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Standard Test Method (Analytical Procedure) Practice for (Analytical Procedure) Tests of Anisotropic Unconfined Aquifers by Neuman Method[1]

This standard is issued under the fixed designation D5920;D5920/D5920M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This test method covers an analytical procedure for determining the transmissivity, storage coefficient, specific yield, and horizontal-to-vertical hydraulic conductivity ratio of an unconfined aquifer. It is used to analyze the drawdown of water levels in piezometers and partially or fully penetrating observation wells during pumping from a control well at a constant rate.

1.2 The analytical procedure given in this test method is used in conjunction with Guide D4043 and Test Method D4050.

1.3 The valid use of the Neuman method is limited to determination of transmissivities for aquifers in hydrogeologic settings with reasonable correspondence to the assumptions of the theory.

1.4 The values stated in SI units are to be regarded as standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

D3740 Practice for Minimum Requirements for Agencies Engaged in Testing and/or Inspection of Soil and Rock as Used in Engineering Design and Construction

D4043 Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques

D4050 Test Method for (Field Procedure) for Withdrawal and Injection Well Testing for Determining Hydraulic Properties of Aquifer Systems

D4105 Practice for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method

D4106 Practice for (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions*—For definitions of general technical terms used within this guide, refer to Terminology D653.

3.2 *Symbols and Dimensions:*

3.2.1 *b [L]*—initial saturated thickness of the aquifer.

3.2.2 *d [L]*—vertical distance between top of screen in pumping well and initial position of the water table.

3.2.3 d_D *[nd]*—dimensionless *d*, equal to *d/b*.

3.2.4 $J_0(x)$—zero-order Bessel function of the first kind.

3.2.5 K_r $[LT^{-1}]$—hydraulic conductivity in the plane of the aquifer, radially from the control well.

[1] This test method practice is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

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3.2.6 K_Z *[LT^{−1}]*—hydraulic conductivity normal to the plane of the aquifer.

3.2.6.1 *Discussion*—

The use of the symbol *K* for the hydraulic conductivity is the predominant usage in groundwater literature by hydrogeologists, whereas, the symbol *k* is commonly used for this term in soil and rock mechanics and soil science.

3.2.7 *l [L]*—vertical distance between bottom of screen in control well and initial position of water table.

3.2.8 l_D *[nd]*—dimensionless *l*, equal to *l/b*.

3.2.9 *Q* $[L^3T^{-1}]$—discharge rate.

3.2.10 *r [L]*—radial distance from control well.

3.2.11 *s [L]*—drawdown.

3.2.12 s_c *[L]*—corrected drawdown.

3.2.13 s_D *[nd]*—dimensionless drawdown, equal to $4\pi Ts/Q$.

3.2.14 s_{wt} *[L]*—drawdown of the water table.

3.2.15 *S [nd]*—storage coefficient, equal to $S_s b$.

3.2.16 S_s $[L^{-1}]$—specific storage.

3.2.17 S_y *[nd]*—specific yield.

3.2.18 *t [T]*—time since pumping started.

3.2.19 t_r *[T]*—time since recovery started.

3.2.20 t_s *[nd]*—dimensionless time with respect to S_s, equal to Tt/Sr^2.

3.2.21 t_y *[nd]*—dimensionless time with respect to S_y, equal to $Tt/S_y r^2$.

3.2.22 t_β *[T]*—time, *t*, corresponding to intersection of a horizontal line through the intermediate data with an inclined line through late data on semilogarithmic paper.

3.2.23 $t_{y\beta}$ *[nd]*—dimensionless time, t_y, corresponding to the intersection of a horizontal line through intermediate data with an inclined line through late data in Fig. 1.

3.2.24 $(t/r^2)_e$ *[T]*—t/r^2 corresponding to the intersection of a straight line through the early data with *s* = 0 on semilogarithmic paper $[TL^{-2}]$.

3.2.25 $(t/r^2)_l$ *[T]*—t/r^2 corresponding to the intersection of a straight line through the late data with *s* = 0 on semilogarithmic paper.

