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RELATIONSHIP BETWEEN PUMPING-TEST AND SLUG-TEST
PARAMETERS: SCALE EFFECT OR ARTIFACT?

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ABSTRACT

In most field investigations, one obtains information about hydraulic conductivity (K) through pumping or slug tests. Over the years, a considerable body of data has been amassed that indicates that the K estimate from large-scale pumping tests is on average considerably larger than the estimate obtained from a program of slug tests in the same formation. Although these data could be interpreted as indicating a scale dependence in K, it is difficult to invoke a general theory to support that interpretation. An alternate explanation is that the slug-test K is artificially low as a result of incomplete well development and, to a much lesser extent, failure to account for vertical anisotropy. Incomplete development will often result in only the most permeable zones being cleared of drilling fluids, with the majority of the screened interval remaining undeveloped. More cursory development can leave a low-K skin along the entire screened interval. In both cases, the skin may be dynamic in nature, resulting in dramatically different K estimates being obtained from slug tests performed at the same well. Failure to recognize such conditions can result in a slug-test K much lower than that of the portion of the formation in the vicinity of the well. In the case of a pumping test, such effects can be avoided through use of semilog analyses and/or observation wells. The major uncertainty for pumping tests is what value to use for formation thickness when converting the transmissivity estimate to an average K. These points will be supported using hypothetical examples and data from Kansas Geological Survey field sites.

INTRODUCTION

Pumping and slug tests are the primary means by which hydrogeologists obtain in-situ estimates of the transmissive properties of a formation (Kruseman and de Ridder, 1989). Since the duration of most pumping tests is on the order of hours to days, the formation volume that is affected by the average pumping test is considerably larger than that affected by a slug test. Given the different formations volumes involved, it is not surprising that these tests can yield different parameter estimates when performed at the same well. One might expect that the average value obtained from a program of slug tests would converge on the estimate obtained from a large-scale pumping test as the number and spatial coverage of slug tests increased. However, a large body of field data indicates that the hydraulic conductivity (K) estimate obtained from a series of slug tests is on average considerably lower than that obtained from pumping tests in the same formation (e.g., Bradbury and Muldoon, 1990). Recently, several authors (e.g., Rovey and Cherkauer, 1995) have interpreted these data as indicating a scale dependence in K. The basic hypothesis is that a pumping test is strongly affected by infrequent-in-space channels (conduits) of high K, while a slug test rarely samples these "rare heterogeneities".

In this paper, we examine the relationship between pumping-test and slug-test parameters in an attempt to offer another explanation for the observed difference. We show that it is difficult to theoretically substantiate the high-K conduit hypothesis. Instead, we propose that the difference is primarily a function of incomplete well development and, to a lesser degree, uncertainty concerning formation thickness and a failure to account for vertical anisotropy.

EXAMINATION OF THE HIGH-K CONDUIT HYPOTHESIS

Butler and Liu (1991, 1993) developed a series of analytical solutions to investigate the effects of lateral heterogeneities on pumping-induced drawdown in idealized nonuniform formations. These same solutions can be used to assess the influence of rare, high-K conduits on parameter estimates obtained from pumping tests. Figures 1A and 1B show two simple models of lateral heterogeneities in which a high-K zone (an infinite strip in Figure 1A and a circular disk in Figure 1B) is embedded in a uniform matrix of lower K. These idealized configurations can be used to demonstrate a few basic points concerning pumping-induced drawdown in heterogeneous formations.

Figure 2 displays the dependence of pumping-induced drawdown on the magnitude of the contrast between the strip and matrix K for the case of a pumping well located a distance of (0.5*d) from the strip of Figure 1A. Note that there are three segments marked on the drawdown curve for the case of $K_{st} = 100K_{fm}$. Segment A reflects radial flow before the front of the cone of depression passes through the right hand boundary of the strip; a Cooper-Jacob semilog analysis (Cooper and Jacob, 1946; Kruseman and de Ridder, 1989) of this interval will yield the K of the matrix. Segment B reflects conditions as the front of the cone of depression passes through the strip. If a straight line can be identified for this period, a Cooper-Jacob analysis will yield a hydraulic conductivity that is an arithmetic average of the strip and matrix K (Streltsova, 1988). Segment C reflects the large-time behavior of the system. A Cooper-Jacob analysis of this segment will yield a K equal to that of the matrix, since the changes in drawdown at large times are independent of the properties of the strip (Butler and Liu, 1991).

Figure 3 shows how the relationships of Figure 2 depend

on distance from the strip. Clearly, the influence of the strip diminishes quickly as the distance between the pumping well and the strip increases. From these results, it is difficult to see how a rare, high-K channel would have a significant effect on pumping-induced drawdown in the general case.

Figures 2 and 3 display results for the case of a high-K channel of infinite length. If the high-K zone is of finite extent, its influence may be considerably less. Figure 4 displays results analogous to Figure 3 for the circular disk configuration shown in Figure 1B. In this case, if the circular disk is more than a few radii (a) away from the pumping well, its influence is insignificant. As shown by Butler and Liu (1993), a Cooper-Jacob analysis of the large-time data will again yield the K of the matrix.

The conclusion of this simple analysis is that, in general, rare, high-K zones will have a very limited impact on pumping-induced drawdown. If such a zone does have an impact on the drawdown from a particular pumping test, it should be clearly revealed on a semilog plot. If pumping-induced drawdown display the idealized behavior predicted by Cooper and Jacob (1946), then one can be very confident that the resulting K estimate is not significantly affected by a zone of anomalous properties. Based on this analysis, one would expect that the average parameter estimate obtained from a series of slug tests should be quite close to the estimate obtained from a large-scale pumping test, even when rare, high-K zones are present. Thus, the difference between pumping-test and slug-test parameters does not appear to be a result of infrequent-in-space, high-K zones.

AN ALTERNATE HYPOTHESIS

An alternative to the high-K conduit hypothesis is that the observed difference in parameter estimates is primarily a result of incomplete well development. Since slug tests are extremely sensitive to near-well conditions, incomplete well development can result in the K estimates being more reflective of the altered, near-well material than the formation as a whole. Based on a large number of slug tests performed by Kansas Geological Survey (KGS) personnel, it appears that incomplete well development is an extremely common situation. Two examples drawn from KGS investigations carried out in the fall of 1995 can be used to illustrate the type of conditions that are often found in the field.

Figure 5 displays the results of a series of slug tests done on the same day at a site in Stafford County, Kansas. In all three tests, the slug-induced disturbance produced flow out of the well. T_0 is the basic time lag of Hvorslev (1951) and is inversely proportional to the K estimate. Based on the T_0 values in Figure 5, the K estimates for these tests vary by a factor of 3.5. This large variation in K between tests performed consecutively on the same day is an example of what Butler et al. (1996) term an "evolving" or "dynamic" skin. Apparently, fine material is being mobilized by the introduction of the slug and is moving in a manner that produces dramatic changes in K between tests. Note that these tests were done after this well had been very extensively developed in late 1994. A test done at the same well approximately 14 years earlier, after relatively little development, yielded a T_0 estimate of over 20,000 seconds. Interestingly, repeat slug tests performed at this well using the shut-in or pressurized slug-test approach (Neuzil, 1982) did not show any sign of a dynamic skin. In this case, the flow was

insufficient to mobilize the fine material, so the low-K skin was not modified during the tests (an example of a "static" skin).

