

A Simple Constant-Head Injection Test for Streambed Hydraulic Conductivity Estimation

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Abstract

A fast, efficient constant-head injection test (CHIT) for in situ estimation of hydraulic conductivity (K) of sandy streambeds is presented. This test uses constant-head hydraulic injection through a manually driven piezometer. Results from CHIT compare favorably to estimates from slug testing and grain-size analysis. The CHIT combines simplicity of field performance, data interpretation, and accuracy of K estimation in flowing streams.

Introduction

Numerous studies have shown that streambed hydraulic properties play a considerable role in ground water/surface water interaction (McDonald and Harbaugh 1984; Sophocleous et al. 1995; Hunt 1999; Zlotnik and Huang 1999; Butler et al. 2001; Kollet et al. 2002). Characterization of heterogeneous streambed hydraulic properties is a time- and resource-consuming procedure. Calver (2001) published data on streambed hydraulic conductivity (K) values in many river systems that range from 0.001 to 100 m/day, although higher K values are not uncommon.

Landon et al. (2001) recently assessed available methods for in situ estimation of K in sandy streambeds. These included slug tests, constant-head extraction tests, combination of seepage meters and potentiometers, falling- and constant-head permeameter tests, and grain-size analysis.

Among these tests, slug tests that use manually driven piezometers were found to be the most accurate means for determining the K distribution of sandy streambeds. This approach was initially demonstrated by Hinsby et al. (1992) in Denmark, who used a jackhammer, and Zlotnik and Ferlin (1994) in the United States, who used vibracoring for

piezometer positioning. Most of the limited number of direct investigations on streambed K employed slug tests (Duwelius 1996; Springer et al. 1999; Landon et al. 2001; Rus et al. 2001), and direct-push techniques make this method even more attractive.

Recently, staff members of the U.S. Environmental Protection Agency developed a field procedure for estimating K using a specialized truck-mounted Geoprobe® direct-push system (Wilson et al. 1997; Cho et al. 2000). After well point installation, a steady-state constant-head extraction test is performed at each tested depth. Scaturro and Widdowson (1997) and Butler et al. (2001) investigated the various aspects of pneumatically initiated slug tests using a similar system. These methods are effective in delivering piezometers to depths on the order of 30 m in sandy aquifers. Recent work has demonstrated the accuracy that can be achieved through slug tests with direct-push systems (Butler et al. 2002; Butler 2002).

Application of hydraulic testing methods in modern streambeds requires optimal combination of instrumentation, field procedures, and data interpretation. Commonly, streambed characterization is limited to the top several decimeters or meters. The relatively easy use of a manually driven small piezometer does not require any heavy equipment and allows investigations at even deeper locations. In addition, availability of stream water allows for easy water disposal in case of pumping tests or an unlimited water supply for injection tests. The field advantage of the injection test is based on the ability to observe visually the water level in the piezometer above the stream stage and on the maintenance of a constant-head in the piezometer (Figure 1).

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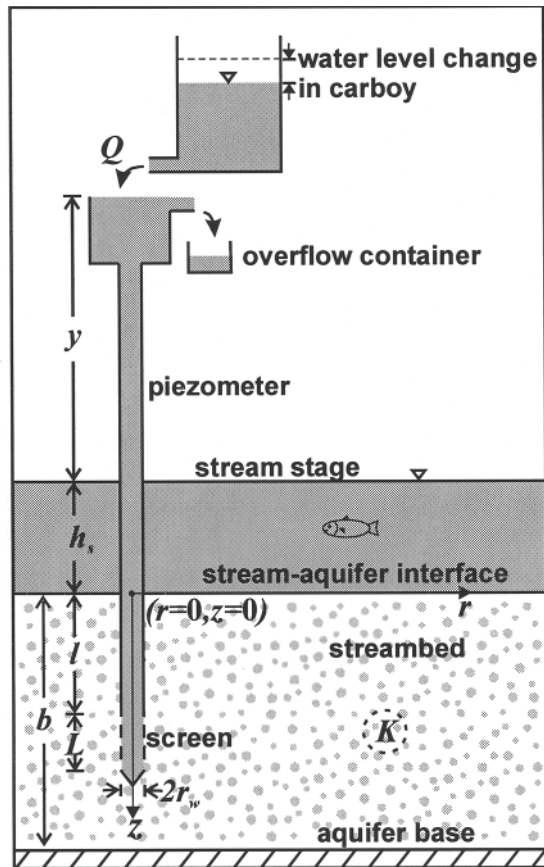


Figure 1. Schematic diagram of constant-head injection test.

