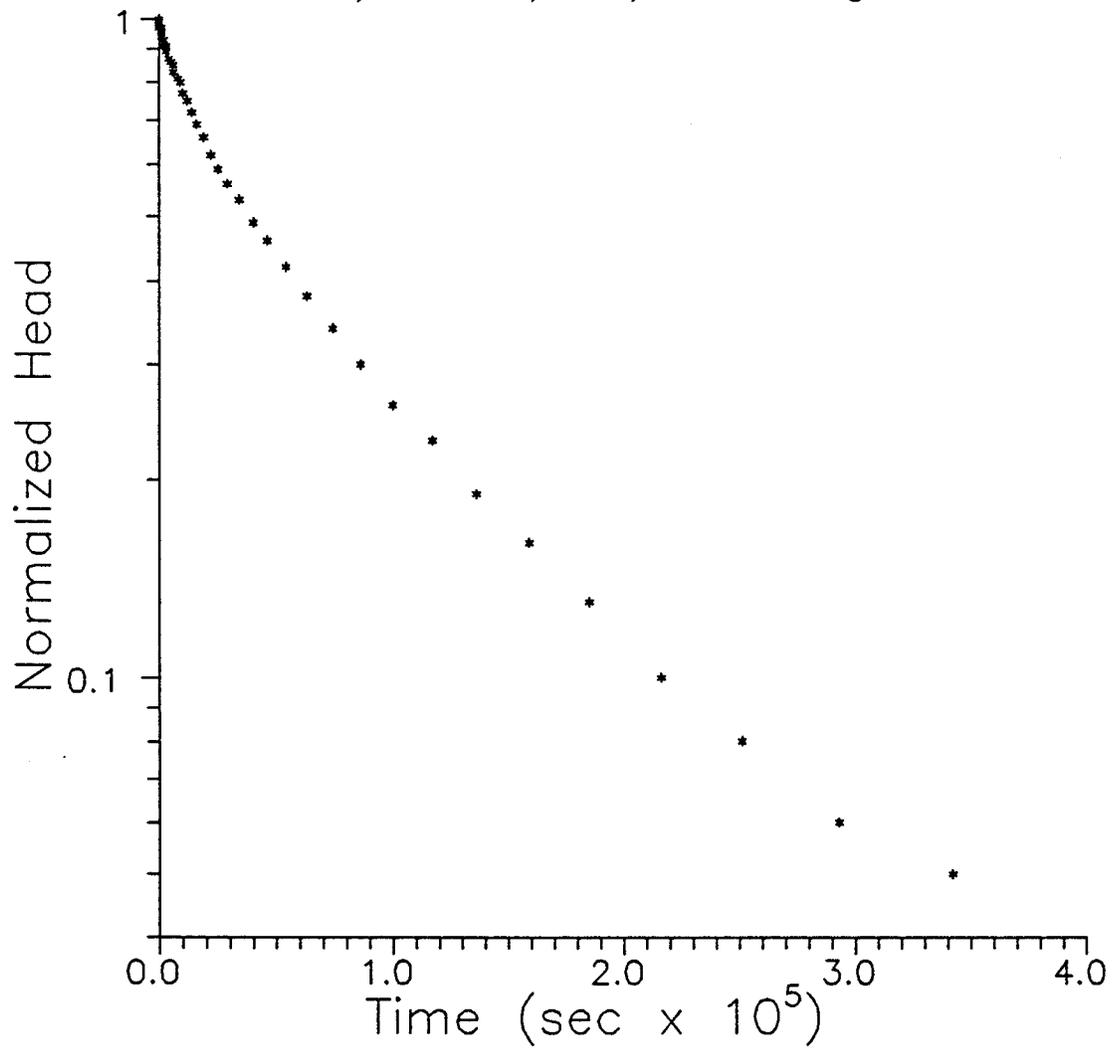
Figure 8
Butler
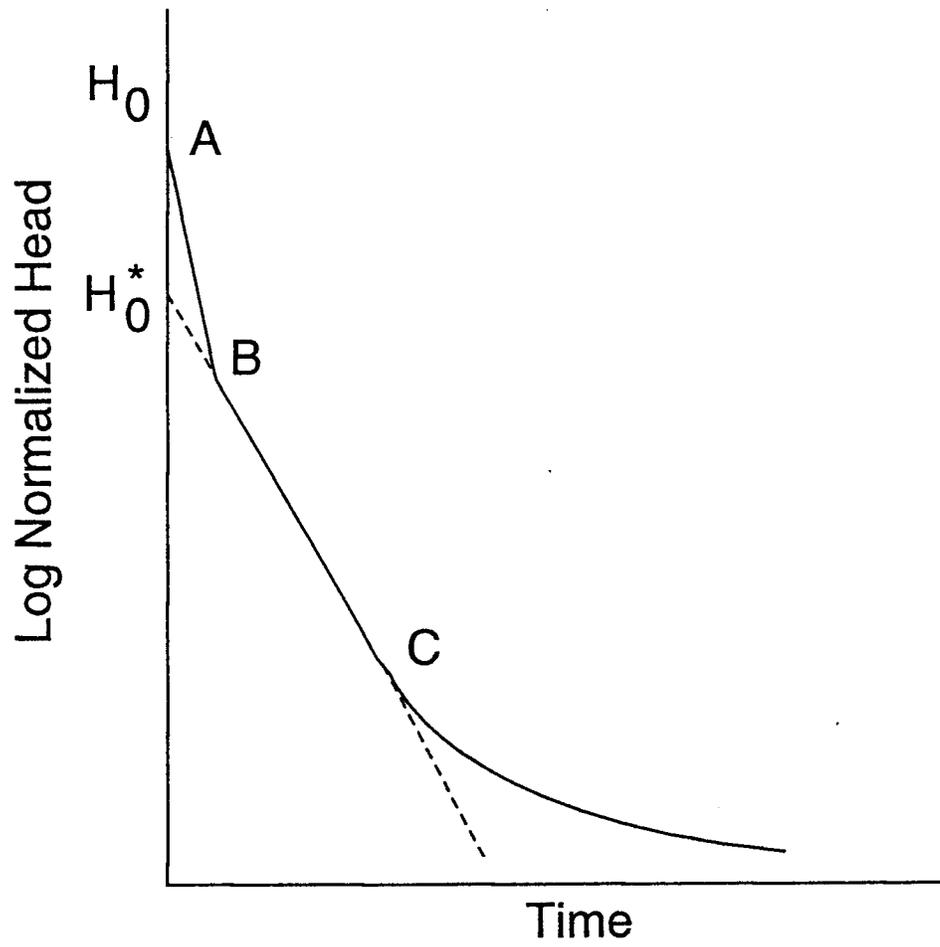
Example of Slug Introduced in
Noninstantaneous Fashion

Analysis of Impact of Noninstantaneous Slug Introduction