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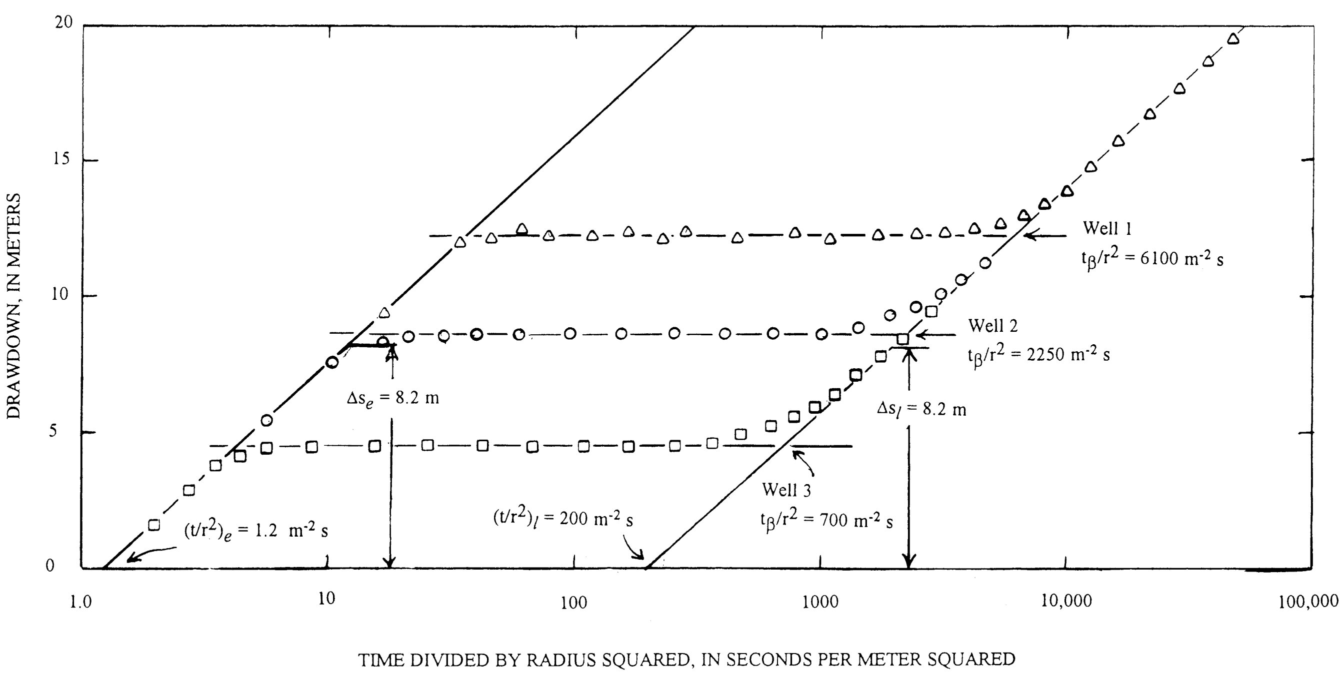

FIG. 1 Aquifer-Test Analysis, Example Two

3.2.26 *T* $[L^2T^{-1}]$—transmissivity, $K_r b$.

3.2.27 *z* *[L]*—vertical distance above the bottom of the aquifer.

3.2.28 z_1 *[L]*—vertical distance of the bottom of the observation well screen above the bottom of the aquifer.

3.2.29 z_2 *[L]*—vertical distance of the top of the observation well screen above the bottom of the aquifer.

3.2.30 z_D *[nd]*—dimensionless elevation, equal to *z/b*.

3.2.31 z_{1D} *[nd]*—dimensionless elevation of base of screen, equal to z_1/b.

3.2.32 z_{2D} *[nd]*—dimensionless elevation of top of screen, equal to z_2/b.

3.2.33 α—degree of anisotropy, equal to K_z/K_r.

3.2.34 β *[nd]*—dimensionless parameterα r^2/b^2.

3.2.35 Δs_e *[L]*—the difference in drawdown over one log cycle of time along a straight line through early data on semilogarithmic paper.

3.2.36 Δs_l [L]—the difference in drawdown over one log cycle of time along a straight line through late data on semilogarithmic paper.

3.2.37 σ *[nd]*—dimensionless parameter S/S_y.

4. Summary of Test Method

4.1 *Procedure*—This test method describes a procedure for analyzing data collected during a withdrawal well test. This test method should have been selected using Guide D4043 on the basis of the hydrologic characteristics of the site. The field test (Test Method D4050) requires pumping a control well that is open to all or part of an unconfined aquifer at a constant rate for a specified period and observing the drawdown in piezometers or observation wells that either partly or fully penetrate the aquifer. This test method may also be used to analyze an injection test with the appropriate change in sign. The rate of drawdown of water levels in the aquifer is a function of the location and depths of screened open intervals of the control well, observation wells, and piezometers. The drawdown may be analyzed to determine the transmissivity, storage coefficient, specific yield, and ratio of vertical to horizontal hydraulic conductivity of the aquifer. The accuracy with which any property can be determined depends on the location and length of the well screen in observation wells and piezometers. Two methods of analysis, a type curve method and a semilogarithmic method, are described.

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4.2 *Solution*—The solution given by Neuman (**1**)[3] can be expressed as:

$$s(r,z,t) = \frac{Q}{4\pi T}\int_0^{\infty} 4yJ_0(y\beta^{1/2})\left[u_0(y) + \sum_{n=1}^{\infty} u_n(y)\right] dy \tag{1}$$

where, for piezometers, Neuman's (**1**) Eqs 27 and 28 are as follows:

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$$u_0(y) = \frac{\{1 - exp\{-t_s\beta(y^2 - \gamma_0^2)]\}\cosh(\gamma_0 z_D)}{\{y^2 + (1+\sigma)\gamma_0^2 - (y^2 - \gamma_0^2)^2/\sigma\}\cosh(\gamma_0)} \tag{2}$$

$$\cdot\frac{\sinh[\gamma_0(1-d_D)] - \sinh[\gamma_0(1-l_D)]}{(l_D - d_D)\sinh(\gamma_0)}$$

and:

$$u_n(y) = \frac{\{1 - exp[-t_s\beta(y^2 + \gamma_n^2)]\}\cos(\gamma_n z_D)}{\{y^2 - (1+\sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\}\gamma_n} \tag{3}$$

$$\cdot\frac{\sin[\gamma_n(1-d_D)] - \sin[\gamma_n(1-l_D)]}{(l_D - d_D)\sin(\gamma_n)}$$

and the terms γ_0 and γ_n are the roots of the following equations:

$$\sigma\gamma_0\sinh(\gamma_0) - (y^2 - \gamma_0^2)\cosh(\gamma_0) = 0 \tag{4}$$

$$\gamma_0^2 < y^2$$

$$\sigma\gamma_n\sin(\gamma_n) + (y^2 + \gamma_n^2)\cos(\gamma_n) = 0 \tag{5}$$

$$(2n-1)(\pi/2) < \gamma_n < n\pi \quad n \geq 1$$

4.2.1 The drawdown in an observation well is the average over the screened interval, of which $u_0(y)$ and $u_n(y)$ are described by Neuman's (**1**) Eqs 29 and 30:

[3] The boldface numbers in parentheses refer to a list of references at the end of the text.

$$u_0(y) = \frac{\{1 - exp[-t_s\beta(y^2 - \gamma_0^2)]\}[\sinh(\gamma_0 z_{2D}) - \sinh(\gamma_0 z_{1D})]\{\sinh[\gamma_0(1-d_D)] - \sinh[\gamma_0(1-l_D)]\}}{\{y^2 + (1+\sigma)\gamma_0^2 - (y^2 - \gamma_0^2)^2/\sigma\}\cosh(\gamma_0)\cdot(z_{2D} - z_{1D})\gamma_0(l_D - d_D)\sinh(\gamma_0)} \quad (6)$$

$$u_n(y) = \frac{\{1 - exp[-t_s\beta(y^2 + \gamma_n^2)]\}[\sin(\gamma_n z_{2D}) - \sin(\gamma_n z_{1D})]\{\sin[\gamma_n(1-d_D)] - \sin[\gamma_n(1-l_D)]\}}{\{y^2 - (1+\sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\}\cos(\gamma_n)\cdot(z_{2D} - z_{1D})\gamma_n(l_D - d_D)\sin(\gamma_n)} \quad (7)$$

~~4.2.2 In the case in which the control well and observation well fully penetrate the aquifer, the equations reduce to Neuman's (**1**) Eqs 2 and 3 as follows:~~

$$u_0(y) = \frac{\{1 - exp[-t_s\beta(y^2 - \gamma_0^2)]\}\tanh(\gamma_0)}{\{y^2 + (1+\sigma)\gamma_0^2 - [(y^2 - \gamma_0^2)^2/\sigma]\}\gamma_0} \quad (8)$$

~~and:~~

$$u_n(y) = \frac{\{1 - exp[-t_s\beta(y^2 + \gamma_n^2)]\}\tan(\gamma_n)}{\{y^2 - (1+\sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\}\gamma_n} \quad (9)$$

~~5. Significance and Use~~

~~5.1 *Assumptions:*~~

~~5.1.1 The control well discharges at a constant rate, *Q*.~~

~~5.1.2 The control well, observation wells, and piezometers are of infinitesimal diameter.~~

~~5.1.3 The unconfined aquifer is homogeneous and really extensive.~~

~~5.1.4 Discharge from the control well is derived initially from elastic storage in the aquifer, and later from gravity drainage from the water table.~~

~~5.1.5 The geometry of the aquifer, control well, observation wells, and piezometers is shown in Fig. 2. The geometry of the test wells should be adjusted depending on the parameters of interest.~~

~~5.2 *Implications of Assumptions:*~~

~~5.2.1 Use of the Neuman (**1**) method assumes the control well is of infinitesimal diameter. The storage in the control well may adversely affect drawdown measurements obtained in the early part of the test. See 5.2.2 of Test Method D4106 for assistance in determining the duration of the effects of well-bore storage on drawdown.~~

~~5.2.2 If drawdown is large compared with the initial saturated thickness of the aquifer, the late-time drawdown may need to be adjusted for the effect of the reduction in saturated thickness. Section 5.2.3 of Test Method D4106 provides guidance in correcting for the reduction in saturated thickness. According to Neuman (**1**) such adjustments should be made only for late-time values.~~

~~5.3 Practice D3740 provides evaluation factors for the activities in this guide.~~

~~NOTE 1—The quality of the result produced by this guide is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this guide are cautioned that compliance with Practice D3740 does not in itself ensure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.~~