Figure 6 is another illustration of the sensitivity of slug-test responses to near-well conditions. In this series of tests, T_0 varied by close to two orders of magnitude. The tests labelled "in" were configured so that the slug-induced disturbance produced a flow of water into the well, while the test labelled "out" was configured so that the disturbance produced a flow of water out of the well. The differences seen among the tests labelled "in" were again thought to be an example of a dynamic skin, while the differences between the tests labelled "in" and "out" were thought to be a result of the buildup of a bacterial mat (consisting of bacteria, associated byproducts, and oxyhydroxide deposits) at either the screen-gravel pack interface or the gravel pack-formation interface. At either location, larger pores are located on the well side of the interface, so flow into the well is much less impacted by the buildup than outward flow. Note that this well was installed and moderately developed about a year prior to the performance of these tests. Undoubtedly, slug tests performed shortly after well installation and development would not have displayed such a dramatic dependence on flow direction.

Clearly, slug-test estimates may be heavily influenced by altered, near-well conditions. Therefore, it is critical that the design, performance, and analysis of slug tests be directed at the identification of such conditions. Butler et al. (1996) propose approaches to help assess the presence of a low-K skin using slug tests.

Parameter estimates from pumping tests, in contrast to those from slug tests, will not be heavily impacted by near-well conditions. As explained by Butler (1990), pumping-test drawdown can be analyzed using the Cooper-Jacob semilog

method to remove the effect of near-well conditions from K estimates. If an observation well at some distance from the pumping well is employed, low-K skin(s) at the pumping and/or observation well will have a very limited impact on parameter estimates, regardless of the method used to analyze the drawdown data.

A hypothetical example can be used to illustrate these points. In this example, CCFDWT, a numerical model developed at the Kansas Geological Survey (Butler et al., 1994), was used to simulate hydraulic tests in the configuration shown in Figure 7. CCFDWT has undergone extensive testing against analytical solutions for a variety of hydraulic tests. In all cases, the comparison between analytical solutions and CCFDWT has been quite good. Figure 8 shows the results of a comparison of CCFDWT with the KGS Model (Hyder et al., 1994; Liu and Butler, 1995) for a slug test in a thick, isotropic formation. In the hypothetical example considered here (Figure 7), the model parameters were as follows: higher K = 20 m/day, average K = 4 m/day, lower K = 1.0 m/day, low-K skin = 0.10 m/day, gravel-pack K = 200 m/day, total aquifer thickness = 10 m, layer thickness (all layers of equal thickness) = 1 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 = 0.114 m, radius of mud-invaded zone = 0.197 m, low-K skin assumed to block all but the two higher K layers intersecting the gravel pack.

Figure 9 displays the results of a constant-rate pumping test simulated in this hypothetical layered system (drawdown at the pumping well). The large drawdown in the interval marked A is a product of the low-K skin and the partially penetrating nature of the well (partial penetration is exacerbated here by the low-K skin). The rate of drawdown in interval B is much less

and appears to be the result of the full thickness of the aquifer contributing to flow to the well. A Cooper-Jacob semilog analysis of this interval yielded a transmissivity estimate of 76.6 m^2/day, which is very close to the actual transmissivity of 76.0 m^2/day. In this case, the full thickness of the aquifer must be employed to convert the transmissivity estimate into an average K (7.7 m/day) for the layered system.

Figure 10 displays the results of a slug test simulated in the same configuration. In this case, application of the Hvorslev method produced a transmissivity estimate of 7.8 m^2/day, which is almost an order of magnitude lower than that obtained from the pumping test. As is often the case with slug tests, there may be considerable uncertainty about what quantity to employ for the effective screen length. If the nominal screen length is employed, the resulting K estimate (3.9 m/day) is considerably less than both the average value obtained from the pumping test and the average value of the interval adjacent to the screen. One might be tempted to use the length of the gravel pack for the effective screen length, since the gravel pack is considerably more permeable than the formation. This, however, would produce a much lower K estimate (1.1 m/day). If one could somehow recognize that virtually all of the flow is moving into the aquifer via the higher K layer opposite the screen, then an effective screen length of 1 meter would be used. Although the resulting K estimate (7.8 m/day) is, by chance, close to the average value for the layered system, it is much less than the K for that layer (20 m/day) because the mud-invaded zones and the lower K layers are imparting a considerable degree of anisotropy to the system. Failure to recognize this anisotropy can result in a considerable underprediction of K (Hyder et al., 1994; Butler et al., 1994). Unfortunately, as shown in this example, commonly met field conditions such as layering and mud

invasion can result in slug-test K estimates that are only rough approximations of the transmissive properties of the system.

The general conclusion of this hypothetical example is that pumping tests can yield reasonable estimates of the average K, even in the presence of mud-invaded zones, partial penetration, and significant layering, as long as the full thickness of the aquifer is employed to convert the transmissivity estimate into a average K for the system. However, slug tests (at least as conventionally performed by hydrogeologists) should not be expected to yield estimates of the same quality under those same conditions. Under conditions similar to those considered here, pumping-test K estimates will virtually always be considerably larger than those obtained from slug tests.

FIELD EXAMPLE

A field example will help illustrate several of the points of this presentation. In May of 1994, a KGS monitoring well was drilled into a sand body in the Dakota Formation in Trego County, Kansas (Figure 11). In July of 1994, a 21.5 hour constant-rate (Q ≈ 52 gpm) pumping test was performed using this well as both the pumping and observation well. Recovery data were employed to estimate transmissivity using the standard superposition-based approach (Kruseman and de Ridder, 1989). Figure 12A displays the complete record of recovery data (note the similarities to Figure 9), while Figure 12B is a closeup of the interval of analysis. Figure 12B shows that the data display the large-time linear relationship that would be predicted from theory. An analysis of this linear segment produced a transmissivity of 581 m^2/day. Since the purpose of this test was to obtain an estimate of the average hydraulic conductivity of the Dakota sand, the transmissivity estimated from the recovery data needed to be converted into an average K. In order to make this conversion, some estimate of the thickness of the sand unit had to be made. Figure 11 shows natural gamma logs from the monitoring well (labelled "Trego") and two nearby petroleum wells (depths in feet). Note that the "Trego" well was installed only in the upper portion of the Dakota sands, so it is impossible to estimate sand thickness from this well alone. The logs from the two nearby wells indicate the presence of discontinuous shale lenses in the Dakota sands. If the major shale lens shown in the Conner 1 log is used as the lower boundary of the sand unit, an average K estimate of 21.2 m/d is obtained. This value would certainly be on the high end of K estimates obtained for the Dakota sands. If the approximate thickness of the total sand interval for both the Conner 1 and Schaus 1 logs is used (44 m),

a more-reasonable estimate of 13.1 m/d is obtained. Note that if the nominal screen interval of 4.6 meters is employed, an average K of 127 m/d is obtained, an estimate that is extremely large for the semiconsolidated Dakota sand. Clearly, the average K estimate can vary over a large range depending on what value is assigned for the sand thickness. In this particular case, the apparent discontinuous nature of the shale lenses, in conjunction with the simulation results of the previous section, support the use of the total thickness of the sand interval to compute the average K.

Figure 6 shows a subset of the series of slug tests performed at this well. The test labelled 10/25 Test 1 was the most rapid test of the series. If data from this test are analyzed using the Hvorslev method, the effective screen length is assumed to be the nominal screen length, and isotropic conditions are assumed, a K estimate of 5.0 m/d is calculated. Since we strongly suspect that slug tests at this well are being impacted by a dynamic skin and the buildup of a bacterial mat, and that the effective screen length is less than the nominal screen length for the reasons illustrated in Figure 7, the estimate obtained from this test must be considered a lower bound for K. If we could remove the effects of the low-K skin, we suspect that the pumping-test and slug-test estimates would be very close at this site. The data collected at this site demonstrate how easily a difference of an order of magnitude or more between pumping-test and slug-test estimates can be obtained. Clearly, incomplete well development and uncertainty regarding formation thickness can play an important role in producing the commonly observed difference between pumping-test and slug-test parameters.

