AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)
Pumping Test

1. D 4043 – 96. Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques.

2. D 4044 – 96. Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifiers.

3. D 4050 – 96. Standard Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems.

4. D 4104 – 96. Standard Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Tests).

5. D 4105 – 96. Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method.

6. D 4106 – 96. Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method.

7. D 4630 – 96. Standard Test Method for Determining Transmissivity and Storage Coefficient of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test.

8. D 4631 – 95. Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In Situ Measurements Using Pressure Pulse Technique.

9. D 4750 – 87. Standard Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well).

10. D 5269 – 96. Standard Test Method for Determining Transmissivity of Nonleaky Confined Aquifers by the Theis Recovery Method.

11. D 5270 – 96. Standard Test Method for Determining Transmissivity and Storage Coefficient of Bounded, Nonleaky, Confined Aquifers.

12. D 5472 – 93. Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well.

13. D 5473 – 93. Standard Test Method for (Analytical Procedure for) Analyzing the Effects of Partial Penetration of Control Well and Determining the Horizontal and Vertical Hydraulic Conductivity in a Nonleaky Confined Aquifer.

14. D 5716 – 95. Standard Test Method for Measuring the Rate of Well Discharge by Circular Orifice Weir.

15. D 5785 – 95. Standard Test Method for (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Underdamped Well Response to Instantaneous Change in Head (Slug Test).

16. D 5786 – 95. Standard Practice for (Field Procedure) for Constant Drawdown Tests in Flowing Wells for Determining Hydraulic Properties of Aquifer Systems.

17. D 5850 – 95. Standard Test Method for (Analytical Procedure) Determining Transmissivity, Storage Coefficient, and Anisotropy Ratio from a Network of Partially Penetrating Wells.

18. D 5881 – 95. Standard Test Method for (Analytical Procedure) Determining Transmissivity of Confined Nonleaky Aquifers by Critically Damped Well Response to Instantaneous Change in Head (Slug).

19. D 5912 – 96. Standard Test Method for (Analytical Procedure) Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change in Head (Slug).

20. D 5920 – 96. Standard Test Method (Analytical Procedure) for Tests of Anisotropic Unconfined Aquifers by Neuman Method.

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100 Barr Harbor Dr., West Conshohocken, PA 19428

Standard Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques[1]

This standard is issued under the fixed designation D 4043; 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.

ϵ^1 NOTE—Section 1.5 was added editorially in January 1999.

1. Scope

1.1 This guide is an integral part of a series of standards that are being prepared on the in situ determination of hydraulic properties of aquifer systems by single- or multiple-well tests. This guide provides guidance for development of a conceptual model of a field site and selection of an analytical test method for determination of hydraulic properties. This guide does not establish a fixed procedure for determination of hydrologic properties.

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

1.3 *Limitations*—Well techniques have limitations in the determination of hydraulic properties of ground-water flow systems. These limitations are related primarily to the simplifying assumptions that are implicit in each test method. The response of an aquifer system to stress is not unique; therefore, the system must be known sufficiently to select the proper analytical method.

1.4 *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.*

1.5 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4044 Test Method (Field Procedure) for Instantaneous Change in Head (Slug Tests) for Determining Hydraulic Properties of Aquifers[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4104 Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Test)[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4630 Test Method for Determining Transmissivity and Storativity of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test[2]

D 4631 Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In Situ Measurements Using the Pressure Pulse Technique[2]

D 5269 Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by the Theis Recovery Method[3]

D 5270 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Bounded, Nonleaky, Confined Aquifers[3]

D 5472 Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well[3]

D 5473 Test Method (Analytical Procedure) for Determining the Ratio of Horizontal to Vertical Hydraulic Conductivity in a Nonleaky Confined Aquifer[3]

D 5716 Test Method to Measure the Rate of Well Discharge

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

by Circular Orifice Weir[3]

D 5785 Test Method (Analytical Procedure) for Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change in Head (Slug Test)[3]

D 5786 Test Method (Field Procedure) for Constant Drawdown Tests in Flowing Wells for Determining Hydraulic Properties of Aquifer Systems[3]

D 5850 Test Method (Analytical Procedure) for Determining Transmissivity, Storage Coefficient, and Anisotropy Ratio from a Network of Partially Penetrating Wells[3]

D 5881 Test Method (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Critically Damped Well Response to Instantaneous Change in Head (Slug Test)[3]

D 5912 Test Method (Analytical Procedure) for Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change in Head (Slug Test)[3]

D 5920 Test Method (Analytical Procedure) for Test of Anisotropic Unconfined Aquifers by the Neuman Method[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *aquifer, unconfined*—an aquifer that has a water table.