The objectives of this note are to present the instrumentation, field procedures, and data interpretation for a constant-head injection test (CHIT) that was applied at the Prairie Creek site, Nebraska, for collecting three-dimensional data set on hydraulic conductivity of a modern streambed.

Instrumentation and Field Procedures

The screened drive point (by Johnson Screens®) had the following specifications: diameter of 3.2 cm (corresponding to 4.9 cm actual outer diameter and 2.5 cm actual inner diameter), slot size of 0.2 mm, and screen length of 20 cm. This drive point was attached to a galvanized steel pipe using drive couplings. The total length of this pipe varied according to the testing depth and stream stage.

Water was injected into the piezometer from a graduated carboy (Figure 1) (Note: the stream water being injected should not have a high suspended load, which could clog the screen and streambed materials being tested). The flow rate from the carboy was adjusted until a desired water level in the piezometer above the stream stage (y) was attained. Discharge from the piezometer to the aquifer (injection rate) Q was measured by using the graduations on the carboy and a timer, while y was measured manually. Unlike in the pumping/extraction test proposed by Wilson et al. (1997) and Cho et al. (2000), this setup drastically simplifies determining the operating head because it can be measured directly and can be easily controlled by concurrent visual inspection.

Test duration was determined by stabilization of injection rate that usually lasted for tens of seconds to a few minutes at our site. In cases where K is too low, water may be allowed to overflow from the constant-head apparatus.

Known test geometry, injection rate, and operational head y allow for simple test interpretation.

Theory for CHIT

Constant-head injection tests are standard tools for soil scientists and engineers (Tavenas et al. 1990). These methods were developed primarily for low- K media such as clays. We propose a modified constant-head injection test that is suitable for higher K media.

We consider an anisotropic aquifer with horizontal hydraulic conductivity K_r and vertical hydraulic conductivity K_z and saturated thickness b below the stream. Steady-state ground water flow equation for hydraulic head $h(r, z)$ in Cartesian coordinates (r, z) with the origin on the streambed surface (Figure 1) is as follows:

$$\frac{K_r}{r} \frac{\partial}{\partial r} \left(r \frac{\partial h}{\partial r} \right) + K_z \frac{\partial^2 h}{\partial z^2} = 0, \quad r_w < r < \infty, 0 < z < b \quad (1)$$

where r_w is radius of the piezometer.

The aquifer base is impermeable:

$$\frac{\partial h(r, b)}{\partial z} = 0, \quad 0 < r < \infty \quad (2)$$

and a constant head (h_s) at the stream-aquifer interface is equal to the stream stage:

$$h(r, 0) = h_s, \quad r_w < r < \infty, \quad (3)$$

This boundary condition at the stream-aquifer interface is exact, whereas in water-table aquifers this condition is only an approximation of real conditions, because water injection may generally affect the horizontal shape of the water table (Dagan 1978).

In the process of the CHIT, a constant operating head y is applied to the tested screen length L :

$$h(r_w, z) = h_s + y, \quad l < z < l + L \quad (4)$$

where the top of the screen is located at the depth l . Otherwise, the piezometer casing is impermeable:

$$\frac{\partial h(r_w, z)}{\partial r} = 0, \quad 0 < z < l \quad (5)$$

We also assume that the constant head is undisturbed at a large distance from the piezometer screen:

$$h(r, z) = h_s, \quad 0 < z < b, \quad r \rightarrow \infty \quad (6)$$

The injection rate Q can be calculated from the hydraulic head distribution as follows:

$$Q = 2\pi r_w K_r \int_l^{l+L} \frac{\partial h(r_w, z)}{\partial r} dz \quad (7)$$

Dimensional analysis shows the linear relationship between the Q and y is

$$Q = 2 \pi P K_r y L \quad (8)$$

where the dimensionless coefficient P is the shape factor that depends on r_w , l , L , b , K_r , and K_z (Zlotnik 1994).

