Hydraulic Tests With Direct Push Equipment

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Abstract

The potential of direct-push technology for hydraulic characterization of saturated flow systems was investigated at a field site with a considerable degree of subsurface control. Direct-push installations were emplaced by attaching short lengths of screen (shielded and unshielded) to the bottom end of a tool string that was then advanced into the unconsolidated sediments. A series of constant-rate pumping tests were performed in a coarse sand and gravel aquifer using direct-push tool strings as observation wells. Very good agreement (within 4%) was found between hydraulic conductivity (K) estimates from direct-push installations and those from conventional wells. A program of slug tests was performed in direct-push installations using small-diameter adaptations of solid-slug and pneumatic methods. In a sandy silt interval of moderate hydraulic conductivity, K values from tests in a shielded screen tool were in excellent agreement (within 2%) with those from tests in a nearby well. In the coarse sand and gravel aquifer, K values were within 12% of those from multilevel slug tests at a nearby well. However, in the more permeable portions of the aquifer (K >70 m/day), the smaller-diameter direct-push rods (0.016 m inner diameter [I.D.]) attenuated test responses, leading to an underprediction of K. In those conditions, use of larger-diameter rods (e.g., 0.038 m I.D.) is necessary to obtain K values representative of the formation. This investigation demonstrates that much valuable information can be obtained from hydraulic tests in direct-push installations. As with any type of hydraulic test, K estimates are critically dependent on use of appropriate emplacement and development procedures. In particular, driving an unshielded screen through a heterogeneous sequence will often lead to a buildup of low-K material that can be difficult to remove with standard development procedures.

Introduction

In the last decade, direct push technology has become a widely used alternative to conventional drilling-based approaches for environmental site investigations in unconsolidated formations. This technology uses hydraulic rams supplemented with vehicle weight (cone penetrometer (CPT)) and/or high-frequency percussion hammers to rapidly advance small-diameter tools into the subsurface. The use of this technology for ground water applications has accelerated in recent years because of several advantages over conventional drilling methods (Thornton et al. 1997). These include greater mobility/access, simpler operation, no generation of drilling cuttings, and less subsurface disturbance. Although direct push methods for ground water applications have primarily been limited to collection of soil gas, water, and core samples, this technology has the potential to provide much more (e.g., Lunne et al. 1997; U.S. EPA 1998; Hurt et al. 2000; Lieberman 2000; Shinn 2000). The investigation of that potential for the hydraulic characterization of unconsolidated aquifers is the primary focus of this paper.

A variety of approaches have been used to determine the hydraulic conductivity (K) of saturated formations with direct push technology. Geotechnical engineers have developed empirical relationships for prediction of K from sediment classification information produced by CPT surveys (e.g., Farrar 1996). Although the information can be obtained rapidly, the resulting K values are, at best, only order of magnitude estimates of formation conductivity. Pore pressure dissipation tests accompanying CPT surveys have been used to determine K from a relationship between hydraulic conductivity and the consolidation properties of the formation (Baligh and Levadoux 1980). Lunne et al. (1997), however, caution that this relationship results in very approximate K values. Recently, a number of efforts have been made to more directly estimate K using extensions of conventional hydraulic tests. These include the performance of constant drawdown pumping tests (Wilson et al. 1997; Cho et al. 2000) and slug tests (Hinsby et al. 1992; Scaturo and Widdowson 1997; McCall 1998) in direct push equipment, and drive-time injection monitoring (Pitkin 1998; Pitkin and Rossi 2000). Some of these approaches provide valuable information about relative variations in hydraulic conductivity, but many questions still remain regarding their capability for direct determination of K. Apparently, the most successful direct push approach for K determination was the mini-slug test method of Hinsby et al. (1992). In that work, the vertical distribution of conductivity in a sandy glaciofluvial aquifer was estimated using slug tests performed in small-diameter piping attached to a driven unshielded well point. The slug test results

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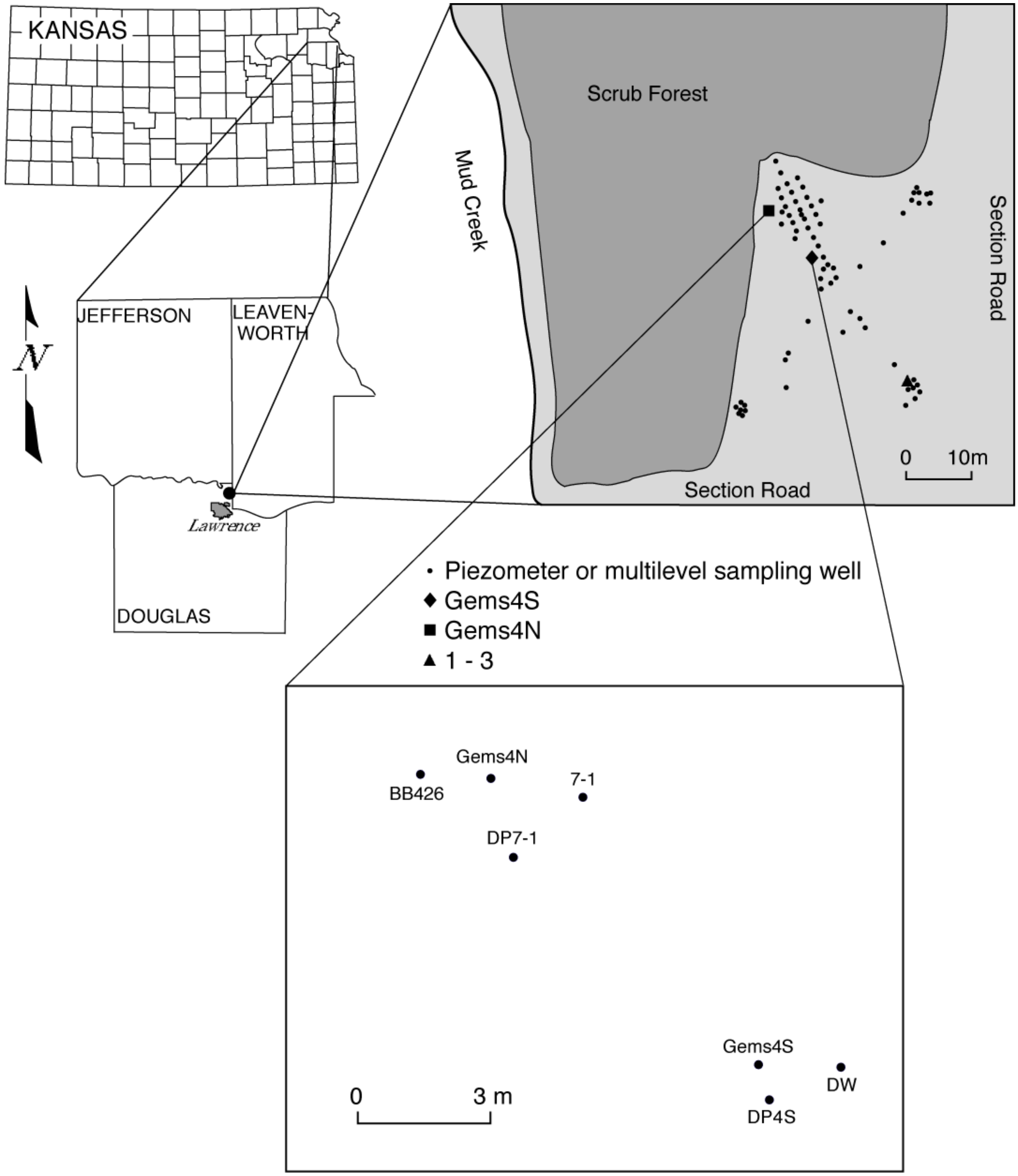