3.1.3 *barometric efficiency*—the ratio of the change in depth to water in a well to the change in barometric pressure, expressed in length of water.

3.1.4 *conceptual model*—a simplified representation of the hydrogeologic setting and the response of the flow system to stress.

3.1.5 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.6 *control well*—well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.1.7 *hydraulic conductivity (field aquifer tests)*—the volume of water at the existing kinematic viscosity that will move in a unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.8 *observation well*—a well open to all or part of an aquifer.

3.1.9 *piezometer*—a device used to measure static head at a point in the subsurface.

3.1.10 *specific capacity*—the rate of discharge from a well divided by the drawdown of the water level within the well at a specific time since pumping started.

3.1.11 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.12 *specific yield*—the ratio of the volume of water that the saturated rock or soil will yield by gravity to the volume of the rock or soil. In the field, specific yield is generally determined by tests of unconfined aquifers and represents the change that occurs in the volume of water in storage per unit area of unconfined aquifer as the result of a unit change in head. Such a change in storage is produced by the draining or filling of pore space and is, therefore, mainly dependent on particle size, rate of change of the water table, and time of drainage.

3.1.13 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.14 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.2 For definitions of other terms used in this guide, see Terminology D 653.

4. Significance and Use

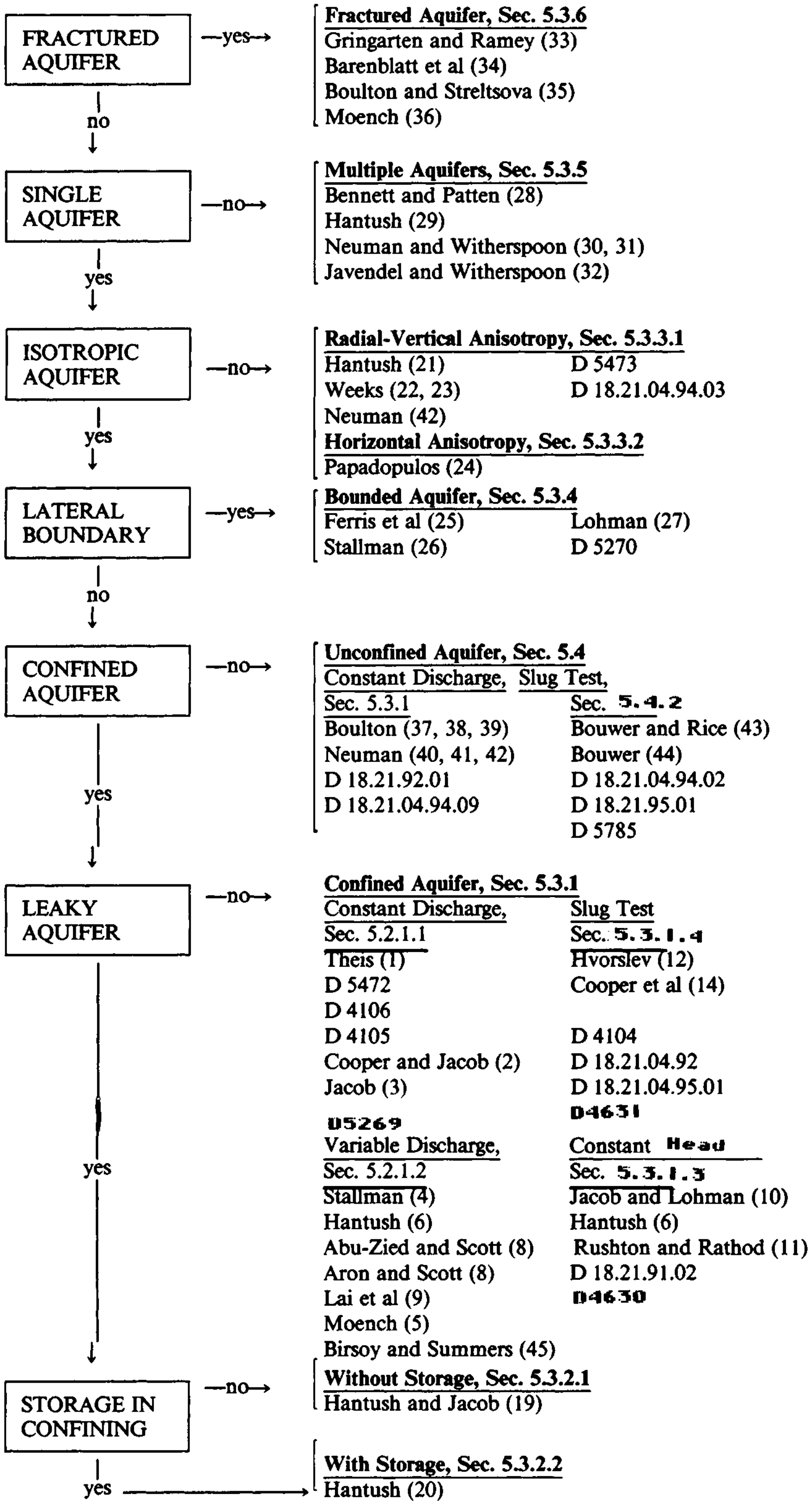
4.1 An aquifer test method is a controlled field experiment made to determine the approximate hydraulic properties of water-bearing material. The hydraulic properties that can be determined are specific to the test method. The hydraulic properties that can be determined are also dependent upon the instrumentation of the field test, the knowledge of the aquifer system at the field site, and conformance of the hydrogeologic conditions at the field site to the assumptions of the test method. Hydraulic conductivity and storage coefficient of the aquifer are the basic properties determined by most test methods. Test methods can be designed also to determine vertical and horizontal anisotropy, aquifer discontinuities, vertical hydraulic conductivity of confining beds, well efficiency, turbulent flow, and specific storage and vertical permeability of confining beds.