This theoretical development results in a model for the analysis of CHIT that is the same as that of Cho et al. (2000) for constant-head discharge tests in unconfined aquifers.

Interpretation of the Test Data

Equation 8 can be used for estimation of K . It is important to note that on the submeter scale, most sedimentary aquifers exhibit a very low degree of anisotropy, and for practical purposes the streambed can be assumed isotropic (Burger and Belitz 1997; Izbicki 2002):

$$Kr = Kz = K \quad (9)$$

Therefore, the final formula for K estimates is as follows:

$$K = \frac{Q}{2\pi L P y} \quad (10)$$

Various approaches were proposed for estimation of the shape factor in isotropic conditions. Among these, the Bouwer and Rice (1976) approximate method is most commonly used for its simplicity (Cho et al. 2000), although it can overestimate the actual shape factor by 20% to 25%:

$$P = \frac{1.1}{\ln((l + L)/r_w)} + \frac{A + B \ln[b - (l + L)/r_w]}{L/r_w} \quad (11)$$

where A and B are dimensionless coefficients that were originally given in graphic form. These coefficients were approximated by Van Rooy (1988) (see details in Butler 1998, p. 109 and p. 130). Note that Bouwer and Rice (1976) used notation $P = \ln(R_e/r_w)$ where R_e was called "effective" radius.

Verification of Assumptions and Comparison with Other Techniques

CHIT was tested at the Prairie Creek site on the Platte River watershed near Columbus, Nebraska (Cardenas 2002). We tested the assumption of linearity of relationship between Q and y and verified the accuracy of the test by comparison with other techniques.

It is assumed in the theory of CHIT that operating head y is linearly related to the injection rate Q (see Equations 8 and 10). Nonlinear relations between y and Q may exist when major turbulence effects and friction losses caused by excessive velocities in the pipes along junctions and along the screen are present. An experiment conducted to evaluate nonlinear effects shows that y and Q are linearly correlated ($R^2 = 0.99$, where R is the correlation coefficient; Figure 2). CHIT was conducted at a depth of 1.02 m from the water table. The test resulted in $K = 41.6 \pm 2.8$ m/day (error ranges are based on three repeat tests with the same

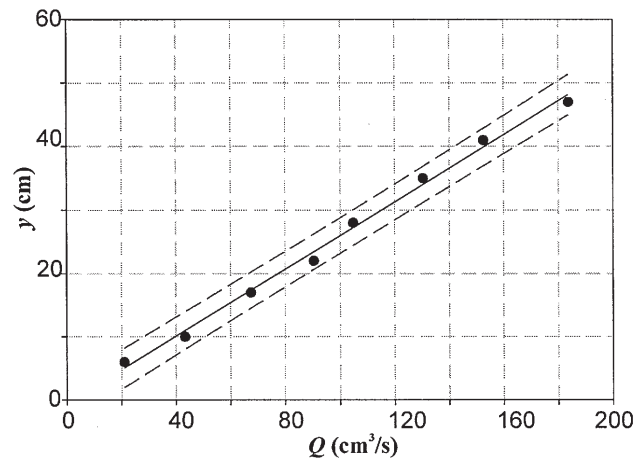


Figure 2. Linear correlation between head change y and discharge Q : $y = 0.26Q - 0.53$, $R^2 = 0.99$. Dashed lines show 95% confidence interval. K in this case is 41.6 ± 2.8 m/day.

y). In case of much higher K values, the appropriate corrections can be made using coefficients for head losses (Zurbuchen et al. 2002).

It is well known that K estimates obtained from various instruments for hydraulic testing can differ if characteristic test scales—the screen lengths—are different (Zlotnik et al. 2000). To assess the suitability of CHIT for sandy to gravelly streambeds, we compared it to multilevel slug tests (MLSTs) and grain-size analyses using data collected at the same elevations. Our MLST technique follows the methodology by Hinsby et al. (1992).