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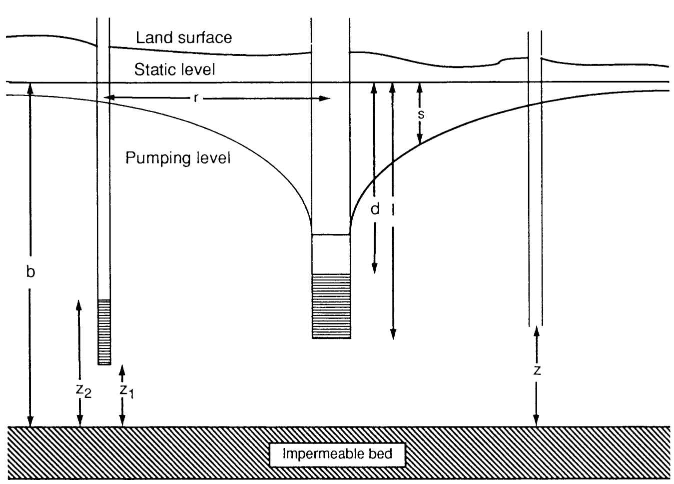

FIG. 2 Cross Section Through a Discharging Well Screened in Part of an Unconfined Aquifer

6. Apparatus

6.1 *Analysis*—Analysis of data from the field procedure (see Test Method D4050) by this test method requires that the control well and observation wells meet the requirements specified in the following subsections.

6.2 *Construction of Control Well*—Install the control well in the aquifer, and equip with a pump capable of discharging water from the well at a constant rate for the duration of the test.

6.3 *Construction of Observation Wells*— Construct one or more observation wells or piezometers at a distance from the control well. For this test method, observation wells may be open through all or part of the thickness of the aquifer.

6.4 *Location of Observation Wells*— Wells may be located at any distance from the control well within the area of influence of pumping.

7. Procedure

7.1 *Procedure*—The procedure consists of conducting the field procedure for withdrawal well tests (see Test Method D4050), and analyzing the field data as addressed in this test method.

7.2 *Analysis*—Analyze the field test data by plotting the data and recording parameters as specified in Section 8.

8. Calculation and Interpretation of Results

8.1 *Methods*—The drawdown data collected during the aquifer test may be analyzed by either the type-curve method or the semilogarithmic method. Any consistent set of units may be used.

8.1.1 Refer to Practice D6026 on the use of significant digits in the calculations.

NOTE 2—The procedures used to specify how data are collected/recorded and calculated in this guide are regarded as the industry standard. In addition, they are representative of the significant digits that should generally be retained. The procedures used do not consider material variation, purpose for obtaining the data, special purpose studies, or any considerations for the user's objectives; and it is common practice to increase or reduce significant digits of reported data to commensurate with these considerations. It is beyond the scope of this guide to consider significant digits used in analysis methods for engineering design.

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8.1.2 *Type-Curve Method*—Plot drawdown, s, on the vertical axis and time divided by the square of the radius to the well or piezometer, t/r^2, on the horizontal axis using log-log paper. Group data for all wells or piezometers that have screened intervals the same elevation above the base of the aquifer, z_D (for piezometers), or z_{1D} and z_{2D} (for observation wells).

8.1.2.1 Prepare a family of type curves for different values of β. For tests in which both the control well and the observation wells fully penetrate the aquifer, the values in Table 1 and Table 2 may be used to prepare the type curves, as shown in Fig. 3. For piezometers, or tests in which the control well or observation wells do not effectively penetrate the full thickness of the aquifer, the values of s_D corresponding to values of t_s and t_y for a range of values of β must be computed using computer programs such as those of Dawson and Istok (**2**), or Moench (**3**) . The program requires that values for the dimensionless parameters l_D and d_D be supplied for the control well, and values of z_D be supplied for the piezometers, or that the values of z_{1D} and z_{2D} be supplied for observation wells. Only drawdowns for which these dimensionless parameters are similar may be analyzed using the same family of type curves. Prepare as many data plots and families of type curves as necessary to analyze the test.

8.1.2.2 Holding the axes parallel, overlay the data plot on the type curves. Match as many of the early time-drawdown data as possible to the left-most part of the type curve (Type A curves). Select an early-time match point, and record the values of s, t/r^2, s_D and t_s. Moving the data plot horizontally, match as many as possible of the late-time data to the right-most part of the type curves (Type B curves) and select a late-time match point. Record the values of s, s_D, t/r^2, and t_y for this match point. The values of s and s_D should be the same for each match point, that is, the data curves should be shifted only horizontally, not vertically, on the type curve, and the values of β for each observation well should be the same for early and late times.

8.1.2.3 Repeat the procedure in 8.1.2.2 for all additional data plots and type curves. The values of s and s_D should be the same for all plots in a single test. If necessary, repeat the analysis for each plot until a consistent set of values is obtained between all plots. Calculate the value of the term β/r^2 for every observation well or piezometer. Because the remaining terms in the definition of β, α/b^2, should be nearly constant over the area of the test, the term β/r^2 should be independent of radius. If not, a new set of match points should be obtained, and β/r^2 computed for each well until the values are independent of radius.