CONCLUSIONS

Field data from many different sources have repeatedly shown that K estimates obtained from large-scale pumping tests are larger than the average K estimates obtained from slug tests performed in the same formation. The primary purpose of this presentation was to evaluate various possible explanations for this difference. The results of this evaluation can be summarized as follows:

1. Infrequent-in-space, high-K zones will have a very limited impact on parameter estimates obtained from pumping tests. Thus, it is difficult to explain the difference between pumping-test and slug-test parameters on the basis of the existence of rare, high-K conduits;

2. Slug tests are extremely sensitive to altered, near-well conditions. Low-K skins, whether they be dynamic or static in nature, can produce slug-test K estimates that may be orders of magnitude lower than the average K of the formation. However, drawdown from pumping tests can be analyzed using the Cooper-Jacob semilog method to remove the effects of such low-K skins from parameter estimates;

3. In a pumping test, the full aquifer thickness should be used to analyze the drawdown data. In the case of a slug test, the effective screen length is required for the analysis. Unfortunately, the effective screen length may be quite difficult to estimate in practice. Use of the nominal screen length may introduce considerable error into the slug-test estimate;

4. Uncertainty about vertical anisotropy can produce

considerable error in K estimates from slug tests. Thus, attempts should be made to recognize anisotropy in the analysis process (e.g., Butler et al., 1996).

The overall conclusion of this presentation is that the observed difference between pumping-test and slug-test parameters is much more likely to be an artifact introduced by effects related to well installation and development than to be a product of a scale dependence in hydraulic conductivity. Further efforts to assess this relationship should therefore focus on removing the effects of well installation and development from slug-test estimates (e.g., Butler et al., 1996). Only when both types of hydraulic tests are providing representative estimates of the transmissive nature of the media can possible scaling relationships be rigorously evaluated.

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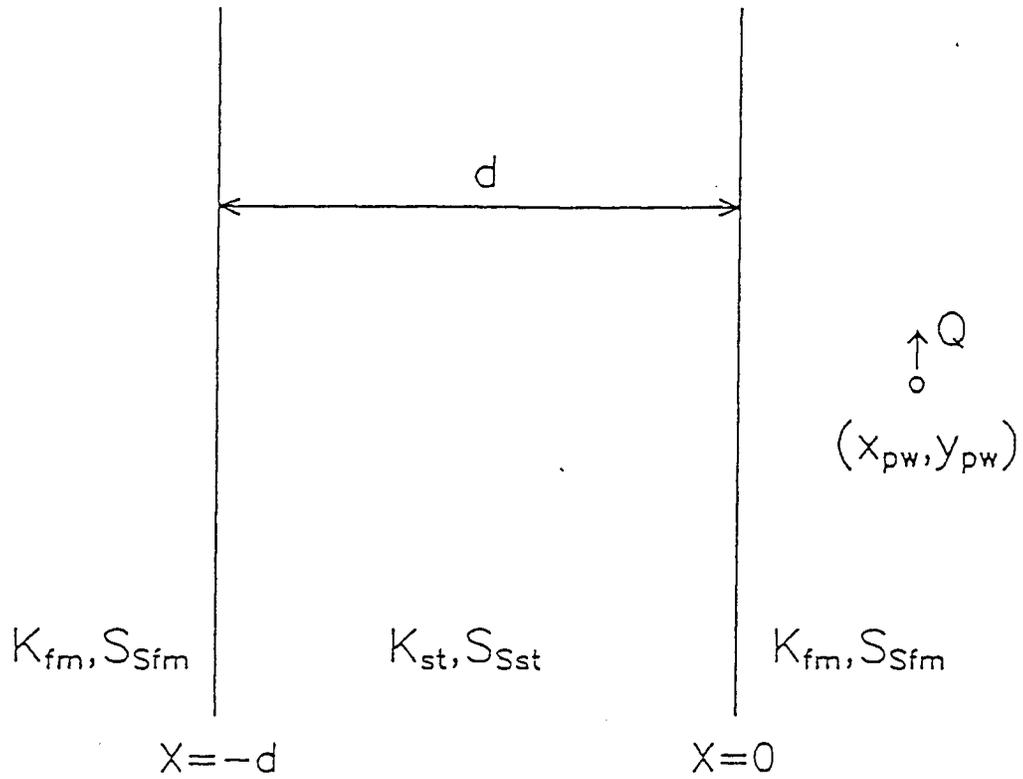# Figure 1A
Infinite Strip Case

$$d$$

$$\uparrow Q$$
$$\circ$$
$$(x_{pw}, y_{pw})$$

$$K_{fm}, S_{Sfm} \qquad K_{st}, S_{Sst} \qquad K_{fm}, S_{Sfm}$$

$$X=-d \qquad\qquad X=0$$

Figure 1B
Circular Disk Case

$$K_1, S_{S1}$$

$$a$$

$$Q$$
$$\nearrow$$
$$\circ$$
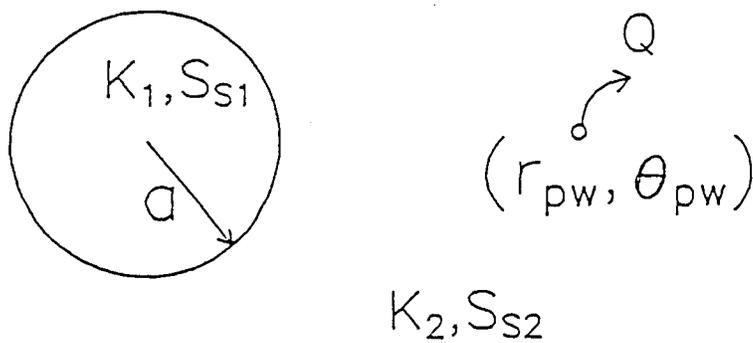$$(r_{pw}, \theta_{pw})$$
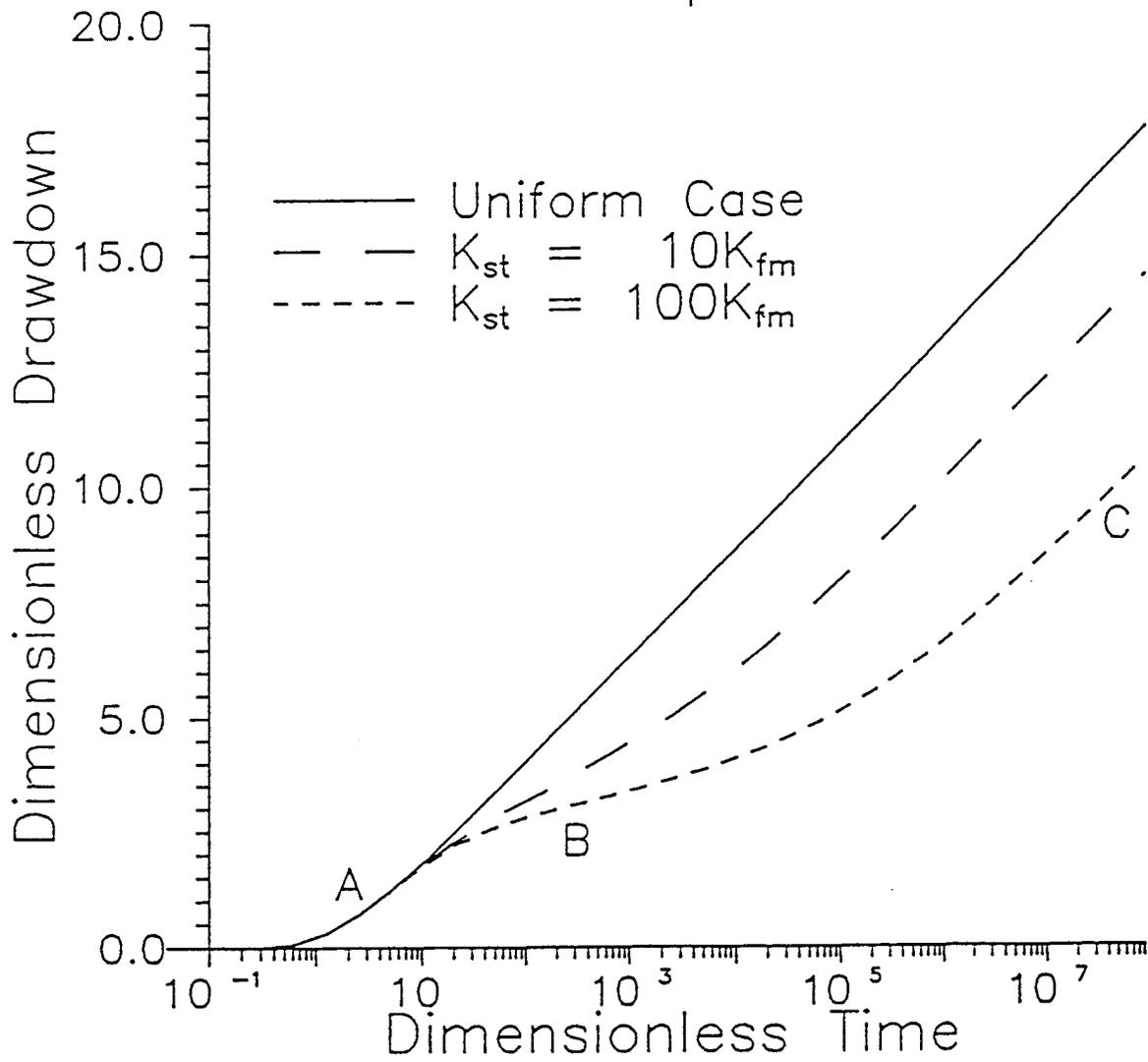
$$K_2, S_{S2}$$