Figure 1 – Location map for the Geohydrologic Experimental and Monitoring Site (GEMS) with inset showing direct-push installations (DP4S, DP7-1, and BB426) and conventional wells (Gems4N, Gems4S, 7-1, and DW) used in this work.

compared well with K values from natural gradient tracer tests performed at the site. Concerns have been raised regarding the model used to analyze the slug test data (Butler 1997, p. 82), and thus the significance of the reported comparison, as well as the generalization of the approach to more heterogeneous sequences. Despite these concerns, however, the general conceptual approach utilized by Hinsby et al. (1992) appears sound and will therefore serve as the starting point for the work described here.

The major objective of this article is to define a general approach for the performing hydraulic tests with direct-push equipment. Although a brief discussion of the use of direct push installations as pumping wells is provided for completeness, the primary focus will be on the

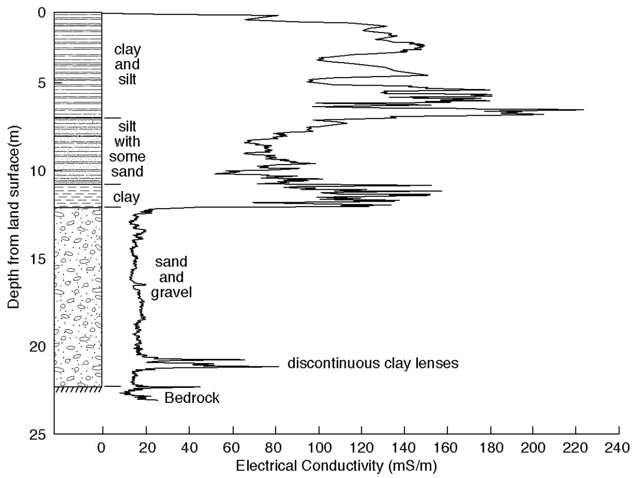

Figure 2 - Generalized GEMS stratigraphy with example electrical conductivity log.

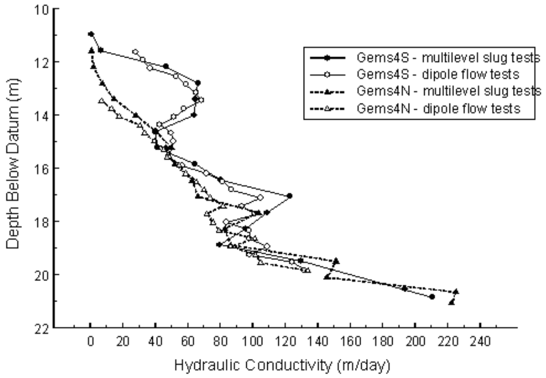

Figure 3 - Vertical variation in hydraulic conductivity determined at Gems4S and Gems4N from multilevel slug tests and dipole flow tests (datum is top of casing at Gems4S; lateral separation between Gems4N and Gems4S is 9.7 m; dipole flow tests performed using tool described in Zlotnik and Zurbuchen (1998)).

use of direct push tool strings as observation wells for constant-rate pumping tests and as stressed wells for slug tests. The proposed procedures are illustrated using examples from investigations at a field site with considerable subsurface control. Results from these investigations will be utilized to evaluate a variety of issues ranging from pipe diameter to the importance of well development. This paper concludes with a summary of the major findings of the field investigations.

Description of Field Site

The procedures described in this article were evaluated at a research site of the Kansas Geological Survey (KGS). This site, the Geohydrologic Experimental and Monitoring Site (GEMS), is located in the floodplain of the Kansas River just north of Lawrence, Kansas (Figure 1). The shallow subsurface at the site consists of 21+ m of unconsolidated Holocene sediments of the Kansas River alluvium that overlie and are adjacent to materials of Pennsylvanian and Pleistocene age. Figure 2 displays a vertical profile of the shallow subsurface at GEMS with electrical conductivity logging data obtained using a direct-push unit (Christy et al. 1994), and a geologic interpretation from core and logging data. As shown in the figure, the heterogeneous alluvial facies assemblage at GEMS essentially consists of 11.5 m of primarily clay and silt overlying 10.7 m of sand and gravel. For the last decade, GEMS has been the site of extensive research on flow and transport in heterogeneous formations (McElwee et al. 1991; Butler et al. 1998, 1999a,1999b; Bohling 1999). This previous work enables the procedures discussed here to be evaluated in a controlled field setting.

Figure 4 - Small-diameter pressure transducer and unshielded screen tool.

Direct push-based hydraulic tests were performed in both the sand-gravel and silt-sand intervals shown in Figure 2. In this article, the results of direct-push tests in the sand-gravel interval are primarily compared to those from tests performed using two conventional wells (Gems4N and Gems4S; 0.102 m ID; installed with hollow-stem augers; Figure 1). Figure 3 presents the results of a series of multilevel slug tests and dipole flow tests performed in these wells as part of earlier work on techniques for estimation of vertical variations in K (Butler et al. 1998). The excellent agreement between K estimates obtained with completely different approaches enables the profiles of Figure 3 to be considered as standards to which the direct push slug test results from the sand-gravel section can be compared. For the silt-sand interval, the results of slug tests in a direct-push installation are compared to those from slug tests in a nearby monitoring well (1-3; 0.052 m ID; installed with hollow-stem augers; Figure 1) screened over the same interval. Note that the top of casing at well Gems4S is used as the site datum throughout this paper.

Pumping Tests With Direct-Push Equipment

Measurement of Drawdown

Drawdown is measured in direct push installations with small-diameter pressure transducers (outer diameter [O.D.]—0.01 m sensor, 0.006 m cable; Figure 4) and electric tapes (O.D.<0.006 m). The transducer is the preferred device because measurements can be acquired rapidly without need for cable movement. Butler et al. (1999b) have recently proposed an inexpensive alternative to a small-diameter pressure transducer. That approach involves placing small-diameter