5. Procedure

5.1 The procedure for selection of an aquifer test method or methods is primarily based on selection of a test method that is compatible with the hydrogeology of the proposed test site. Secondarily, the test method is selected on the basis of the testing conditions specified by the test method, such as the method of stressing or causing water-level changes in the aquifer and the requirements of a test method for observations of water level response in the aquifer. The decision tree in Table 1 is designed to assist, first, in selecting test methods applicable to specific hydrogeologic site characteristics. Secondly, the decision tree will assist in selecting a test method on the basis of the nature of the stress on the aquifer imposed by the control well. The decision tree references the sections in this guide where the test methods are cited.

5.2 *Pretest-selection Procedures*—Aquifer test methods are highly specific to the assumptions of the analytical solution of the test method. Reliability of determination of hydraulic properties depends upon conformance of the hydrologic site characteristics to the assumptions of the test method. A prerequisite for selecting an aquifer test method is knowledge of the hydrogeology of the test site. A conceptual understanding of the hydrogeology of the aquifer system at the prospective test site should be gained in as much detail as possible from existing literature and data, and a site reconnaissance. In developing a site characterization, incorporate geologic mapping, driller's logs, geophysical logs, records of existing wells,

TABLE 1 Decision Tree for Selection of Aquifer Test Method



Fractured Aquifer, Sec. 5.3.6
Gringarten and Ramey (33)
Barenblatt et al (34)
Boulton and Streltsova (35)
Moench (36)

Multiple Aquifers, Sec. 5.3.5
Bennett and Patten (28)
Hantush (29)
Neuman and Witherspoon (30, 31)
Javendel and Witherspoon (32)

Radial-Vertical Anisotropy, Sec. 5.3.3.1
Hantush (21) D 5473
Weeks (22, 23) D 18.21.04.94.03
Neuman (42)
Horizontal Anisotropy, Sec. 5.3.3.2
Papadopulos (24)

Bounded Aquifer, Sec. 5.3.4
Ferris et al (25) Lohman (27)
Stallman (26) D 5270

Unconfined Aquifer, Sec. 5.4

Constant Discharge, Sec. 5.3.1	Slug Test, Sec. 5.4.2
Boulton (37, 38, 39)	Bouwer and Rice (43)
Neuman (40, 41, 42)	Bouwer (44)
D 18.21.92.01	D 18.21.04.94.02
D 18.21.04.94.09	D 18.21.95.01
	D 5785

Confined Aquifer, Sec. 5.3.1

Constant Discharge, Sec. 5.2.1.1	Slug Test Sec. 5.3.1.4
Theis (1)	Hvorslev (12)
D 5472	Cooper et al (14)
D 4106	
D 4105	D 4104
Cooper and Jacob (2)	D 18.21.04.92
Jacob (3)	D 18.21.04.95.01
D5269	D4631

Variable Discharge, Sec. 5.2.1.2	Constant Head Sec. 5.3.1.3
Stallman (4)	Jacob and Lohman (10)
Hantush (6)	Hantush (6)
Abu-Zied and Scott (8)	Rushton and Rathod (11)
Aron and Scott (8)	D 18.21.91.02
Lai et al (9)	D4630
Moench (5)	
Birsoy and Summers (45)	

Without Storage, Sec. 5.3.2.1
Hantush and Jacob (19)

With Storage, Sec. 5.3.2.2
Hantush (20)

water-level and water-quality data, and results of geophysical surveys. Include information on the thickness, lithology, stratification, depth, attitude, continuity, and extent of the aquifer and confining beds.