CHITs and MLSTs were conducted at successive 20 cm intervals (which is equal to the screen length) in the same test locations in the sandy to gravelly streambed. In addition, cores were collected in a cross pattern in four locations 0.5 m away from the test hole (see inset map in Figure 3). These cores were divided into 10 cm intervals that were analyzed for grain size.

The implemented MLST's geometry and setup correspond to the Bouwer and Rice (1976) method, and K from

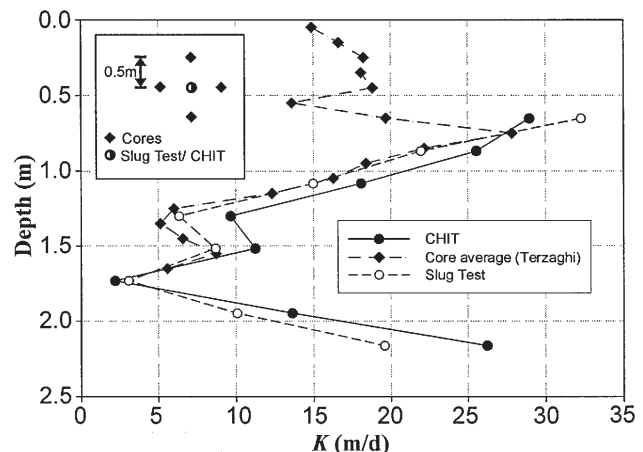


Figure 3. K profiles using different techniques. Estimates from cores are mean at same intervals from four cores that are 0.5 m away from the test hole where hydraulic tests were conducted (inset location map).

the MLSTs (K_{MLST}) was interpreted using AQTESOLV (HydroSOLVE Inc. 2000). Three displacements were applied at each interval to test for reproducibility at each depth, to assess nonlinear effects, and to check for development of the media. The water level was depressed using a pneumatic water-level depressor. Three repeat CHITs were likewise conducted at the same location, although y was kept constant at each interval because varying it was not expected to cause major discrepancies (see Figure 2). However, we advise that repeat tests with different displacements be conducted when using this method in order to further verify the assumptions. It is apparent that CHITs and the MLSTs give similar values (Figure 3).

Regression analysis of K from CHIT (K_{CHIT}) and K_{MLST} estimates on Figure 4 shows that the two methods give results that are related through the equation $K_{MLST} = 0.97 K_{CHIT} - 1.85$ ($R^2 = 0.9$), which is close to the line of one-to-one correspondence ($K_{CHIT} \approx K_{MLST}$). Constraining the regression to a line passing through the origin ($K_{MLST} = K_{CHIT}$) results in $R^2 = 0.83$. Furthermore, a matched-pair t -test showed that there is no significant difference between the two tests at a 5% level of significance.

Eleven empirical equations were used to estimate K from grain-size distributions using the codes of Vukovic and Soro (1992, the reader is referred to this manuscript for a detailed comparison of the formulas). The complete results are presented by Cardenas (2002). Expectedly, despite similarity in patterns, the different equations gave a range of values for K . Among the equations, the estimates using the Terzaghi equation agreed very well with estimates from the two hydraulic tests (Figure 3).

Limitations of CHIT

CHIT was applied in modern sandy streambeds. The applicability of the presented method in clay or clayey environments cannot be ascertained. Butler et al. (2002) has shown the effects of clay stringers on K estimates when conducting hydraulic tests using direct-push equipment. Similar problems may occur in muddy streambeds. Furthermore, only river water with low suspended load should be used for injection to avoid screen or aquifer clogging. Water filtering or using an alternative water source reduces the simplicity of the approach presented herein.

CHIT is applicable only when Q and y are linearly related. Thus, this assumption should always be verified through repeat tests with both similar and varying displacements. Nonlinear effects due to head losses should be corrected appropriately (Zurbuchen et al. 2002; Butler 2002).

Summary

CHIT allows for K estimation on a dense three-dimensional grid of sampling points. For example, Cardenas and Zlotnik (in press) collected an extensive K data set on a heterogeneous streambed that included 456 local K values ranging from 0.15 to 74.5 m/day.