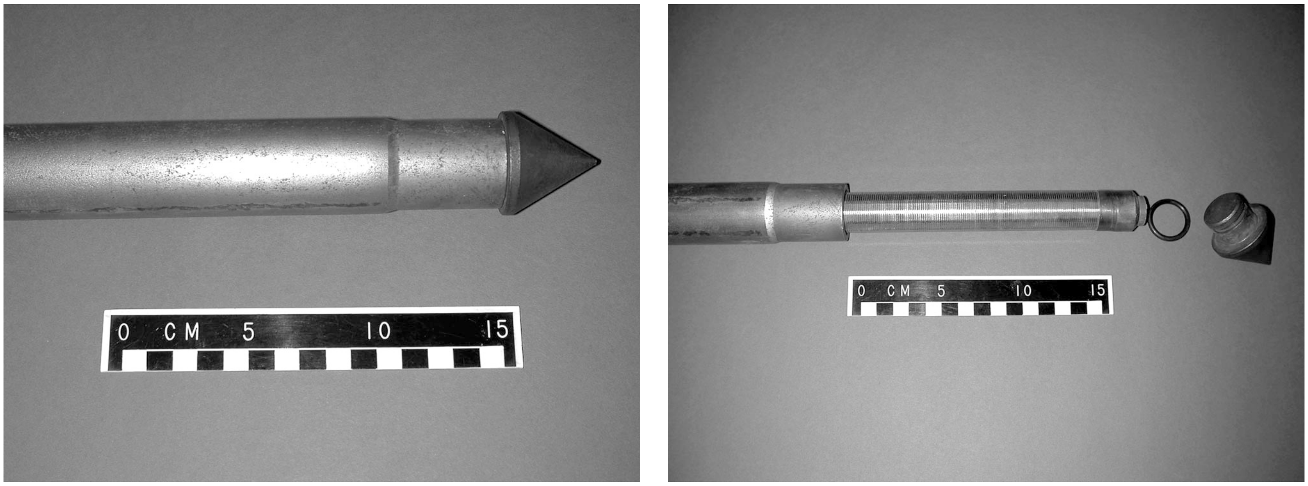

Figure 5. (a) Shielded screen tool with screen shroud in place; (b) Shielded screen tool after screen shroud has been pulled back (well point with O-ring always left in formation; rubber plug at bottom of screen can be knocked out for retraction grouting).

polyethylene tubing (O.D.<0.007 m) in the direct push pipe and measuring air-pressure changes above the water column in the tubing.

Direct Push Installations as Pumping Wells

Although direct push installations can be used for single well pumping tests to obtain information about vertical variations in hydraulic conductivity, there has been relatively little reported work on this topic. The small-diameter pipe (ID<0.02 m) used in most direct push tool strings limits the general applicability of this approach, as space restrictions make it difficult to both obtain a flow rate large enough to produce measurable drawdown and to measure that drawdown. Cho and coworkers (Wilson et al. 1997; Hurt 1998; Cho et al. 2000) have proposed a method for performing constant drawdown tests with a suction pump in an attempt to reduce the impact of the space restrictions. In their approach, drawdown is not measured with a downhole device. Instead, the lower end of the suction-pump tubing is placed a small distance (d) below the static water level. The pumping rate is adjusted until a mixed stream of air and water is produced, which usually indicates that the end of the tubing is at the same position as the water level in the pipe, i.e., drawdown equals d. Hydraulic conductivity can then be estimated from the drawdown and steady-state flow rate.

Single well pumping tests, such as those proposed by Cho et al. (2000), were not used in this work because use of a suction pump limits the depth to water (lift cannot exceed 8 m in most cases) and often the K range (i.e., the maximum flow rate may not produce measurable drawdown in intervals of high K) at which the approach can be used. Performance of pumping tests in injection mode would alleviate these flow and depth limitations, but injection tests are more likely to lead to the formation of a low-K skin as result of inadvertent injection of entrained air and sediments. Since slug tests do not have these disadvantages, they are often a better method for estimation of vertical variations in hydraulic conductivity. Although the analysis procedure for slug tests can be more involved than that for pumping tests run to steady-state conditions, computerized analysis methods make this minor disadvantage. Thus, in this work, slug tests were used as an alternative to single-well pumping tests for obtaining information about vertical variations in hydraulic conductivity.

Direct Push Installations as Observation Wells

Direct push installations can be used as observation wells for pumping tests to obtain information about the average transmissive and storage properties of a formation. A series of constant rate pumping tests were performed at GEMS in the spring and summer of 1999 using direct push installations as temporary observation wells to demonstrate the quality of the drawdown data that can be obtained with this approach. The installations consisted of a screen at the lower end of the direct-push tool string. In all cases, the screen was shielded during driving through the upper clay-silt interval shown in Figure 2. In the initial series of tests, an unshielded screen (Figure 4, Geoprobe GP 14401) was driven from the top of the sand and gravel to the selected depth. In later tests, the screen was shielded (Figures 5a and b, Geoprobe GW 1512K) until the selected depth was attained. Head data were collected using a small-diameter pressure transducer (Figure 4 - Druck PDCR 35/D-8070) connected to a data logger (Campbell Scientific 23X, acquisition rate 5 Hz or less).

The first series of tests involved pumping a conventional well (DW; 0.127 m ID; installed with hollow stem augers; Figure 1). Well Gems4S, which is also screened across the sand and gravel, is located 1.85 m from this pumping well. A direct push installation (DP4S; Figure 1) was placed 1.85 m from the pumping well and 0.99 m from Gems4S. The bottom of the 0.23 m direct push screen was 17.68 m below datum in the central portion of the sand-gravel section. Figure 6 is a plot of drawdown versus the logarithm of time since the start of pumping for one test from this series (pumping rate of 4.0 l/sec (63.3 gpm)). The S-shaped pattern seen in the first 10-20 seconds is an inertia-induced feature that is often observed in pumping tests performed in high-K functions (Zhan and Butler 2001). Although the drawdown is different at Gems4S and DP4S, the plots become parallel after 15-20 seconds. These parallel plots, which reflect the large-scale hydraulic characteristics of the aquifer, are what would be expected for a test in a confined aquifer (Butler and Liu 1993; Schad and Teutsch 1994; Meier et al. 1998). A straight line fit to the direct-push drawdown

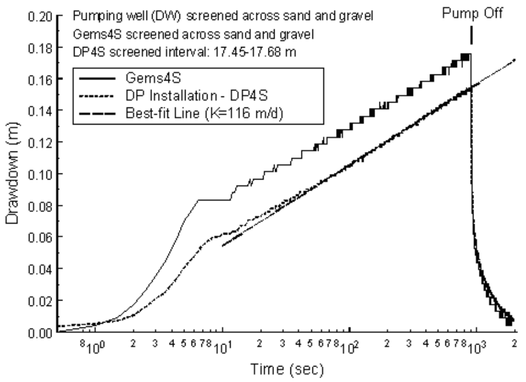

Figure 6 - Drawdown versus logarithm of time plot for March 16, 1999, pumping test (pumping rate = 4.0 L/sec).

between 50 and 910 seconds (termination of test) is shown in Figure 6. A Cooper-Jacob analysis (Cooper and Jacob 1946) using the slope of this line results in a K estimate of 116 m/day. This value is within 4% of K estimates calculated from previous pumping tests performed using this same pumping well and various other observation wells (Butler et al. 1999b).

The test shown in Figure 6 used a pumping well screened across the entire sand-gravel interval. In order to evaluate conditions produced by pumping at a partially penetrating well, additional tests were performed in well Gems4N. Although Gems4N is also screened across the entire sand and gravel section, a partially penetrating configuration was produced by using straddle packers to isolate a 0.61 m interval that was connected to the surface with a drop pipe. This interval, the position of which could be readily changed by moving the drop pipe and packers, was pumped at 1.4 l/sec (22.2 gpm). A monitoring well (7-1; Figure 1) screened across the entire sand-gravel interval and located 2.15 m from Gems4N served as a conventional observation well. A direct push installation (DP7-1; Figure 1) was placed 2.15 m from the pumping well and 2.24 m from 7-1. The bottom of the 0.09 m screened interval of this installation was 19.85 m below datum in the lower portion of the sand and gravel.