8.1.2.4 Calculate the transmissivity, specific yield, storage coefficient, and horizontal hydraulic conductivity from the values of s, s_D, t/r^2, t_s and t_y:

$$T = Q s_D / 4\pi s \tag{10}$$

$$S_y = (T/t_y)(t/r^2) \tag{11}$$

$$S = (T/t_s)(t/r^2) \tag{12}$$

$$K_r = T/b \tag{13}$$

The anisotropy can be calculated from:

$$\alpha = (\beta/r^2) b^2 \tag{14}$$

TABLE 1 Values of S_D for the Construction of Type A Curves for Fully Penetrating Wells (1)[A]

t_a	β = 0.001	β = 0.004	β = 0.01	β = 0.03	β = 0.06	β = 0.1	β = 0.2	β = 0.4	β = 0.6
1×10^{-1}	2.48×10^{-2}	2.43×10^{-2}	2.41×10^{-2}	2.35×10^{-2}	2.30×10^{-2}	2.24×10^{-2}	2.14×10^{-2}	1.99×10^{-2}	1.88×10^{-2}
2×10^{-1}	1.45×10^{-1}	1.42×10^{-1}	1.40×10^{-1}	1.36×10^{-1}	1.31×10^{-1}	1.27×10^{-1}	1.19×10^{-1}	1.08×10^{-1}	9.88×10^{-2}
3.5×10^{-1}	3.58×10^{-1}	3.52×10^{-1}	3.45×10^{-1}	3.31×10^{-1}	3.18×10^{-1}	3.04×10^{-1}	2.79×10^{-1}	2.44×10^{-1}	2.17×10^{-1}
6×10^{-1}	6.62×10^{-1}	6.48×10^{-1}	6.33×10^{-1}	6.01×10^{-1}	5.70×10^{-1}	5.40×10^{-1}	4.83×10^{-1}	4.03×10^{-1}	3.43×10^{-1}
1×10^{0}	1.02×10^{0}	9.92×10^{-1}	9.63×10^{-1}	9.05×10^{-1}	8.49×10^{-1}	7.92×10^{-1}	6.88×10^{-1}	5.42×10^{-1}	4.38×10^{-1}
2×10^{0}	1.57×10^{0}	1.52×10^{0}	1.46×10^{0}	1.35×10^{0}	1.23×10^{0}	1.12×10^{0}	9.18×10^{-1}	6.59×10^{-1}	4.97×10^{-1}
3.5×10^{0}	2.05×10^{0}	1.97×10^{0}	1.88×10^{0}	1.70×10^{0}	1.51×10^{0}	1.34×10^{0}	1.03×10^{0}	6.90×10^{-1}	5.07×10^{-1}
6×10^{0}	2.52×10^{0}	2.41×10^{0}	2.27×10^{0}	1.99×10^{0}	1.73×10^{0}	1.47×10^{0}	1.07×10^{0}	6.96×10^{-1}	...
1×10^{1}	2.97×10^{0}	2.80×10^{0}	2.61×10^{0}	2.22×10^{0}	1.85×10^{0}	1.53×10^{0}	1.08×10^{0}	...	...
2×10^{1}	3.56×10^{0}	3.30×10^{0}	3.00×10^{0}	2.41×10^{0}	1.92×10^{0}	1.55×10^{0}	...	...	...
3.5×10^{1}	4.01×10^{0}	3.65×10^{0}	3.23×10^{0}	2.48×10^{0}	1.93×10^{0}	...	...	...	...
6×10^{1}	4.42×10^{0}	3.93×10^{0}	3.37×10^{0}	2.49×10^{0}	1.94×10^{0}	...	...	...	...
1×10^{2}	4.77×10^{0}	4.12×10^{0}	3.43×10^{0}	2.50×10^{0}	...	...	...	...	...
2×10^{2}	5.16×10^{0}	4.26×10^{0}	3.45×10^{0}	...	...	...	...	...	...
3.5×10^{2}	5.40×10^{0}	4.29×10^{0}	3.46×10^{0}	...	...	...	...	...	...
6×10^{2}	5.54×10^{0}	4.30×10^{0}	...	...	...	...	...	...	...
1×10^{3}	5.59×10^{0}	...	...	...	...	...	...	...	...
2×10^{3}	5.62×10^{0}	...	...	...	...	...	...	...	...
3.5×10^{3}	5.62×10^{0}	4.30×10^{0}	3.46×10^{0}	2.50×10^{0}	1.94×10^{0}	1.55×10^{0}	1.08×10^{0}	6.96×10^{-1}	5.07×10^{-1}
β = 0.8	β = 1.0	β = 1.5	β = 2.0	β = 2.5	β = 3.0	β = 4.0	β = 5.0	β = 6.0	β = 7.0
1.79×10^{-2}	1.70×10^{-2}	1.53×10^{-2}	1.38×10^{-2}	1.25×10^{-2}	1.13×10^{-2}	9.33×10^{-3}	7.72×10^{-3}	6.39×10^{-3}	5.30×10^{-3}
9.15×10^{-2}	8.49×10^{-2}	7.13×10^{-2}	6.03×10^{-2}	5.11×10^{-2}	4.35×10^{-2}	3.17×10^{-2}	2.34×10^{-2}	1.74×10^{-2}	1.31×10^{-3}
1.94×10^{-1}	1.75×10^{-1}	1.36×10^{-1}	1.07×10^{-1}	8.46×10^{-2}	6.78×10^{-2}	4.45×10^{-2}	3.02×10^{-2}	2.10×10^{-2}	1.51×10^{-2}
2.96×10^{-1}	2.56×10^{-1}	1.82×10^{-1}	1.33×10^{-1}	1.01×10^{-1}	7.67×10^{-2}	4.76×10^{-2}	3.13×10^{-2}	2.14×10^{-2}	1.52×10^{-2}
3.60×10^{-1}	3.00×10^{-1}	1.99×10^{-1}	1.40×10^{-1}	1.03×10^{-1}	7.79×10^{-2}	4.78×10^{-2}	...	2.15×10^{-2}	...
3.91×10^{-1}	3.17×10^{-1}	2.03×10^{-1}	1.41×10^{-1}	...	...	...	...	...	...
3.94×10^{-1}	...	...	...	...	...	...	...	...	...
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3.94×10^{-1}	3.17×10^{-1}	2.03×10^{-1}	1.41×10^{-1}	1.03×10^{-1}	7.79×10^{-2}	4.78×10^{-2}	3.13×10^{-2}	2.15×10^{-2}	1.52×10^{-2}