Figure 2
Infinite Strip Case

Figure 3
Infinite Strip Case
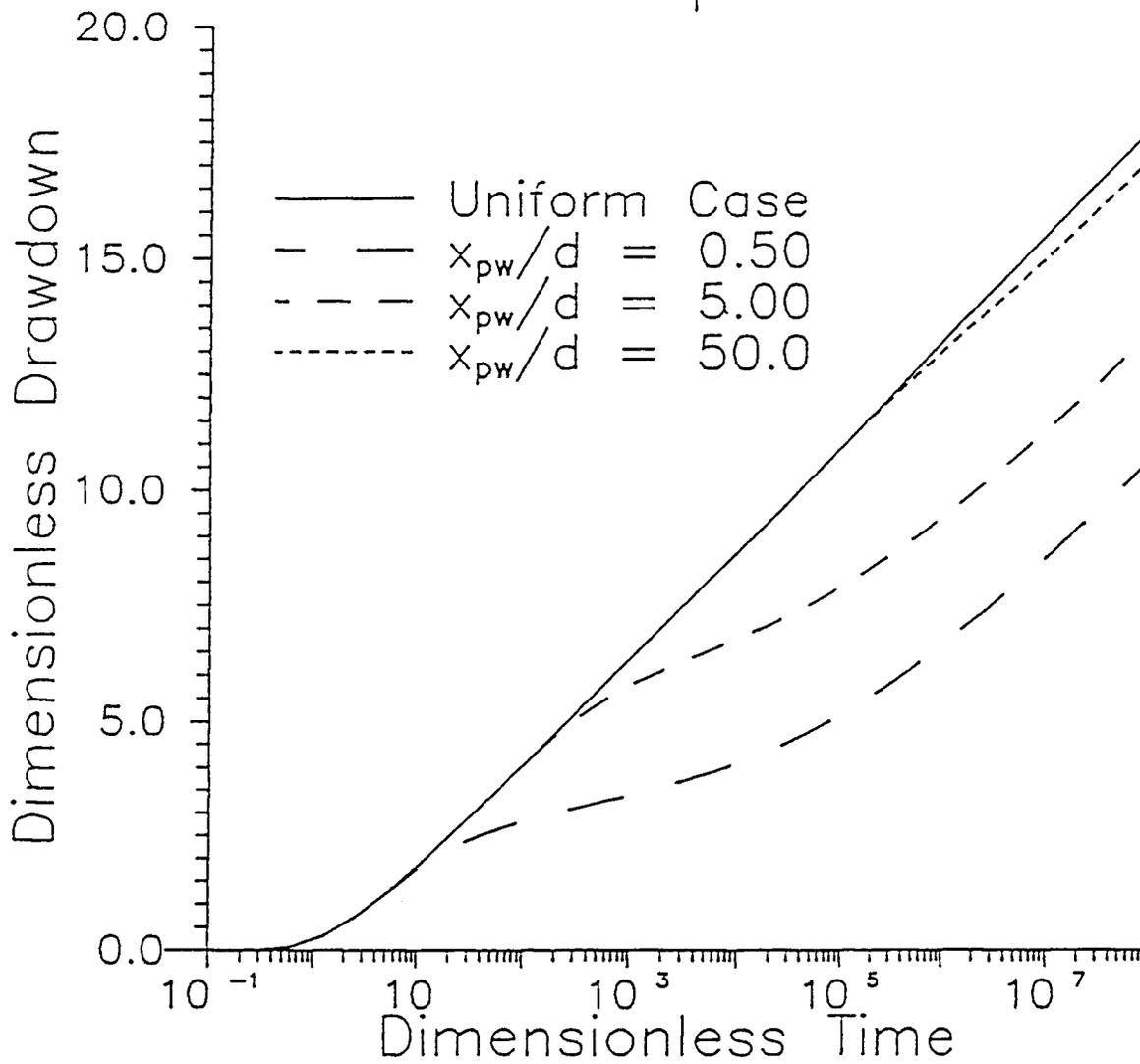
Figure 4
Circular Disk Case
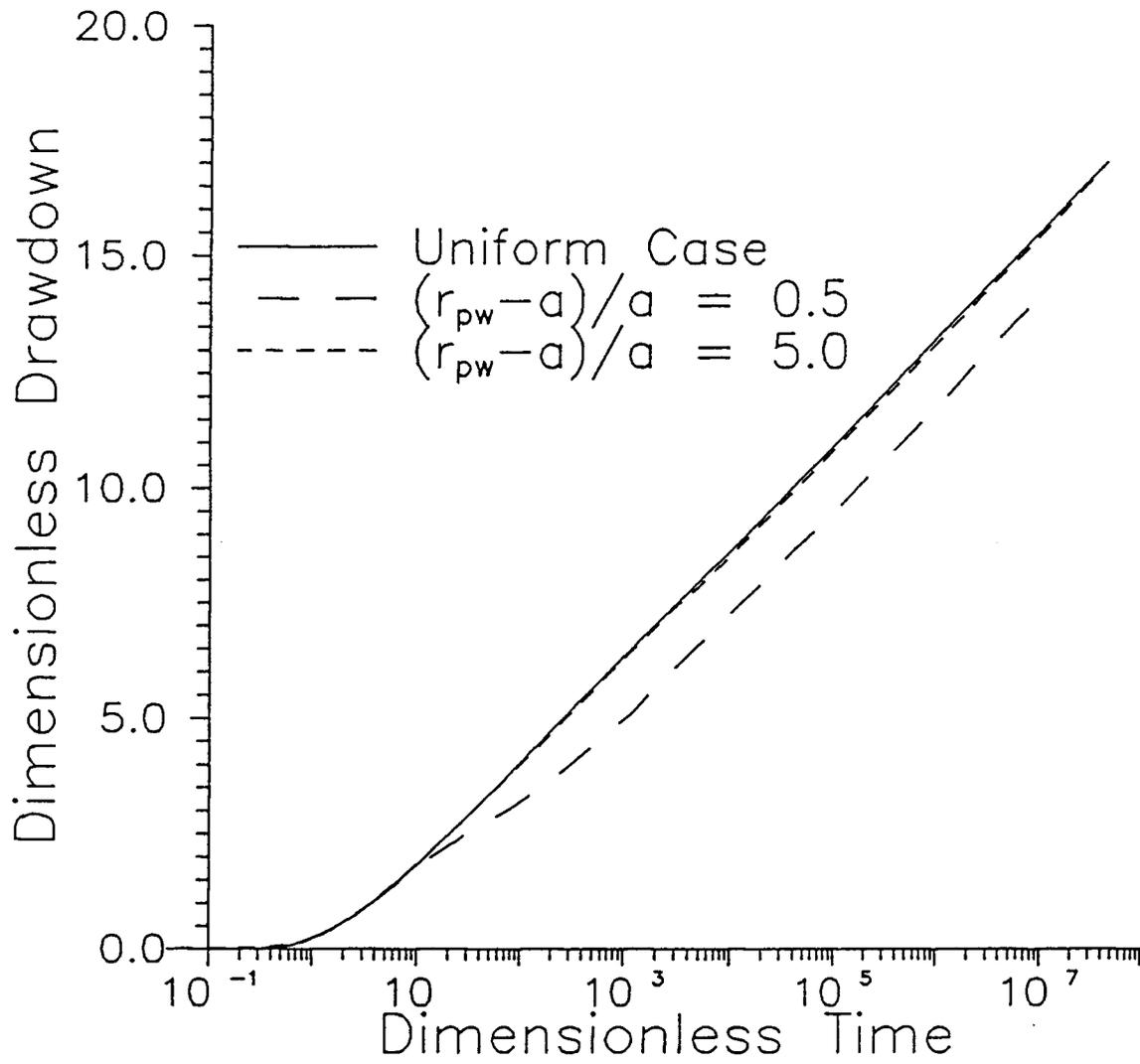
Figure 5
Stafford County Site 18
9/11/95 Tests