Figures 7a and 7b present drawdown plots from pumping tests performed in this partially penetrating configuration. Figure 7a shows results from a test in which the isolated zone in the pumping well was centered at 19.80 m below datum. A straight line with the slope determined from the analysis of Figure 6 is fit to drawdown between 10 and 100 seconds. Despite the test being performed at a different pumping rate and in a different well (Gems4N is approximately 11 m from well DW), drawdown is consistent with that observed in the previous test shown in Figure 6. About 600 seconds into the test, a nearby pump is turned on producing a dramatic increase in drawdown at both 7-1 and DP7-1 for the remainder of the test and during the recovery period.

In Figure 7a, the drawdown produced at DP7-1 is greater than that observed in the fully screened observation well because the pumping interval is opposite the screen of the direct-push installation. When the pumping interval is located a considerable distance above the direct push screen, the drawdown in the fully screened observation well is greater than that in DP7-1 (Figure 7b). The concave-upward curvature displayed in Figure 7b for both the drawdown and recovery periods is again a product of nearby pumping activity. Note that the difference between the drawdown measured at DP7-1 in Figures 7a and 7b is a product of the distance from the pumping interval and formation heterogeneity. The component produced by heterogeneity could potentially be exploited to learn more about the K distribution as discussed in Butler (1999b).

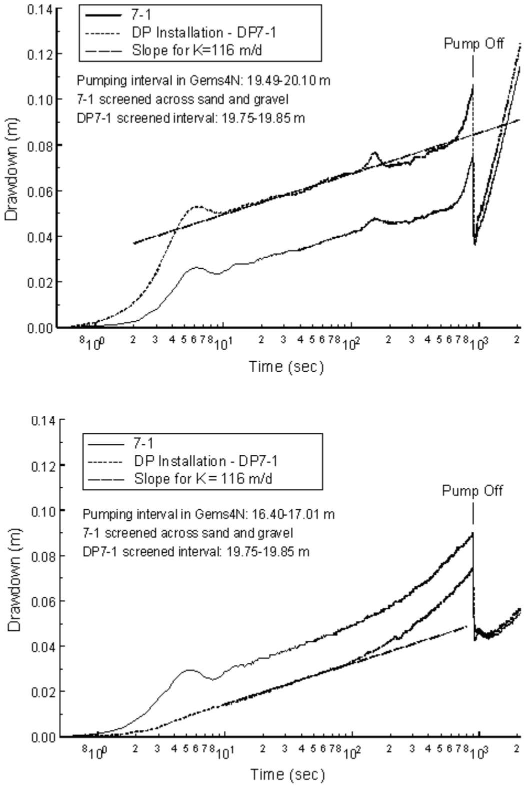

Figure 7 - Drawdown versus logarithm of time plots for August 13, 1999, pumping tests: (a) Pumping interval in Gems4N 19.49-20.10 m below datum; (b) Pumping interval in Gems4N 16.40-17.01 m below datum (pumping rate=1.4 L/sec; note oscillatory drawdown at early time; perturbation in drawdown between 100 and 200 seconds in Figure 7a produced by an adjustment of backpressure in the discharge line.).

Slug Tests With Direct-Push Equipment

Initiation Methods

Slug tests in direct push tool strings can be initiated with small-diameter adaptations of conventional methods. The methods used here were chosen so that tests could be initiated without adding or removing water, an important consideration at sites of suspected ground water contamination.

For intervals of moderate or lower hydraulic conductivity, tests can be initiated by rapidly introducing/removing a solid object (slug) to/from the water column. To avoid problems presented by space limitations (such as entangling of cables), McCall (1998) proposed using the

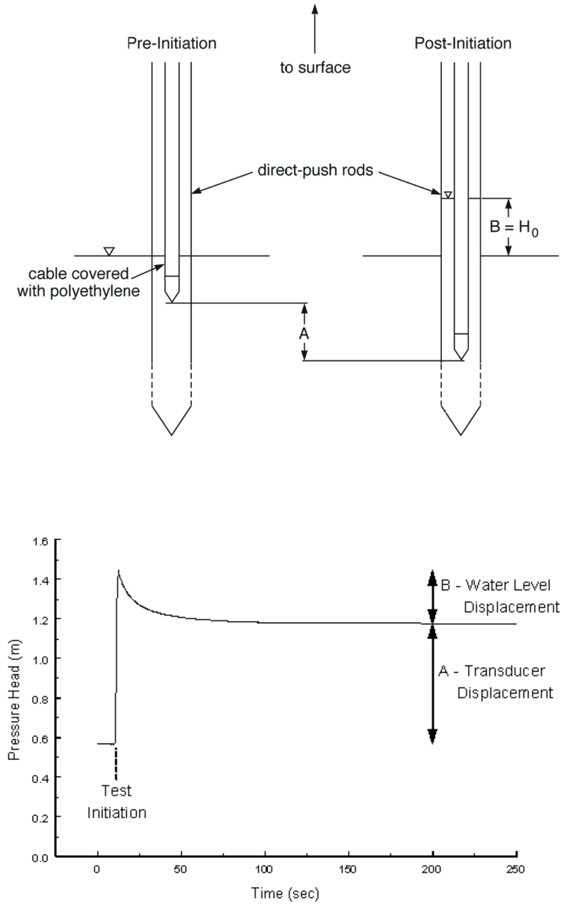

Figure 8 – (a) Schematic of solid-slug initiation method of McCall (1998); (b) Pressure head versus time plot of slug test initiated with the solid-slug method (A and B defined in text; H_0 is magnitude of initial displacement).

pressure transducer cable as the slug. This approach involves raising or lowering the transducer in the water column (Figure 8a). The water level displacement is equal to that produced by adding/removing a length of cable to/from the water column. A length of polyethylene tubing can be placed over the lower portion of the transducer cable to increase the water level change produced by moving a certain length of cable (McCall 1998). As with a conventional solid slug, pre-test calibration in a piece of blank casing is used to determine how much water level change to expect for movement of a certain length of cable (McCall 1998). As with a conventional solid slug, pretest calibration in a piece of closed pipe is used to determine how much water level change to expect for movement of a given length of cable (i.e., value to use for normalization of response data [H_0]). An example of a test initiated with this approach is shown in Figure 8b. Interval A represents the change in head produced by lowering the transducer in the water column, while interval B represents the actual water level displacement produced by cable immersion.