5.3 *Select Applicable Aquifer Test Methods*—Select a test method based on conformation of the site hydrogeology to assumptions of the test model and the parameters to be determined. A summary of principal aquifer test methods and their applicability to hydrogeologic site conditions is given in the following paragraphs. The decision tree for aquifer test selection, Table 1, provides a graphic display of the hydrogeologic site conditions for each test method and references to the section where each test method is cited.

5.3.1 *Extensive, Isotropic, Homogeneous, Confined, Nonleaky Aquifer*:

5.3.1.1 *Constant Discharge*—Test Method in which the discharge or injection rate in the control well is constant are given by the nonequilibrium method of Theis **(1)**[4] for the drawdown and recovery phases. The Theis test method is the most widely referenced and applied aquifer test method and is the basis for the solution to other more complicated boundary condition problems. The Theis test method for the pumping or injection phase is given in Test Method D 4106. Cooper and Jacob **(2)** and Jacob **(3)** recognized that for large values of time and small values of distance from the control well, the Theis solution yields a straight line on semilogarithmic plots of various combinations of drawdown and distance from the control well. The solution of the Theis equation can therefore be simplified by the use of semilogarithmic plots. The modified Theis nonequilibrium test method is given in Test Method D 4105. A test method for estimating transmissivity from specific capacity by the Theis method is given in Test Method D 5472.

5.3.1.2 *Variable Discharge*—Test methods for a variably discharging control well have been presented by Stallman **(4)** and Moench **(5)** and Birsoy and Summers **(45)**. These test methods simulate pumpage as a sequence of constant-rate stepped changes in discharge. The test methods utilize the principle of superposition in constructing type curves by summing the effects of successive changes in discharge. The type curves may be derived for control wells discharging from extensive, leaky, and nonleaky confined aquifers or any situation where the response to a unit stress is known. Hantush **(6)** developed drawdown functions for three types of decreases in control-well discharge. Abu-Zied and Scott **(7)** presented a general solution for drawdown in an extensive confined aquifer in which the discharge of the control well decreases at an exponential rate. Aron and Scott **(8)** proposed an approximate test method of determining transmissivity and storage from an aquifer test in which discharge decreases with time during the early part of the test. Lai et al **(9)** presented test methods for determining the drawdown in an aquifer taking into account storage in the control well and having an exponentially and linearly decreasing discharge.

5.3.1.3 *Constant Drawdown*—Test methods have been presented to determine hydraulic-head distribution around a discharging well in a confined aquifer with near constant drawdown. Such conditions are most commonly achieved by shutting in a flowing well long enough for the head to fully recover, then opening the well. The solutions of Jacob and Lohman **(10)** and Hantush **(6)** apply to aerially extensive, nonleaky aquifers. Rushton and Rathod **(11)** used a numerical model to analyze aquifer-test data. Reed **(46)** presents a computer program that includes some of the above procedures and also includes discharge as a fifth-degree polynomial of time.

5.3.1.4 *Slug Test Methods*—Test methods for estimating transmissivity by injecting a given quantity or *slug* of water into a well were introduced by Hvorslev **(12)** and Ferris and Knowles **(13)**. Solutions to overdamped well response to slug tests have also been presented by Cooper et al **(14)**. The solution presented by Cooper et al **(14)** is given in Test Method D 4104. Solutions for slug tests in wells that exhibit oscillatory water-level fluctuations caused by a sudden injection or removal of a volume of water have been presented by Krauss **(15)**, van der Kamp **(16)**, and Shinohara and Ramey **(17)**. The van der Kamp **(16)** solution is given in Test Method D 5785. Kipp **(18)** analyzed the complete range of response of wells ranging from those having negligible inertial effects through full oscillatory behavior and developed type curves for the analysis of slug test data. The procedure given by Kipp **(18)** for analysis of critically damped response is given in Test Method D 5881. The field procedure for slug test methods is given in Test Method D 4044. Analytical procedures for analysis of slug test data are given in Test Methods D 5785, D 4104, D 5881, and D 5912.

5.3.2 *Extensive, Isotropic, Homogeneous, Confined, Leaky Aquifers*—Confining beds above or below the aquifer commonly allow transmission of water to the aquifer by leakage. Test methods that account for this source of water have been presented for several aquifer-confining bed situations.

5.3.2.1 *Leaky Confining Bed, Without Storage*—Hantush and Jacob **(19)** presented a solution for the situation in which a confined aquifer is overlain, or underlain, by a leaky confining layer having uniform properties. Radial flow is assumed in a uniform aquifer. The hydraulic properties of the aquifer and confining bed are determined by matching logarithmic plots of aquifer test data to a family of type curves.