The CHIT allows for rapid analysis of results. Calculations of K can be conducted using a spreadsheet for assessment of shape factor P and do not involve using curve-fitting algorithms or specialized software. This setup

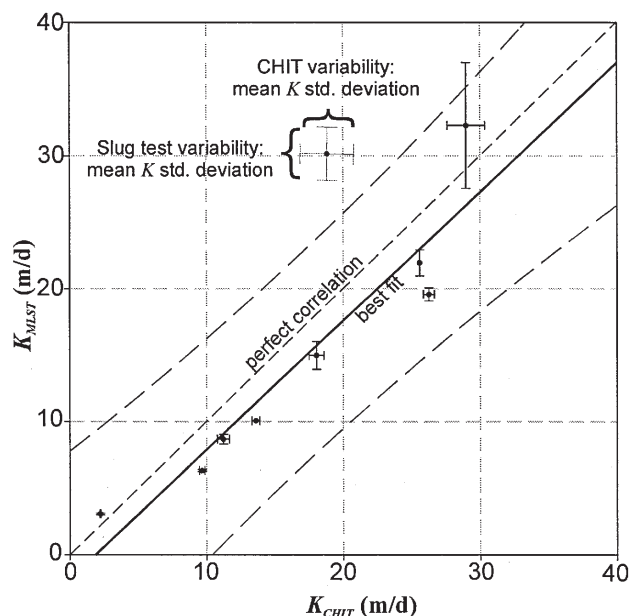


Figure 4. Regression analysis of CHIT-slug test results. Points are mean K for each interval; error bars adjacent to each point represent one standard deviation of the K distribution at interval; long-dashed lines represent 95% confidence interval. Equation of regression line: $K_{MLST} = 0.97K_{CHIT} - 1.8$ ($R^2 = 0.9$); short-dashed line is line of perfect correlation ($K_{MLST} = K_{CHIT}$).

drastically simplifies measurements of operating head that can be directly controlled through visual inspection. Only a few values of P corresponding to different depths are needed if the same piezometer is used.

Considering that the K values observed in most previous streambed studies (0.001 to 100 m/day) are within the range of applicability of the CHIT that we implemented, the use of the current modification of a steady-state test is more suitable for various field studies. This avoids the problems associated with transient tests. Higher K values can be also handled considering the abundance of water supply for field experiments.

Due to a very small number of measured parameters, CHIT equipment in stream environments even with highly permeable media eliminates the need for electronic devices inherent in slug testing (i.e., dataloggers, computers, pressure transducers, and power sources). The same advantages are available in the similar methodology presented by Cho et al. (2000). Our method further simplifies the procedure by eliminating the need for cumbersome pumping equipment. In addition, a constant pumping rate is easier to establish using the setup that we presented.

Considering the CHIT's practical advantages, it should see more application in investigations involving modern sandy streambeds and similar environments.

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Erratum/

In the Technical Note “A simple constant-head injection test for streambed hydraulic conductivity estimation,” M.B. Cardenas and V.A. Zlotnik (2003) presented a constant-head injection test (CHIT) method for mapping hydraulic conductivity of unconsolidated streambed sediments. There is a typographical error (namely, a misplaced parenthesis) in their equation (11) that could lead to erroneous values for the shape factor P .

Equation (11) should read:

$$P = \frac{1.1}{\ln [(l+L)/r_w]} + \frac{A + B \ln \left[\frac{b-(l+L)}{r_w} \right]}{L/r_w} \quad (11)$$

where A and B are coefficients originally defined by Bouwer and Rice (1976), b is the aquifer saturated thickness below the stream, l is the depth to the top of the screen from the stream-aquifer interface, L is the screen length and r_w is the piezometer radius. Note that b in the natural logarithm of the second term in the right-hand side of the equation is also divided by r_w . Not doing so not only results in incorrect values for P but may also result in negative arguments for the terms in the brackets leading to complex values after taking the natural logarithm. In general, this error does not change conclusions in the original note or the applicability of the CHIT method.

We thank Charles F. Pitz of the Washington State Department of Ecology for bringing this error to our attention.

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