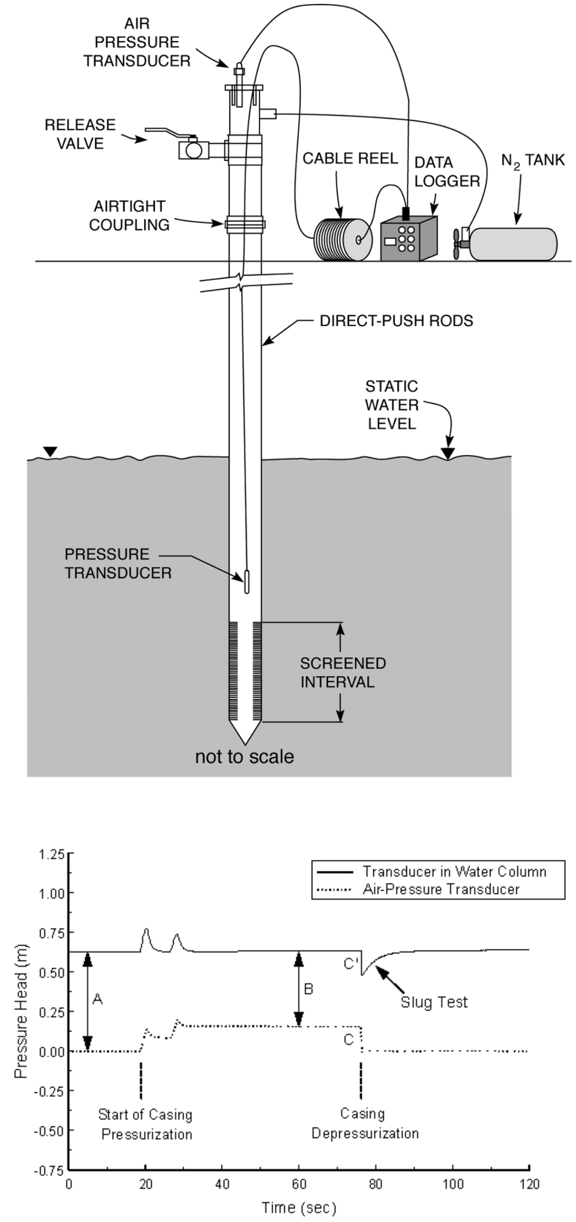

Figure 9 – A) Schematic of the pneumatic initiation method (after McLane et al. 1990; Butler 1997); B) Pressure head versus time plot of slug test initiated with the pneumatic method (A = height of water column above transducer prior to pressurization, B= height of water column above transducer after pressurization, A-B = magnitude of water-level change induced by pressurization = C (change in pressure head in the air column), C'= apparent initial displacement measured by transducer in water column).

The time required to introduce/remove a length of cable to/from the water column coupled with the pressure disturbance produced by moving the transducer makes the solid-slug method of limited use in intervals where the duration of a slug test is on the order of seconds to tens of seconds. For tests in such rapidly responding intervals, the pneumatic approach (Prosser 1981) is more appropriate. Figure 9a is a schematic of the direct-push adaptation of the pneumatic method, and Figure 9b is an example of a test initiated with this method. As described in Butler (1997), the pneumatic method involves pressurizing the air column above the water by the injection of compressed air or nitrogen gas. This pressurization produces a depression of the water level as water is driven out of the pipe in response to the increased air pressure. The water level drops until the magnitude of the water-level

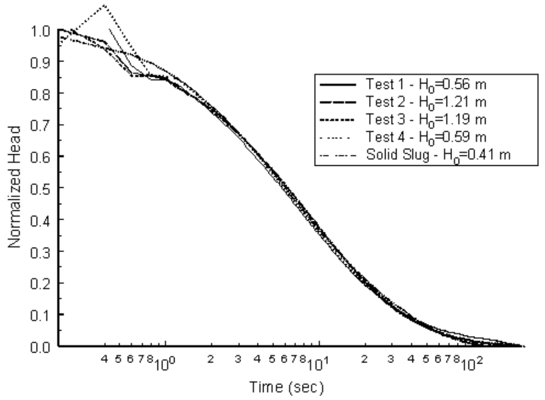

Figure 10 – Normalized head ($H(t)/H_0$, where $H(t)$ is deviation from static and H_0 is magnitude of initial displacement) versus logarithm of time plots for July 27, 1999 slug tests at direct-push installation near well 1-3 (tests 1-4 initiated with pneumatic method; test labeled solid slug initiated with method of McCall (1998)).

change (A-B on Figure 9b) is equal to the increase in the pressure head of the air column (C on Figure 9b). At that point, the well has returned to equilibrium conditions (a transducer in the water column has the same reading as prior to pressurization) and the test can be initiated by rapidly depressurizing the air column. Although small air leaks can be overcome with a regulated gas supply, O-rings or Teflon tape should be used on each pipe joint to minimize the potential for leaks. Response data from a pneumatic slug test are normalized using the initial displacement measured by the air-pressure transducer (C of Figure 9b; Butler 1997, p. 40).

Regardless of which initiation method is used, an effective casing radius (r_c) must be calculated to account for the diameter of the transducer cable or polyethylene tubing (r_{cable}) in the analysis:

$$r_c = (r_{nc}^2 - r_{cable}^2)^{1/2}$$

where r_{nc} is the nominal casing radius. Failure to account for the reduction in the effective casing radius produced by the transducer cable will lead to an overprediction of K (55% overprediction for tests performed in 0.016 m ID rods using the solid slug of McCall [1998]).

Slug Tests in Intervals of Moderate Hydraulic Conductivity

A series of slug tests were performed in the silt-sand interval of Figure 2 and compared to results from a nearby monitoring well screened over the same interval. The direct-push installation was emplaced using a shielded screen to avoid driving an open screen through the overlying clays. Tests were initiated with both the solid-slug and pneumatic methods. Figure 10 displays a comparison of tests initiated with the two approaches. The test initiated with the solid slug lies mostly within the range defined by repeat tests initiated with the pneumatic method, indicating that results are not affected by initiation mechanism in intervals of moderate K.

The near coincidence of normalized plots from repeat tests (Figure 10) indicates that conventional theory appears appropriate for tests in this interval (Butler et al. 1996; Butler 1997). Since there is no dependence on the size of the initial displacement, the test with the largest displacement (test two) was chosen for analysis to increase the signal to noise ratio. Response data were analyzed with two models for slug tests in partially penetrating wells: the Hvorslev (1951) model for tests in vertically infinite aquifers, and the KGS model (Hyder et al. 1994; Butler 1997) for tests in vertically bounded units. Figure 11a is a plot of the results of the Hvorslev analysis. Test data display a pronounced concave-upward curvature, so a straight line was fit to the normalized head interval (0.15-0.25) recommended by Butler (1997). Figure 11b is a plot of the test data and the best-fit type curve from the KGS model. The agreement between the data and a type curve for a physically plausible value of the storage parameter (S_s=0.005 m^{-1}) is quite good, indicating that the K value should be considered a reasonable estimate of the conductivity in that portion of the silt-sand interval (Butler 1997). Since the K estimates from the two models are within 5% of one another, the neglect of vertical boundaries in the Hvorslev model appears to have had little impact.