5.3.2.2 *Leaky Confining Bed, With Storage*—Solutions for determining the response of a leaky confined aquifer where the release of water in the confining bed is taken into account were presented by Hantush **(20)**. Flow in the uniform confined aquifer is assumed to be radial, and flow in the leaky confining beds is assumed to be vertical.

5.3.3 *Extensive, Confined, Anisotropic Aquifer*:

5.3.3.1 *Radial-Vertical Anisotropy*—Solutions to the head distribution in a homogeneous confined aquifer with radial-vertical anisotropy in response to constant discharge of a partially penetrating well are presented by Hantush **(21)**. Weeks **(22, 23)** presented test methods to determine the ratio of horizontal to vertical hydraulic conductivity. Methods for analysis of a pumping test in a radial-vertical anisotropic aquifer are given in Test Methods D 5473 and D 5850.

5.3.3.2 *Horizontal Anisotropy*—Papadopulos **(24)** presented a test method for determination of horizontal plane anisotropy in an aerially extensive homogeneous confined aquifer.

5.3.4 *Areally Bounded Aquifers*—Aquifer test methods discussed previously are based on the assumption that the aquifer is extensive. Effects of limitations in the extent of aquifers by impermeable boundaries or by source boundaries, such as hydraulically connected streams, may preclude the direct

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[4] The boldface numbers in parentheses refer to the list of references at the end of this guide.

application of an aquifer test method. The method of images, described by Ferris et al **(25)**, Stallman **(26)** and Lohman **(27)**, provide solutions to head distribution in finite aquifers. The theory of images for determination of transmissivity and storage coefficient in bounded aquifers is given in Test Method D 5270.

5.3.5 *Multiple Aquifers*—Test methods for multiple aquifers, that is, two or more aquifers separated by a leaky confining bed and penetrated by a control well, require special methods for analysis. Bennett and Patten **(28)** presented a method for testing a multi-aquifer system using downhole metering and constant drawdown. Hantush **(29)** presented solutions for two aquifers separated by a leaky confining bed. Neuman and Witherspoon **(30)** provided solutions for drawdown in leaky confining beds above and below an aquifer being pumped. Neuman and Witherspoon **(31)** developed an analytical solution for the flow in a leaky confined system of two aquifers separated by a leaky confining bed with storage. Javendel and Witherspoon **(32)** presented a finite-element method of analyzing anisotropic multi-aquifer systems.

5.3.6 *Fractured Media*—Solutions for the flow in a single finite fracture are presented by Gringarten and Ramey **(33)**. Barenblatt et al **(34)** presented a test method for solving a double-porosity model. Boulton and Streltsova **(35)** presented a solution for a system of porous layers separated by fractures. Moench **(36)** developed type curves for a double-porosity model with a fracture skin that may be present at the fracture-block interface as a result of mineral deposition or alteration.

5.4 *Extensive, Isotropic, Homogeneous, Unconfined Aquifer*—Conditions governing drawdown due to discharge from an unconfined aquifer differ markedly from those due to discharge from a nonleaky confined aquifer. Difficulties in deriving analytical solutions to the hydraulic-head distribution in an unconfined aquifer result from the following characteristics: (*1*) transmissivity varies in space and time as the water table is drawn down and the aquifer is dewatered, (*2*) water is derived from storage in an unconfined aquifer mainly at the free water surface and, to a lesser degree, from each discrete point within the aquifer, and (*3*) vertical components of flow exist in the aquifer in response to withdrawal of water from a well in an unconfined aquifer.

5.4.1 Boulton **(37, 38, 39)** introduced a mathematical solution to the head distribution in response to discharge at a constant rate from an unconfined aquifer. Boulton's solution invokes the use of a semi-empirical delay index that was not defined on a physical basis. Neuman **(40, 41, 42)** presented solutions for unconfined aquifer tests utilizing fully penetrating and partially penetrating control and observation wells hypothesized on well-defined physical properties of the aquifer. The Neuman solution is given in Test Method D 5920.

5.4.2 A procedure for analysis of the water-level response in an unconfined aquifer given by Bouwer and Rice **(43)** and is presented in Test Method D 5785. Bouwer and Rice **(43)** and Bouwer **(44)** present a slug test method for unconfined aquifer conditions.

6. Keywords

6.1 aquifers; aquifer tests; confining beds; control wells; discharging wells; hydraulic conductivity; observation wells; piezometers; storage coefficient; transmissivity

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Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers[1]

1. Scope

1.1 This test method covers the field procedure for performing an in situ instantaneous change in head (slug) test.

1.2 This test method is used in conjunction with an analytical procedure such as Test Method D 4104 to determine aquifer properties.