[A] Values were obtained from **(2)** by setting $\sigma = 10^{-2}$.

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~~and the vertical permeability from:~~

$$K_z = \alpha K_r \quad (15)$$

~~8.1.2.5 The results of a hypothetical aquifer test are shown in Fig. 4. A control well is discharged at a rate of 0.21 $m^3 s^{-1}$, and water levels are measured in OW1 at a radius of 9 m from the control well, in OW2 (r = 50 m), and OW3 (r = 185 m). A log-log plot of drawdown versus time divided by radius to the control well, squared, is shown for the three observation wells, superimposed on type curves derived from the data in Table 1 and Table 2. Measurements from each observation well fall on a different β curve.~~

~~8.1.2.6 For the example, the transmissivity from Eq 10 is:~~

$$T = Qs_d/4\pi s = (0.21\ m^3\ s^{-1} \times 1.0)/(4 \times 3.14 \times 6.5\ m) = 2.57 \times 10^{-3}\ m^2\ s^{-1},$$

~~and the specific yield from Eq 11 is:~~

$$S_y = (T/t_y)(t/r^2) = (2.57 \times 10^{-3}\ m^2\ s^{-1}/1.0)(88\ m^{-2} s) = 0.23$$

~~The storage coefficient, from Eq 11 is:~~

$$S = (T/t_s)(t/r^2) = (2.57 \times 10^{-3}\ m^2\ s^{-1}/1.0)(0.145\ m^{-2} s) = 3.7 \times 10^{-4}$$

~~The ratio of vertical to horizontal hydraulic conductivity can be calculated from Eq 14 using an assumed aquifer thickness, b of 25 m, and data from OW1 as follows:~~

$$\alpha = (\beta/r^2)b^2 = (0.004/81\ m^2)(625\ m^2) = 0.03$$

~~8.1.3 *Semilogarithmic Method*—This procedure is applicable to tests in which the control and observation wells effectively fully penetrate the aquifer. Plot drawdown on the vertical (arithmetic) axis and time divided by the square of the radius to the control well on the horizontal (logarithmic) axis for all observation wells. The early and late date will tend to fall on parallel straight lines. The intermediate values will fall on horizontal lines between these two extremes.~~

TABLE 2 Values of S_D for the Construction of Type B Curves for Fully Penetrating Wells (1)[A]