Test 1 (T_0=428 secs)
Test 2 (T_0=122 secs)
Test 3 (T_0=248 secs)
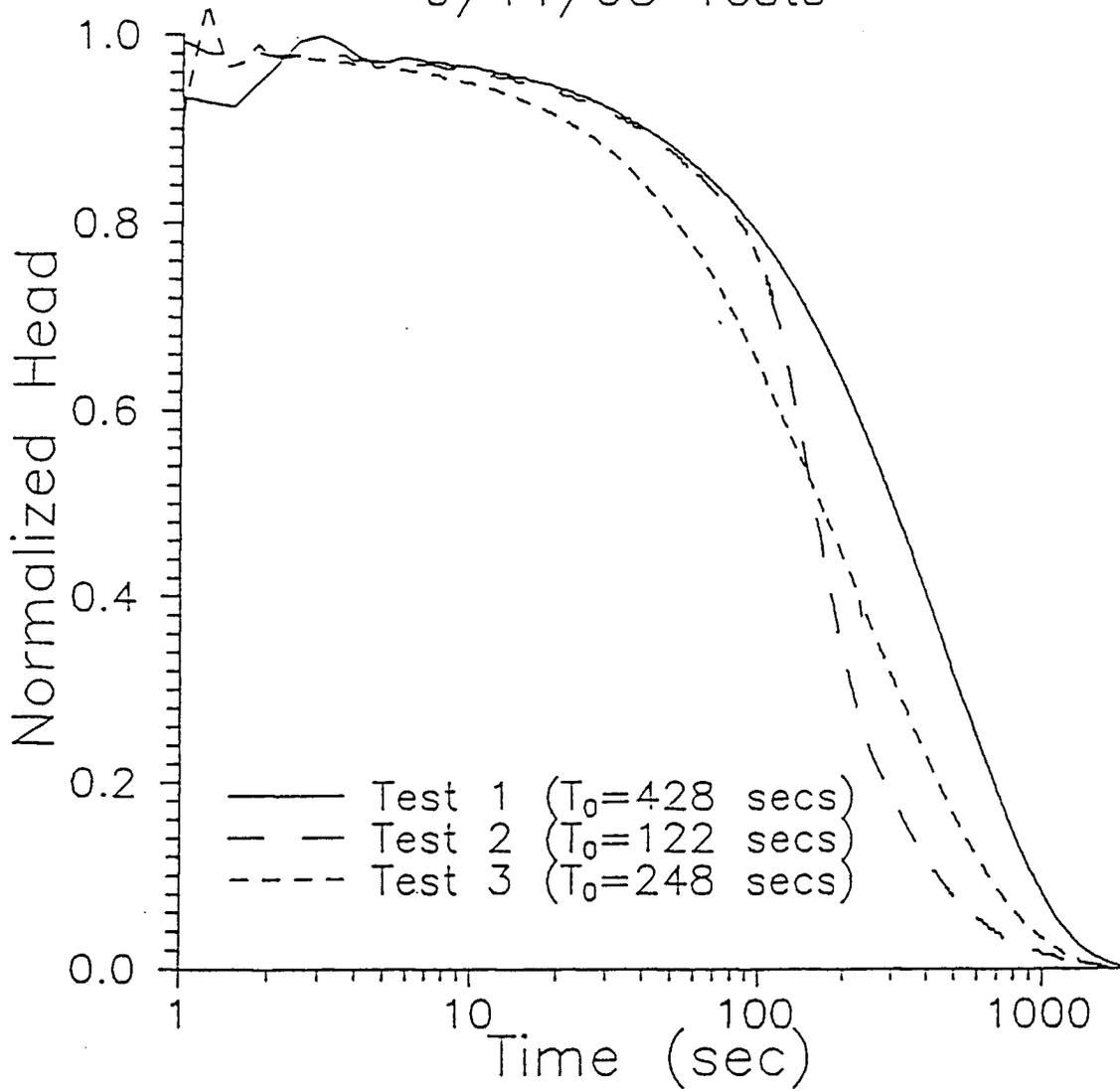
Figure 6
Oct.–Nov. 1995 Slug Tests
Trego County Site

———— 10/25 Test 1 – in (T_0=20.7 s)
———— 10/26 Test 1 – in (T_0=39.5 s)
— — 11/16 Test 2a – out (T_0=2040 s)
- - - - 11/16 Test 2b – in (T_0=40.6 s)