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

1.4 *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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determination of Hydraulic Properties by Well Techniques[2]

D 4104 Test Method (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Test)[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

D 5785 Test Method for (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Underdamped Well Response to Instantaneous Change In Head (Slug Test)[3]

D 5881 Test Method (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Critically Damped Well Response to Instantaneous Change In Head (Slug Test)[3]

D 5912 Test Method (Analytical Procedure) for Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change In Head (Slug Test)[3]

3. Terminology

3.1 *Definitions:* Definitions:

3.1.1 *control well*—well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.1.2 *hydraulic conductivity—(field aquifer tests),* the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.3 *observation well*—a well open to all or part of an aquifer.

3.1.4 *overdamped-well response*—characterized by the water level returning to the static level in an approximately exponential manner following a sudden change in water level. (See for comparison *underdamped well.*)

3.1.5 *slug*—a volume of water or solid object used to induce a sudden change of head in a well.

3.1.6 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, it is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.7 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.8 *underdamped-well response*—characterized by the water level oscillating about the static water level following a sudden change in water level. (See for comparison *overdamped well.*)

3.1.9 For definitions of other terms used in this test method, refer to Terminology D 653.

4. Summary of Test Method

4.1 This test method describes the field procedures involved in conducting an instantaneous head (slug) test. The slug test method involves causing a sudden change in head in a control well and measuring the water level response within that control well. Head change may be induced by suddenly injecting or

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09

removing a known quantity or "slug" of water into the well, rapid removal of a mechanical "slug" from below the water level, increasing or decreasing the air pressure in the well casing, or emplacement of a mechanical slug into the water column.

4.2 The water-level response in the well is a function of the mass of water in the well and the transmissivity and coefficient of storage of the aquifer. One method of analysis of the data from this field practice is described in Test Method D 4104.

5. Significance and Use

5.1 This slug test field procedure is used in conjunction with a slug test analytical procedure, such as Test Method D 4104 to provide quick and relatively inexpensive estimates of transmissivity.

5.2 The slug test provides an advantage over pumping tests in that it does not require the disposal of the large quantities of water that may be produced. This is of special importance when testing a potentially contaminated aquifer. However, slug tests reflect conditions near the well, therefore are influenced by near-well conditions, such as gravel pack, poor well development, and skin effects.

5.3 Slug tests may be made in aquifer materials of lower hydraulic conductivity than generally considered suitable for hydraulic testing with pumping tests.

5.4 The method of data analysis (analytical procedure) should be known prior to the field testing to ensure that all appropriate dimensions and measurements are properly recorded. Selection of the analytical procedure can be aided by using Guide D 4043, Test Method D 5785, Test Method D 5881, and Test Method D 5912.

6. Apparatus

6.1 *Slug-Inducing Equipment*—This test method describes the types of equipment that can be used. Because of the infinite variety of testing conditions and because similar results can be achieved with different apparatus, engineering specifications for apparatus are not appropriate. This test method specifies the results to be achieved by the equipment to satisfy the requirements of this practice.

6.2 *Water-Level Measurement Equipment*—The method of water level measurement may be dependent on the method selected for injection or withdrawal of water, and the nature of the response of the well. For an open-well test, that is, where access to the water level is open to the surface, measure water levels manually as described in Test Method D 4750, by an automatic recording device linked to a float, or with a pressure transducer linked to a data logger or display device. A pressure transducer linked to a data logger will be necessary for a test in a closed well in which water-level changes are induced by vacuum or pressure on the control well and where manual measurements do not provide measurements of adequate frequency (see 9.3).

7. Conditioning

7.1 *Pre-Test Procedure*:

7.1.1 *Measuring Pre-Test Water Levels*—Measure the water level in the control well before beginning the test for a period longer than the duration of the test to determine the pre-test water level fluctuations and to establish pre-pumping water-level trend and to determine a pre-pumping reference water level.

8. Procedure

8.1 Cause a change in water level, either a rise or decline, by one of the following methods:

8.1.1 *Water Slug*—Inject or withdraw water of a known quantity into or from the control well.

8.1.2 *Mechanical Slug*—Inject or withdraw a mechanical slug below or above the water level. The water within the control well will then rise or decline an amount equal to the volume of the mechanical slug.

8.1.3 *Release Vacuum or Pressure*—A method of simulating the injection or withdrawal of a slug of water is by the release of a vacuum or pressure on a tightly capped (shut-in) control well. Before the release, the vacuum or pressure is held constant.