t_y	β = 0.001	β = 0.004	β = 0.01	β = 0.03	β = 0.06	β = 0.1	β = 0.2	β = 0.4	β = 0.6
1×10^{-4}	5.62×10^{0}	4.30×10^{0}	3.46×10^{0}	2.50×10^{0}	1.94×10^{0}	1.56×10^{0}	1.09×10^{0}	6.97×10^{-1}	5.08×10^{-1}
2×10^{-4}	...	...	...	...	...	...	...	...	...
3.5×10^{-4}	...	...	...	...	...	...	...	...	...
6×10^{-4}	...	...	...	...	...	...	...	...	...
1×10^{-3}	...	...	...	...	...	...	...	6.97×10^{-1}	5.08×10^{-1}
2×10^{-3}	...	...	...	...	...	...	...	6.97×10^{-1}	5.09×10^{-1}
3.5×10^{-3}	...	...	...	...	...	...	...	6.98×10^{-1}	5.10×10^{-1}
6×10^{-3}	...	...	...	...	...	...	...	7.00×10^{-1}	5.12×10^{-1}
1×10^{-2}	...	...	...	...	...	...	...	7.03×10^{-1}	5.16×10^{-1}
2×10^{-2}	...	...	...	...	...	1.56×10^{0}	1.09×10^{0}	7.10×10^{-1}	5.24×10^{-1}
3.5×10^{-2}	...	...	...	...	1.94×10^{0}	1.56×10^{0}	1.10×10^{0}	7.20×10^{-1}	5.37×10^{-1}
6×10^{-2}	...	...	...	2.50×10^{0}	1.95×10^{0}	1.57×10^{0}	1.11×10^{0}	7.37×10^{-1}	5.57×10^{-1}
1×10^{-1}	...	...	...	2.51×10^{0}	1.96×10^{0}	1.58×10^{0}	1.13×10^{0}	7.63×10^{-1}	5.89×10^{-1}
2×10^{-1}	5.62×10^{0}	4.30×10^{0}	3.46×10^{0}	2.52×10^{0}	1.98×10^{0}	1.61×10^{0}	1.18×10^{0}	8.29×10^{-1}	6.67×10^{-1}
3.5×10^{-1}	5.63×10^{0}	4.31×10^{0}	3.47×10^{0}	2.54×10^{0}	2.01×10^{0}	1.66×10^{0}	1.24×10^{0}	9.22×10^{-1}	7.80×10^{-1}
6×10^{-1}	5.63×10^{0}	4.31×10^{0}	3.49×10^{0}	2.57×10^{0}	2.06×10^{0}	1.73×10^{0}	1.35×10^{0}	1.07×10^{0}	9.54×10^{-1}
1×10^{0}	5.63×10^{0}	4.32×10^{0}	3.51×10^{0}	2.62×10^{0}	2.13×10^{0}	1.83×10^{0}	1.50×10^{0}	1.29×10^{0}	1.20×10^{0}
2×10^{0}	5.64×10^{0}	4.35×10^{0}	3.56×10^{0}	2.73×10^{0}	2.31×10^{0}	2.07×10^{0}	1.85×10^{0}	1.72×10^{0}	1.68×10^{0}
3.5×10^{0}	5.65×10^{0}	4.38×10^{0}	3.63×10^{0}	2.88×10^{0}	2.55×10^{0}	2.37×10^{0}	2.23×10^{0}	2.17×10^{0}	2.15×10^{0}
6×10^{0}	5.67×10^{0}	4.44×10^{0}	3.74×10^{0}	3.11×10^{0}	2.86×10^{0}	2.75×10^{0}	2.68×10^{0}	2.66×10^{0}	2.65×10^{0}
1×10^{1}	5.70×10^{0}	4.52×10^{0}	3.90×10^{0}	3.40×10^{0}	3.24×10^{0}	3.18×10^{0}	3.15×10^{0}	3.14×10^{0}	3.14×10^{0}
2×10^{1}	5.76×10^{0}	4.71×10^{0}	4.22×10^{0}	3.92×10^{0}	3.85×10^{0}	3.83×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}
3.5×10^{1}	5.85×10^{0}	4.94×10^{0}	4.58×10^{0}	4.40×10^{0}	4.38×10^{0}	4.38×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}
6×10^{1}	5.99×10^{0}	5.23×10^{0}	5.00×10^{0}	4.92×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}
1×10^{2}	6.16×10^{0}	5.59×10^{0}	5.46×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}