Figure 7

CENTER LINE OF WELL

Confining Bed

average K

lower K

higher K

average K

lower K

higher K

lower K

average K

higher K

lower K

Confining Bed

drilling mud   grout   gravel pack   screened interval

22
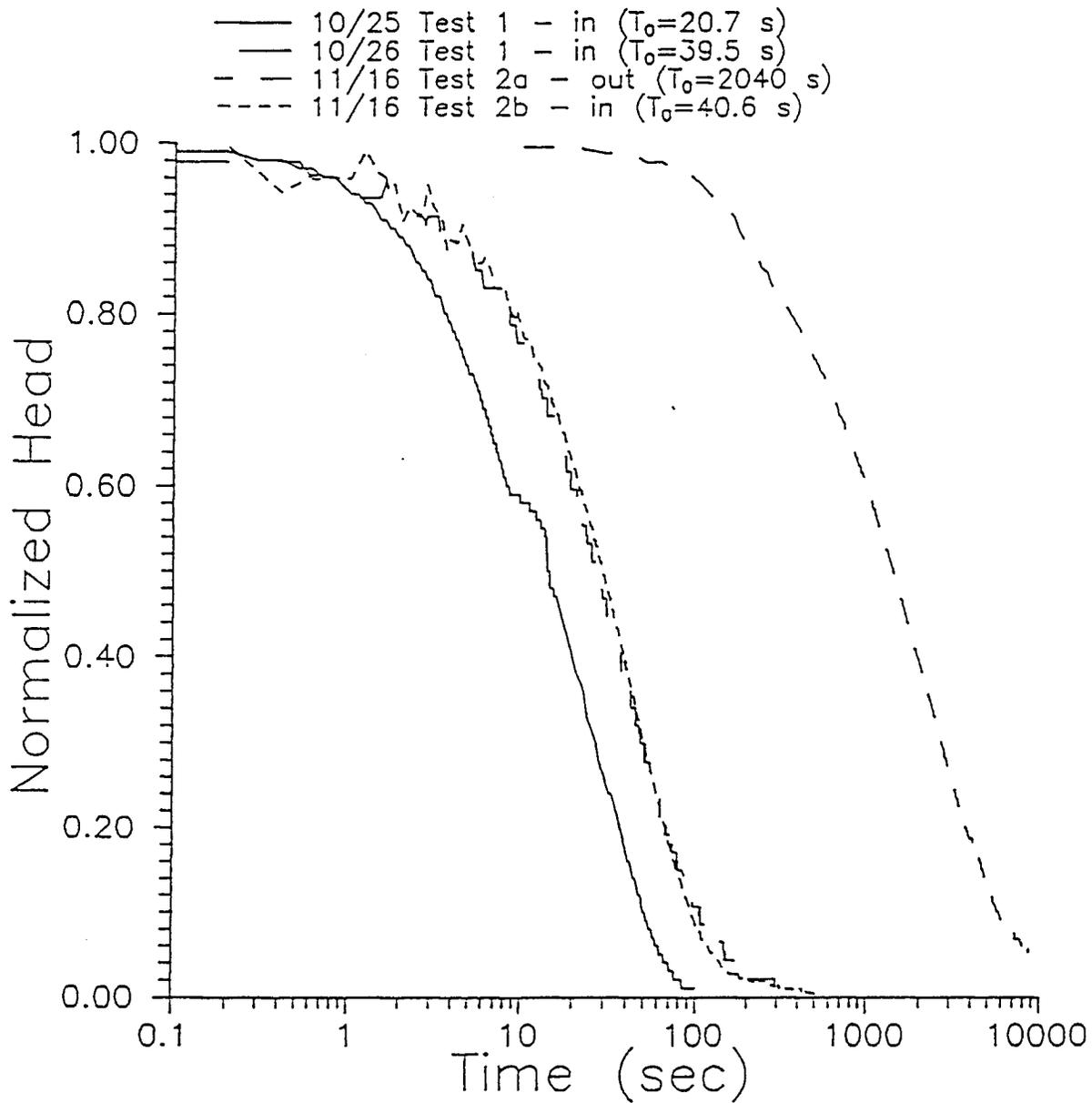
Figure 8
CCFDWT Comparison With KGS Model
Aspect Ratio = 20
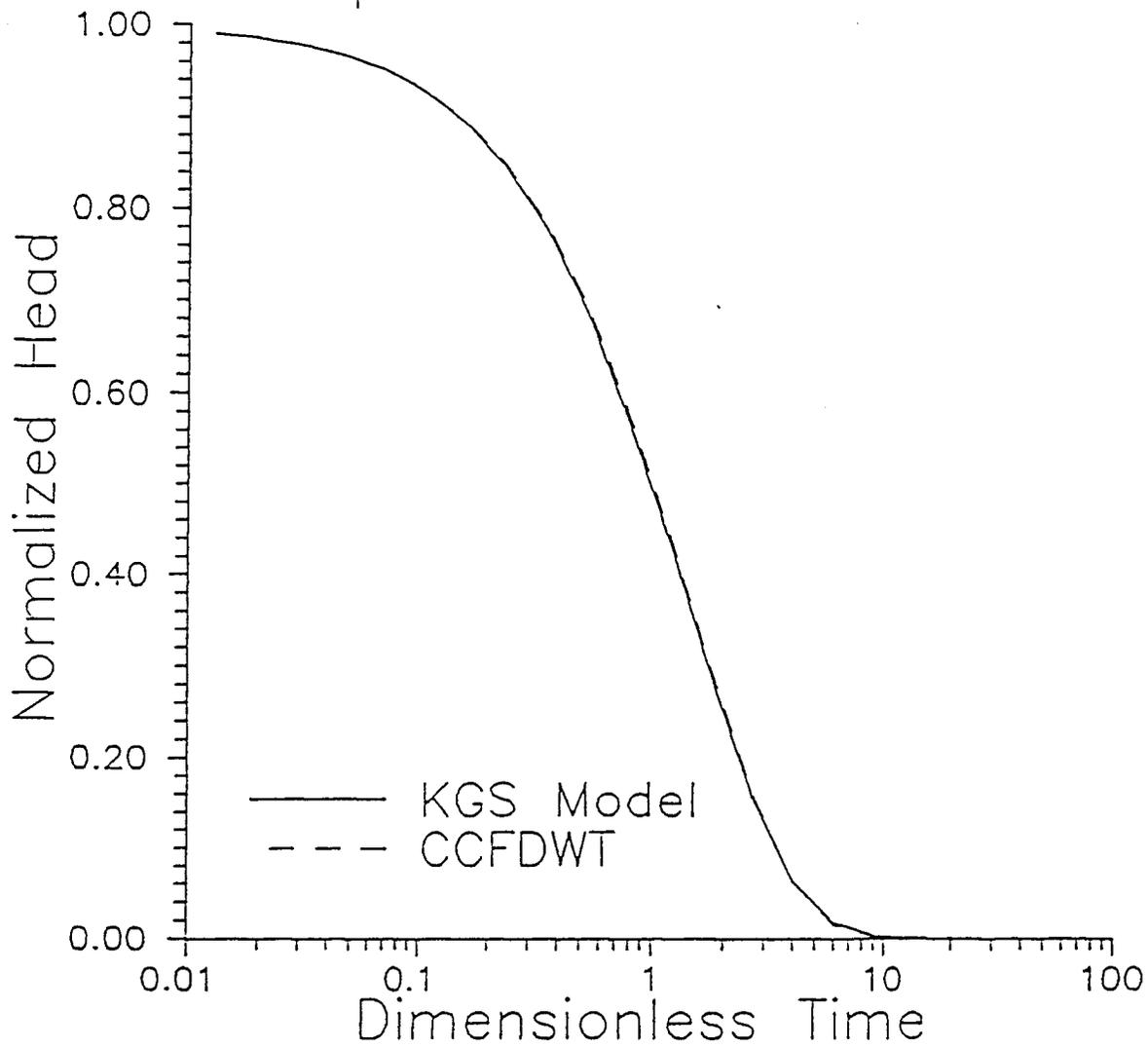
Figure 9
Simulated Pumping Test