NOTE 1—There is no fixed requirement for the magnitude of the change in water level. Similar results can be achieved with a wide range in induced head change. Some considerations include a magnitude of change that can be readily measured with the apparatus selected, for example the head change should be such that the method of measurement should be accurate to 1 % of the maximum head change. Generally, an induced head change of from one-third to one meter is adequate. Although the induced head change should be sufficient to allow the response curve to be defined, excessive head change should be avoided to reduce the possibility of introducing large frictional losses in well bore.

The mechanical model for the test assumes the head change is induced instantaneously. Practically, a finite time is required to effect a head change. Selection of time zero can be selected experimentally. Refer to the method of analysis (such as Test Method D 4104) to determine time zero and to evaluate the suitability of the change effected in the well.

8.2 Measure water-level response to the change in water level. The frequency of water-level measurement during the test is dependent upon the hydraulic conductivity of the material being tested. During the early portions of the test, measure water levels at closely-spaced intervals. Measurements of water level made manually with a tape should be made as frequently as possible until the water level has recovered about 60 to 80 %. Increase the length of time between measurements with increasing duration of the test. Since most methods of data analysis are curve-fitting techniques, it is essential that water levels are measured frequently enough to define the water-level response curve (see Guide D 4043, Test Methods D 4104 and D 5785).

8.2.1 In aquifer-well systems where water-level changes are rapid, it may be necessary to use a pressure transducer linked to an electronic data logger to measure and record the water levels frequently enough to adequately define the waterlevel response. The use of transducers and data loggers generally provides a greater than adequate frequency of measurements, ranging from several measurements per second in the early part of the test to a specified frequency in the later portions of a test. With such equipment, the test analysis may use a reduced data set of measurements to calculate the hydraulic properties (see Guide D 4043, Test Methods D 4104 and D 5785 for analysis of water level data).

8.3 *Post-Test Procedure*—Make preliminary analysis of data before leaving the field and evaluate the test regarding the criteria given in this test method and the method of analysis, such as Test Method D 4104 to determine if the test should be rerun.

9. Report

9.1 Include the information listed below in the report of the field procedure:

9.2 All test reports should include the following:

9.2.1 Date, time, and well identification,

9.2.2 Method of slug withdrawal or injection, as well as whether the test is a falling head (injection) or a rising head (withdrawal) test,

9.2.3 Inside diameter of well screen and well casing above screen,

9.2.4 Depth of well,

9.2.5 Length and depth setting of screen,

9.2.6 Volume of mechanical slug or pressure change imposed on water level, and

9.2.7 Pre-testing water-level trend.

9.3 Establish and record the measurement point from which all measurements of water level are made. Record date, time, and depth to water level below measurement point of all water levels.

9.4 Water levels measured during the test should be recorded with information on date, clock time, and time since test started. If the water levels are measured with a pressure transducer and recorded with an electronic data logger, record the name of the data file on the data logger.

10. Precision and Bias

10.1 It is not practical to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; ground water; hydraulic conductivity; hydraulic properties; instantaneous head test; slug tests; storage coefficient; transmissivity

Standard Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[1]

1. Scope

1.1 This test method describes the field procedure for selecting well locations, controlling discharge or injection rates, and measuring water levels used to analyze the hydraulic properties of an aquifer or aquifers and adjacent confining beds.

1.2 This test method is used in conjunction with an analytical procedure such as Test Methods D 4105 or D 4106 to determine aquifer properties.

1.3 The appropriate field and analytical procedures are selected as described in Guide D 4043.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 2488 Practice for Description and Identification of Soils (Visual-Manual Procedure)[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the head and flow in the aquifer is changed, for example, by pumping, injection, or change of head.

3.1.4 *hydraulic conductivity (field aquifer tests)*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.5 *observation well*—a well open to all or part of an aquifer.

3.1.6 *piezometer*—a device used to measure hydraulic head at a point in the subsurface.

3.1.7 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.8 *storage coefficient* —the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.9 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.10 For definitions of other terms used in this test method, see Terminology D 653.

4. Summary of Test Method

4.1 This test method describes the field practices in conducting withdrawal and injection well tests. These methods involve withdrawal of water from or injection of water to an aquifer through a control well and measurement of the water-level response in the aquifer. The analysis of the data from this

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

field practice is described in standards such as Test Methods D 4105 and D 4106.

5. Significance and Use

5.1 Withdrawal and injection well test field procedures are used with appropriate analytical procedures in appropriate hydrogeological sites to determine transmissivity and storage coefficient of aquifers and hydraulic conductivity of confining beds.