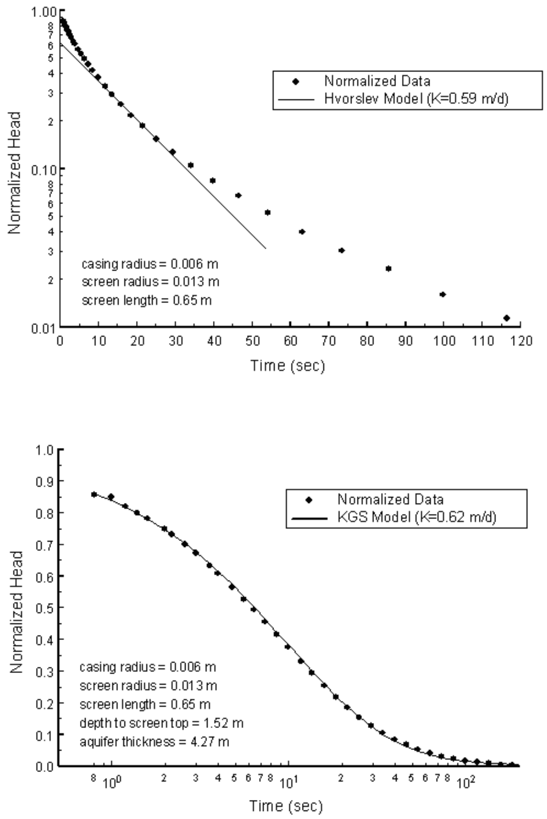

Figure 11 – (a) Logarithm of normalized head versus time plot for July 27, 1999 slug test 2 at direct-push installation near well 1-3 and the best-fit straight line from the Hvorslev model; (b) normalized head versus logarithm of time plot for slug test 2 and the best-fit type curve from the KGS model (S_s= 0.005 m^{-1}).

A series of slug tests was also performed at a monitoring well (well 1-3, 0.051 m ID; Figure 1) screened over the same interval and located 1.7 m from the direct-push installation. An analysis of the response data using the KGS model yielded a type-curve fit similar to that shown in Figure 11b, and the K value (0.61 m/day) was within 2% of that calculated from the direct-push tests. Thus, in this interval of

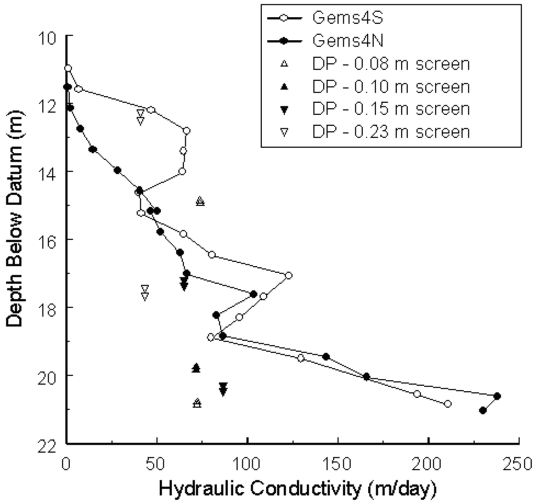

Figure 12 – Comparison of K estimates from direct-push slug tests with estimates from multilevel slug tests performed at Gems4S and Gems4N (inner diameter of direct-push rods=0.016 m; length of test interval for multilevel slug tests = 0.61 m; darkened triangles designate tests near Gems4N; open triangles designate tests near Gems4S; lateral separation between Gems4N and Gems4S is 9.7 m).

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moderate conductivity, slug tests in direct push equipment appear to yield K estimates that are in good agreement with those obtained from conventional wells.

Slug Tests in Intervals of High Hydraulic Conductivity

An extensive series of slug tests was performed in the sand-gravel interval of Figure 2 and compared with results from multilevel slug tests conducted in Gems4N and Gems4S (Figure 3). The pneumatic method was used for test initiation in all cases and response data were analyzed with a high-K form of the Hvorslev model (Butler and Garnett 2000). This high-K form of the Hvorslev model is based on the assumption that the dependence on initial displacement (H_0) that has often been observed in slug tests in formations of very high hydraulic conductivity (e.g., Butler 1997; McElwee and Zenner 1998) is negligible. The validity of that assumption was checked at each interval by the performance of a series of slug tests in which H_0 was varied by a factor of four or more. For all the analyses reported here, repeat tests indicated that the response data did not vary with H_0 for the range of displacements used in the analyses.

Figure 12 compares the results of a series of direct push slug tests (0.016 m ID rods) performed in 1999 and early 2000 with those from multilevel slug tests conducted in the summer of 1999. The comparison reveals a clear trend with depth. In the upper half of the sand and gravel, the K estimates from the direct push tests fluctuate about those from the multilevel slug tests. However, in the lower, more permeable portion of the section, the direct-push estimates are all much smaller than those from the multilevel slug tests. The K values from these direct push slug tests never exceeded 90 m/day, even in zones where the multilevel slug tests yielded values greater than 225 m/day. This underprediction was verified by the performance of additional slug tests in direct push installations screened over the same vertical intervals and located within 1.3 m (lateral separation) of those in Figure 12.

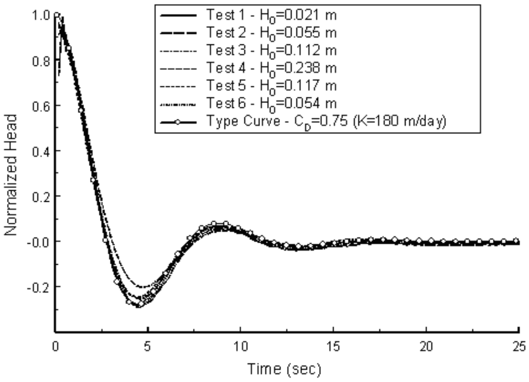

Figure 13 – Normalized head ($H(t)/H_0$, where H_0=C of Figure 9b) versus time plots for April 27, 2000 slug tests at direct-push installation BB426 with the best-fit type curve from the high-K Hvorslev model.

In the late spring and summer of 2000, a large number of direct push slug tests were performed in the lower half of the sand and gravel in an attempt to determine the primary factor(s) responsible for the apparent underprediction of hydraulic conductivity in the more permeable portions of this section. A variety of factors, ranging from well development to screen slot size to the inner diameter of the direct-push rods, were evaluated. Figure 13 displays example response data from a series of tests performed using rods of 0.038 m ID in a very permeable zone near the bottom of the sand and gravel section (19.95-20.17 m below datum). The response data exhibit a dependence on the magnitude of the initial displacement for tests initiated with H_0 greater than 0.06 m, so K estimates were determined from a type curve fit to the tests initiated with smaller H_0. The K value of 180 m/day is over twice the largest value determined from tests performed in the 0.016 m ID rods. As a result of these and additional tests, the inner diameter of the rods was identified as the primary factor responsible for the underprediction in K shown in Figure 12.

Figure 14 presents a comparison of the results from a series of direct push slug tests performed in the 0.038 m ID rods with those from the multilevel slug tests. All of the direct push tests were performed within 2 m of well Gems4N, so the values from that well were used for comparison purposes. In contrast to Figure 12, the results from the direct push and multilevel slug tests are within 12% at all depths. The largest difference is at the bottom of the aquifer and is most probably a product of the greater sensitivity of the multilevel slug tests to the bedrock boundary because of the smaller aspect ratio used in those tests (Figure 5 of Hyder et al. 1994). Differences in effective screen length between the direct-push (1ft.) and multilevel slug tests (2 ft.) could also be responsible for a portion of the observed difference.