Q = 272.6 m³/d
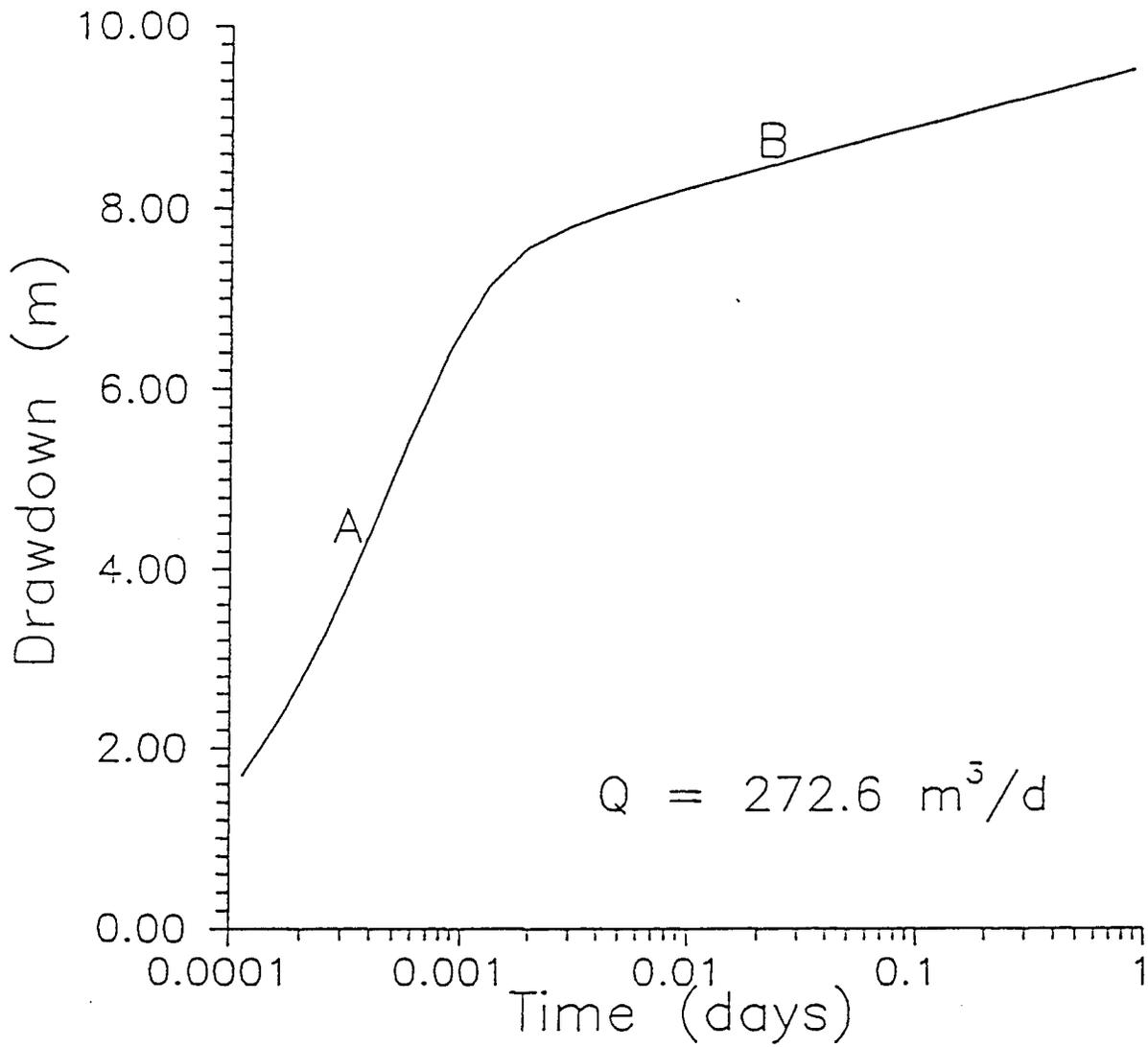
Figure 10
Simulated Slug Test

$T_0 = 4.58e-4$ days

FIGURE 11

T11S R24W

SE ¼ Section 23

Schaus 1

B · A'

Trego

A ·

Conner 1

NE ¼ Section 26

A   B   A'