β = 0.8	β = 1.0	β = 1.5	β = 2.0	β = 2.5	β = 3.0	β = 4.0	β = 5.0	β = 6.0	β = 7.0
3.95×10^{-1}	3.18×10^{-1}	2.04×10^{-1}	1.42×10^{-1}	1.03×10^{-1}	7.80×10^{-2}	4.79×10^{-2}	3.14×10^{-2}	2.15×10^{-2}	1.53×10^{-2}
...	...	...	...	...	7.81×10^{-2}	4.80×10^{-2}	3.15×10^{-2}	2.16×10^{-2}	1.53×10^{-2}
...	...	...	...	1.03×10^{-1}	7.83×10^{-2}	4.81×10^{-2}	3.16×10^{-2}	2.17×10^{-2}	1.54×10^{-2}
...	...	...	...	1.04×10^{-1}	7.85×10^{-2}	4.84×10^{-2}	3.18×10^{-2}	2.19×10^{-2}	1.56×10^{-2}
3.95×10^{-1}	3.18×10^{-1}	2.04×10^{-1}	1.42×10^{-1}	1.04×10^{-1}	7.89×10^{-2}	4.78×10^{-2}	3.21×10^{-2}	2.21×10^{-2}	1.58×10^{-2}
3.96×10^{-1}	3.19×10^{-1}	2.05×10^{-1}	1.43×10^{-1}	1.05×10^{-1}	7.99×10^{-2}	4.96×10^{-2}	3.29×10^{-2}	2.28×10^{-2}	1.64×10^{-2}
3.97×10^{-1}	3.21×10^{-1}	2.07×10^{-1}	1.45×10^{-1}	1.07×10^{-1}	8.14×10^{-2}	5.09×10^{-2}	3.41×10^{-2}	2.39×10^{-2}	1.73×10^{-2}
3.99×10^{-1}	3.23×10^{-1}	2.09×10^{-1}	1.47×10^{-1}	1.09×10^{-1}	8.38×10^{-2}	5.32×10^{-2}	3.61×10^{-2}	2.57×10^{-2}	1.89×10^{-2}
4.03×10^{-1}	3.27×10^{-1}	2.13×10^{-1}	1.52×10^{-1}	1.13×10^{-1}	8.79×10^{-2}	5.68×10^{-2}	3.93×10^{-2}	2.86×10^{-2}	2.15×10^{-2}
4.12×10^{-1}	3.37×10^{-1}	2.24×10^{-1}	1.62×10^{-1}	1.24×10^{-1}	9.80×10^{-2}	6.61×10^{-2}	4.78×10^{-2}	3.62×10^{-2}	2.84×10^{-2}
4.25×10^{-1}	3.50×10^{-1}	2.39×10^{-1}	1.78×10^{-1}	1.39×10^{-1}	1.13×10^{-1}	8.06×10^{-2}	6.12×10^{-2}	4.86×10^{-2}	3.98×10^{-2}
4.47×10^{-1}	3.74×10^{-1}	2.65×10^{-1}	2.05×10^{-1}	1.66×10^{-1}	1.40×10^{-1}	1.06×10^{-1}	8.53×10^{-2}	7.14×10^{-2}	6.14×10^{-2}
4.83×10^{-1}	4.12×10^{-1}	3.07×10^{-1}	2.48×10^{-1}	2.10×10^{-1}	1.84×10^{-1}	1.49×10^{-1}	1.28×10^{-1}	1.13×10^{-1}	1.02×10^{-1}
5.71×10^{-1}	5.06×10^{-1}	4.10×10^{-1}	3.57×10^{-1}	3.23×10^{-1}	2.98×10^{-1}	2.66×10^{-1}	2.45×10^{-1}	2.31×10^{-1}	2.20×10^{-1}
6.97×10^{-1}	6.42×10^{-1}	5.62×10^{-1}	5.17×10^{-1}	4.89×10^{-1}	4.70×10^{-1}	4.45×10^{-1}	4.30×10^{-1}	4.19×10^{-1}	4.11×10^{-1}
8.89×10^{-1}	8.50×10^{-1}	7.92×10^{-1}	7.63×10^{-1}	7.45×10^{-1}	7.33×10^{-1}	7.18×10^{-1}	7.09×10^{-1}	7.03×10^{-1}	6.99×10^{-1}
1.16×10^{0}	1.13×10^{0}	1.10×10^{0}	1.08×10^{0}	1.07×10^{0}	1.07×10^{0}	1.06×10^{0}	1.06×10^{0}	1.05×10^{0}	1.05×10^{0}
1.66×10^{0}	1.65×10^{0}	1.64×10^{0}	1.63×10^{0}	1.63×10^{0}	1.63×10^{0}	1.63×10^{0}	1.63×10^{0}	1.63×10^{0}	1.63×10^{0}
2.15×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}	2.14×10^{0}
2.65×10^{0}	2.65×10^{0}	2.65×10^{0}	2.64×10^{0}	2.64×10^{0}	2.64×10^{0}	2.64×10^{0}	2.64×10^{0}	2.64×10^{0}	2.64×10^{0}
3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}	3.14×10^{0}
3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}	3.82×10^{0}
4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}	4.37×10^{0}
4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}	4.91×10^{0}
5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}	5.42×10^{0}

[A] Values were obtained from Ref **(2)** by setting $\sigma = 10^{-2}$.

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~~8.1.3.1 Fit a straight line to the late data. The intersection of this line with the horizontal axis ($s = 0$) is denoted by $(t/r^2)_l$. The slope of the line over one log cycle of t/r^2 is denoted Δs_l. The transmissivity and specific yield of the aquifer are then calculated from Jacob's (**3**) method, using the procedures described in Test Method D4105.~~

$$T = 2.30\, Q/4\pi \Delta s_l \quad (16)$$

$$S_y = 2.25\, T\, (t/r^2)_l \quad (17)$$

~~8.1.3.2 Fit a horizontal straight line to the intermediate data for each observation well. The intersection of the horizontal straight line with the late-time straight line is denoted t_β. The dimensionless time $t_y\beta$ is then calculated from the following:~~

$$t_{y\beta} = (T/S_y)(t_\beta/r^2) \quad (18)$$

~~Using the values of $t_y\beta$, values of β for each observation well may be obtained by interpolation from Table 3 or be picked from Fig. 5. The values of β should be independent of radius, as in 8.1.2.3.~~

~~8.1.3.3 Fit a straight line to the early part of the time-drawdown data. The intersection of this line with the horizontal axis is denoted by $(t/r^2)_e$, and the slope of this line over one log cycle is Δs_e. The transmissivity and storage coefficient are calculated from:~~

$$T = 2.30\, Q/4\pi \Delta s_e \quad (19)$$