The primary conclusion of the extensive series of direct push slug tests performed in the sand and gravel is that the rod diameter used for a test program should be based on the expected value of hydraulic conductivity. If K is not expected to exceed 60-80 m/day, rods as small

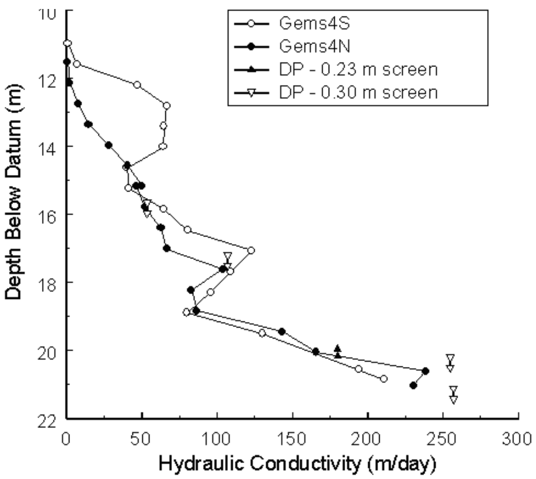

Figure 14- Comparison of K estimates from direct-push slug tests with estimates from multilevel slug tests performed at Gems4S and Gems4N (inner diameter of direct-push rods=0.038 m; length of test interval for multilevel slug tests = 0.61 m; lateral separation between Gems4N and Gems4S is 9.7 m).

as 0.016 m ID can be used. The advantage of the smaller-diameter rods is that they can be driven to greater depths and with less-powerful units. However, if hydraulic conductivity is expected to exceed that range, larger diameter rods are necessary unless a correction for rod diameter, the subject of ongoing work, can be defined. This results shown here indicate that slug tests in 0.038 m ID rods should provide reasonable results in intervals where K is as large as 260 m/day.

The recommended K thresholds given in the previous paragraph are based on tests performed with screens 0.3 m or less in length. These thresholds would significantly decrease with longer screens. For example, Figure 15 displays the results of a series of tests performed in 0.016 m ID rods in which a shielded screen was progressively increased in length between tests. These results, which were duplicated at a nearby (0.84 m separation) installation screened over the same intervals, indicate that the K value significantly decreased when the screen was extended from 0.30 to 0.61 m. Since the same behavior was observed at two different installations, well development is not a likely explanation for this decrease. The most probable explanation is that rod diameter (0.016 m ID) begins to significantly attenuate test responses as the screen is lengthened beyond 0.3 m. Further work is necessary to accurately define the dependence of response data on screen length for rods of various diameters. This dependence may be a function of the length of the water column above the top of the screen, as more oscillatory behavior will be observed for intervals of the same K as the length of the water column increases (Butler 1997). Oscillatory responses will have greater velocities and accelerations, and thus may be more affected by rod diameter. However, a K value of 70 m/day should be a reasonable upper bound for investigations using 0.016 m ID rods and screens less than 0.3 m in length.

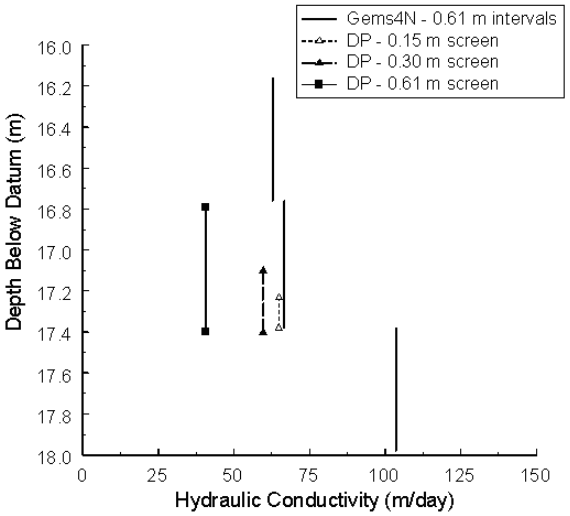

Figure 15- Comparison of K estimates from multilevel slug tests at Gems4N with direct-push slug tests performed with progressively longer screens (inner diameter of direct-push rods=0.016 m; length of test interval for multilevel slug tests = 0.61 m; lateral separation between direct-push installation and Gems4N is 2.16 m)

Dependence on Well Development

The pumping and slug tests discussed in the preceding sections were performed after the direct-push installations had undergone a significant degree of well development. At each interval, hydraulic tests were conducted prior to and following development activities to illustrate the importance of well development. Figures 16a and 16b are examples of the impact of well development on pumping and slug tests, respectively, for the case of an unshielded screen that had been driven approximately 5.6 m through the sand and gravel. In this case, a lengthy period of development was required to remove the fine material that had clogged the unshielded screen. Failure to perform the development would have resulted in an underprediction of K greater than an order of magnitude. These results indicate that well development will be of particular importance when an unshielded screen is driven through sequences with silt and clay layers.

Significantly less development is required when an unshielded screen is driven in a homogeneous unit (Hinsby et al. 1992) or a shielded screen is used. Figure 17 illustrates the impact of well development on the shielded screen installation of Figure 13. In this case, failure to develop the installation for the slug tests would have resulted in an underprediction of K by a factor of approximately 2.5. Additional work has shown that the impact on drawdown during a pumping test can be quite small in this situation.

The required degree of development depends on the purpose for which the direct-push installation is to be used and the manner in which it was emplaced. When the installation is to be used as an observation well, the needed development is less than when it is to be used in a single-well pumping or slug test. Tongpenyai and Raghavan (1981) have shown that the impact of a low-permeability well skin at an observation well depends on the distance from the pumping well (decreases with distance) and the magnitude of well-bore storage (the smaller the radius of the observation well, the smaller the impact).

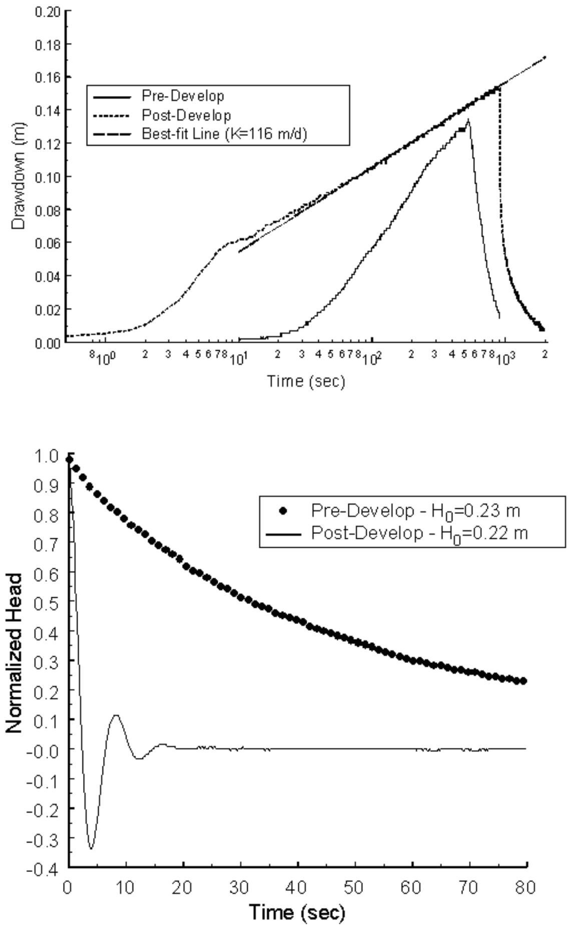

Figure 16 – (a Drawdown versus logarithm of time plot for March 16, 1999 pre- and post-development pumping tests (pumping rate=4.0 l/sec; pumping well screened across the entire sand-gravel interval); (b) Normalized head versus time plots for March 16, 1999 pre- and post-development slug tests (direct-push installation screened from 17.45-17.68 m below datum; unshielded screen driven 5.6 m from the top of the sand and gravel section).