Conner 1   Trego   Schaus 1

900   900   900

950

1000   980   1000
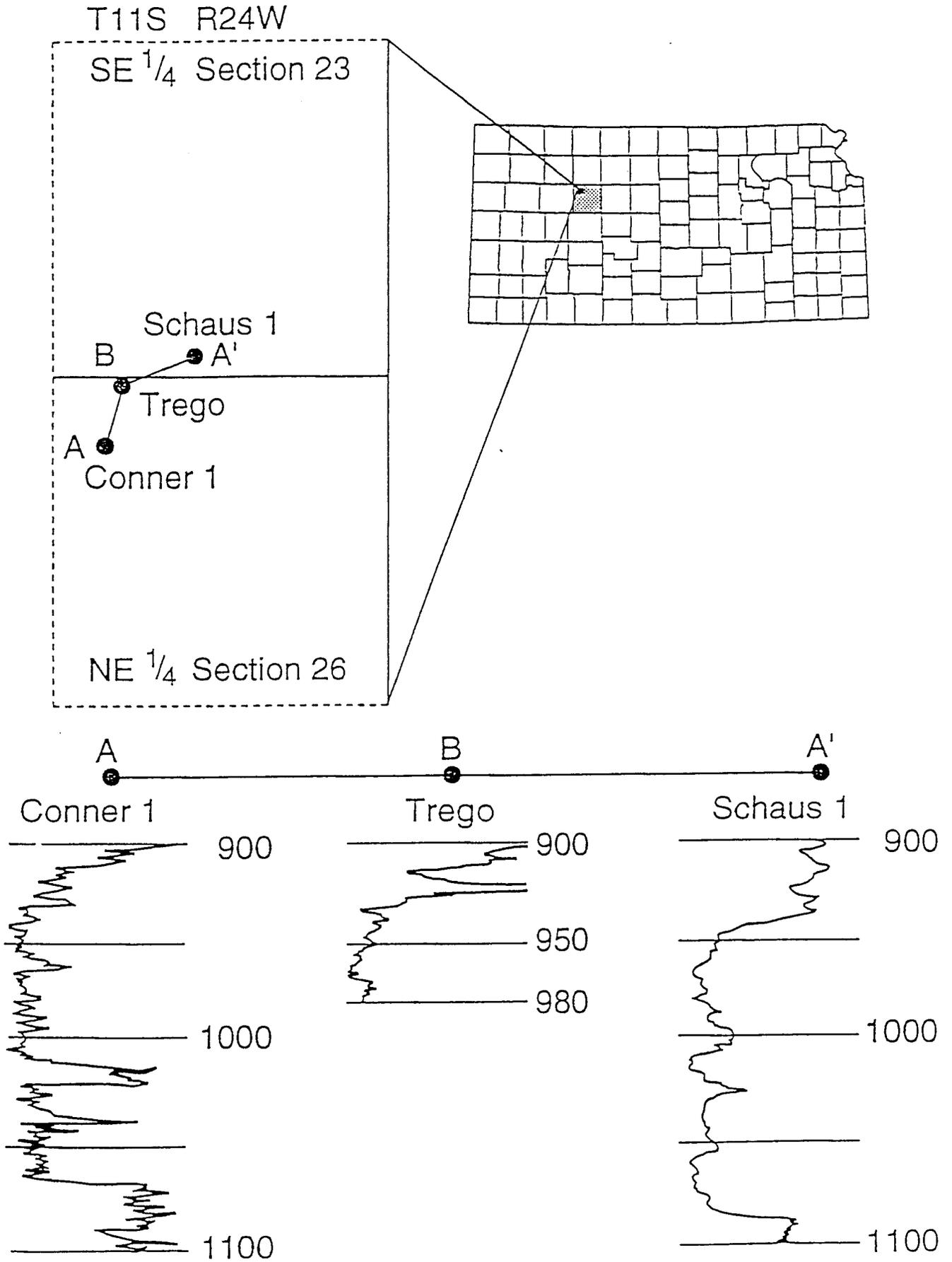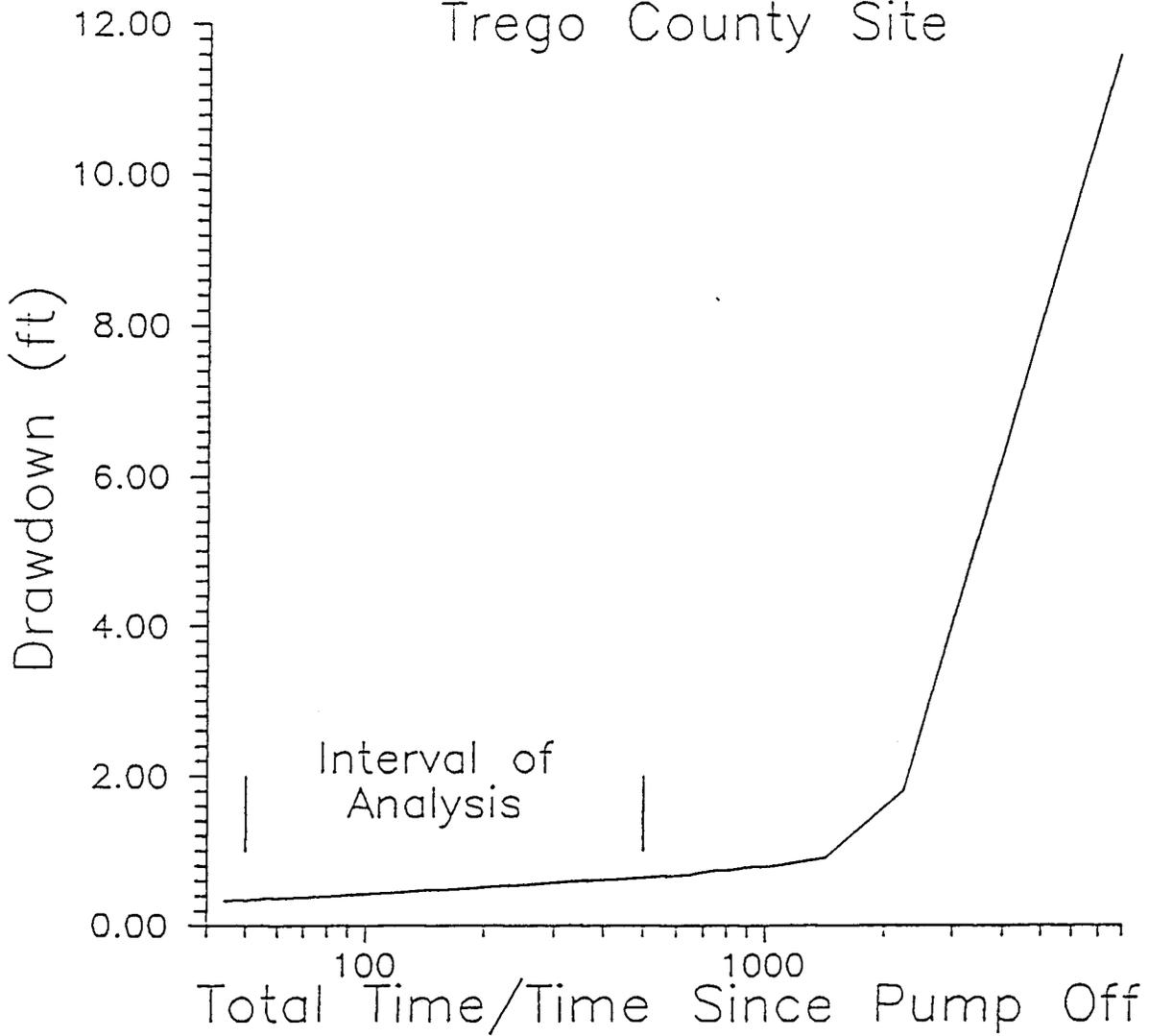
1100   1100
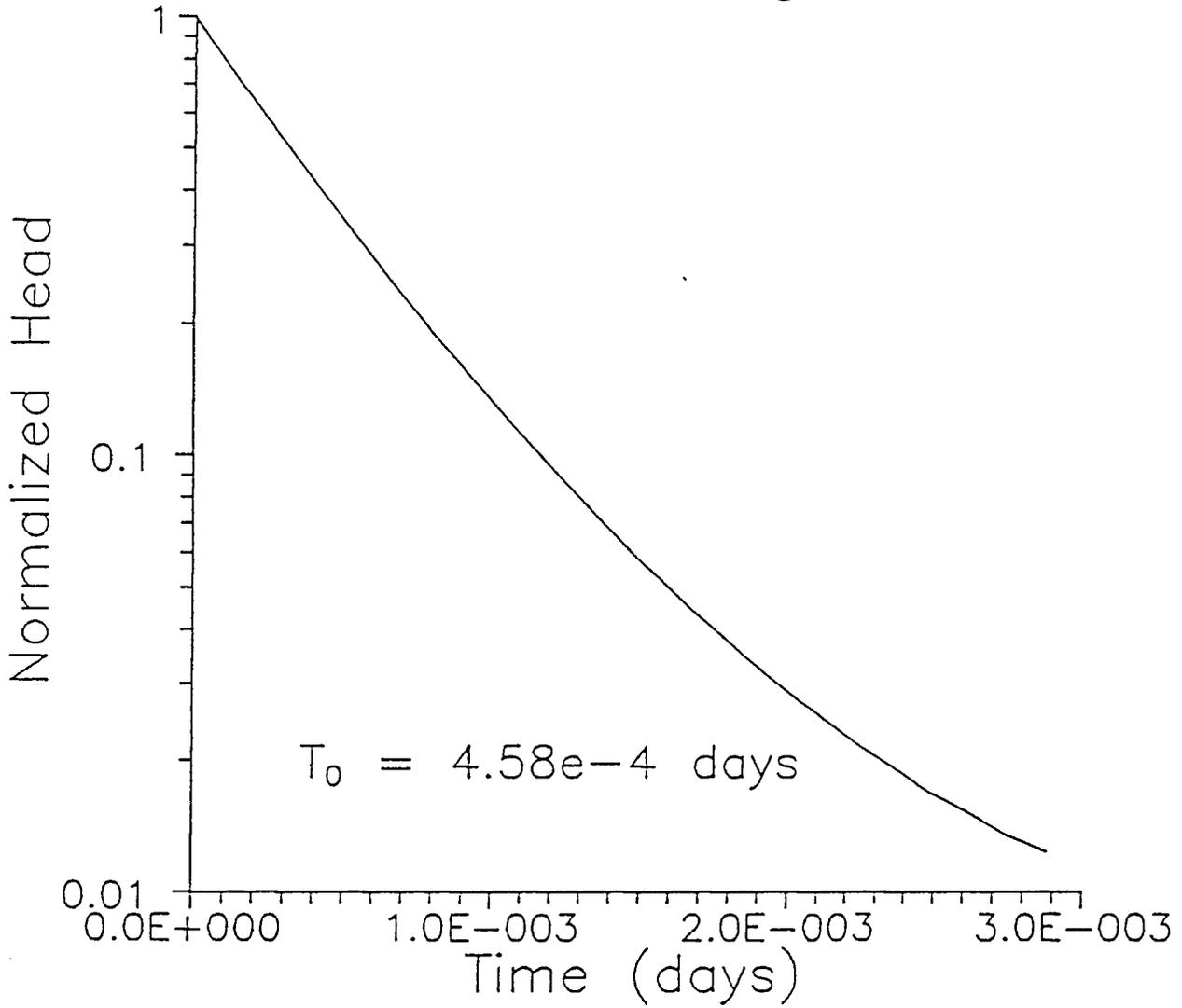
Figure 12A
7/16-7/17/94 Pumping Test
Recovery Data
Trego County Site

Figure 12B
7/16−7/17/94 Pumping Test
Recovery Data
Trego County Site