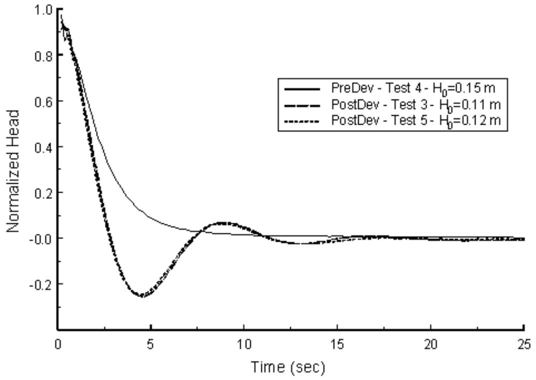

Figure 17 - Normalized head versus time plots for April 27, 2000 pre- and post-development slug tests (direct-push installation BB426 screened from 19.95-20.17 m below datum; shielded screen emplacement).

Although theory would predict that eventually the drawdown at an undeveloped observation well will be reflective of that in the formation, a considerable period of time may be required for that to occur (Figure 16a). If that period is long enough, boundary effects may impact drawdown and significantly increase the difficulty of test interpretation. Thus, development is a critical step when direct push tool strings are used for any type of hydraulic test.

A variety of well development approaches was evaluated in this work. The most effective approach consisted of the following two-stage procedure: The screened interval was first subjected to several minutes of pneumatic surging using the pneumatic slug-test well-head (Figure 9a). The air column above the water was rapidly pressurized and depressurized using pressure heads of up to 1 m. The installation was then pumped for approximately 15 minutes using a suction pump (or an inertial pump if the depth to water was too great) with a check valve at the lower end of the tubing. In the early periods of this pumping, the suction-pump tubing was rapidly raised and lowered in a manner similar to an inertial pump to further stress the test interval. The primary criterion used to assess the sufficiency of development was the coincidence of normalized response data from repeat tests (Figures 10 and 17). If reproducible tests could not be obtained, an additional round of development was performed. Comparisons with results from the multilevel slug tests demonstrate the appropriateness of these procedures (Figure 14). On average, development activities lasted 30 minutes for each test interval. Note that Henebry and Robbins (2000) proposed a related approach using a small-diameter surge block for the development of wells emplaced with direct-push methods.

The results of this work indicate that shielded-screen installations require less development than unshielded screens that have been driven a considerable distance through a heterogeneous sequence. However, inattention to detail can result in shielded-screen installations that are almost completely plugged with fine material. Since O-rings are used at all connections in the shielded-screen rod string, little water enters the rods while driving. If the screen shield is pulled back when there is little to no water in the rods, a tremendous hydraulic gradient is imposed between the interior of the rods and the formation. In a process analogous to the heaving sands commonly encountered in coarse sand and gravel aquifers (McElwee et al. 1991), water entrains fine material and plasters it against the screen. Shielded screens installed in this manner were virtually impossible to develop, and yielded K estimates orders of magnitude lower than that of the formation. In order to prevent this heaving fines phenomenon, water must be added to the rods prior to exposing the screen. Pitkin (1998) advocates injection of water while driving an unshielded screen to, among other things, reduce the buildup of fine material. Further work is necessary to evaluate if that procedure can reduce the required development when an unshielded screen is driven in a heterogeneous sequence. Note that the results of this work were obtained using screens with two difference sizes of slots (0.1 mm and 0.25 mm). There was no significant difference in the impact of development for these slot sizes.

Summary and Conclusions

The potential of direct push technology for the hydraulic characterization of saturated flow systems was investigated in this work. An extensive series of pumping and slug tests was performed at a field site at which a great deal of previous work had been done to characterize the transmissive properties of an alluvial sequence. The major findings of this investigation can be summarized as follows:

1. Direct push tool strings can be very effective as temporary observation wells for pumping tests. Hydraulic conductivity estimates obtained from analysis of drawdown at direct-push installations were essentially indistinguishable from those obtained at conventional wells.
2. Slug tests can be readily performed in direct push tool strings using small-diameter adaptations of conventional methods. Tests performed in a direct-push installation screened in a sandy silt interval of moderate hydraulic conductivity yielded K estimates that were in excellent agreement with those obtained from slug tests at a nearby conventional well screened over the same interval. Tests in direct-push installations in a coarse sand and gravel aquifer yielded K estimates that were in good agreement with those obtained from multilevel slug tests performed at nearby wells.
3. The diameter of the direct push rods can influence slug test results in intervals of very high K. Rods larger than 0.016 m I.D. must be used in intervals where hydraulic conductivity is expected to exceed 70 m/day. Rods of 0.038 m I.D. provide reasonable results for intervals where K is as large as 260 m/day. Ongoing work is currently assessing if a correction for rod diameter can be defined to extend the range of applicability of the smaller-diameter rods.
4. As with any type of hydraulic test, results from pumping and slug tests performed in direct push tool strings are critically dependent on use of appropriate well-development procedures. The amount of development depends on the purpose for which the installation is to be used and the manner in which it was emplaced. The development required at a direct push installation to be used as an observation well in a pumping test is significantly less than that required when the installation is to be used for a slug test. When an installation is emplaced by driving an unshielded screen through a heterogeneous sequence, the amount of development may be significantly more than when a shielded screen is utilized. Development can be quite difficult after an unshielded screen has been driven through a sequence of silt and clay layers;
5. If shielded screen installations are used, water must be added to the rod string prior to exposing the screen in formations of moderate or higher hydraulic conductivity. If not, fine material can surge into the near-well portions of the formation and up against the screen, making development quite difficult.

The overall conclusion of this work is that much valuable information can be obtained from hydraulic tests performed in direct-push equipment. The speed and ease of emplacement of direct-push installations can be exploited to significantly improve knowledge of the hydraulic properties of saturated unconsolidated formations. For example, a network of temporary observation wells can readily be installed to address issues that often introduce ambiguity into the interpretation of pumping-test data (e.g., leakage and anisotropy). Moreover, if questions arise during the course of a pumping test, additional temporary wells can rapidly be installed to help resolve these questions. Direct push-based approaches therefore could significantly reduce the uncertainty introduced into the interpretation of a pumping test by insufficient or nonoptimally situated observation wells. In addition, information can be readily acquired about lateral and vertical variations in hydraulic conductivity, which often play a critical role in determining the movement of a contaminant plume. This information can be obtained without using wells with long screened intervals, a requirement of most current methods for estimation of vertical variations in K but which can serve as conduits for contaminant movement. The direct-push-based methods described here are currently being extended to more readily acquire vertical profiles of hydraulic conductivity (McCall et al. 2000; Lanier et al. 2000) and to exploit the potential of the hydraulic tomography procedure described in Butler et al. (1999b).

Although the methods that were developed in this work should be applicable in a wide variety of hydrogeologic settings, this work has not examined all possible applications of hydraulic testing in direct-push equipment. In particular, slug tests in intervals of low hydraulic conductivity were not discussed. This application is currently the focus of ongoing work (McCall et al. 2000).

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