6. Apparatus

6.1 Various types of equipment can be used to withdraw or inject water into the control well, measure withdrawal and injection rates, and measure water levels. The test procedure may be conducted with different types of equipment to achieve similar results. The objectives to be achieved by the use of the equipment are given in this section and in Sections 7 and 8.

6.2 *Control Well*—Discharge or injection well test methods require that water be withdrawn from or injected into a single well. This well, known as the control well, must be drilled and completed such that it transmits water to or from the aquifer (usually the entire thickness of the aquifer) at rates such that a measurable water level change will occur at observation wells. The control well should be as efficient as possible, to reduce the head loss between the aquifer and the well. Well development should be as complete as possible to eliminate additional production of sand or silt and consequent changes in well efficiency and pumping water levels during the test. The cuttings from the control well should be described and recorded according to Practice D 2488. The analytical method selected for analysis of the data may specify certain dimensions of the control well such as screen length and depth of screen placement. Specific requirements for control wells may be given in standards for specific analytical methods (see, for example, Test Methods D 4105 and D 4106).

6.3 *Observation Wells or Piezometers*—Numbers of observation wells and their distance from the control well and their screened interval may be dependent upon the test method to be employed. Refer to the analytical test method to be used for specifications of observation wells (see, for example, Test Methods D 4105 and D 4106).

6.4 *Control Well Pump*—A pump capable of withdrawal of a constant or predetermined variable rate of water from the control well. The pump and motor should be adequately sized for the designed pumping rate and lift. The pump or motor must be equipped with a control mechanism to adjust discharge rate. In the case of diesel-, gasoline-, or natural-gas-fueled engines, throttle settings should allow for small adjustments in pumping rates. Pumps equipped with electric motors are usually controlled by adjusting backpressure on the pump through a gate valve in the discharge line. Take care to select a discharge rate small enough such that the rate can be maintained throughout the test without fully opening the gate valve. If neither method of control is practical, split the discharge and route part of the discharge back to the well through a separate discharge line.

6.5 Many aquifer tests are made at “sites of opportunity,” that is, using existing production wells as the control well and using other existing wells for observation of water level. In such cases the locations and screened intervals of the wells should be compatible with the requirements of the method of test analysis.

6.6 *Water-Level Measurement Equipment*—Manual measurements can be made with a steel tape or electric tape as described in Test Method D 4750, with a mechanical recorder linked to a float, or combination of pressure transducer and electronic data logger.

6.6.1 *Mechanical Recorders*—Mechanical recorders employ a float in the well to produce a graphic record of water level changes. Early in the test, it may be difficult to distinguish small increments of time on the recorder chart, therefore the recorder should be supplemented with additional early time measurements or by marking the trace of an automatic water-level recorder chart and recording the time by the mark. Check the mechanical recorder periodically throughout the test using the steel tape.

6.6.2 *Pressure Transducers and Electronic Data Loggers*—A combination of a pressure transducer and electronic data logger can provide rapid measurements of water-level change, and can be programmed to sample at reduced frequency late in the test. Select the pressure transducer to measure pressure changes equivalent to the range of expected water level changes. Check the transducer in the field by raising and lowering the transducer a measured distance in the well. Also check the transducer readings periodically with a steel tape.

7. Conditioning

7.1 *Pre-Test Procedures*:

7.1.1 *Selecting Aquifer-Test Method*—Develop a conceptual model of the site hydrogeology and select the appropriate aquifer test method according to Guide D 4043. Observe the requirements of the selected test method with regard to specifications for the control well and observations wells.

7.1.2 *Field Reconnaissance*—Make a field reconnaissance of the site before conducting the test to include as much detail as possible on depth, continuity, extent, and preliminary estimates of the hydrologic properties of the aquifers and confining beds. Note the location of existing wells and water-holding or conveying structures that might interfere with the test. The control should be equipped with a pipeline or conveyance structure adequate to transmit the water away from the test site, so that recharge is not induced near the site. Make arrangements to ensure that nearby wells are turned off well before the test, and automatic pump controls are disabled throughout the anticipated test period. Alternately, it may be necessary to pump some wells throughout the test. If so, they should be pumped at a constant rate, and not started and stopped for a duration equal to that of the test before nor should they be started and stopped during the test.

7.1.3 *Testing of Control Well*—Conduct a short term preliminary test of the control well to estimate hydraulic properties of the aquifer, estimate the duration of the test and establish a pumping rate for the field procedure.

7.1.4 *Testing Observation Wells*—Test the observation wells or piezometers prior to the aquifer test to ensure that they are hydraulically connected to the aquifer. Accomplish this by adding or withdrawing a known volume of water (slug) and measure the water-level response in the well. The resultant response should be rapid enough to ensure that the water level in the piezometer will reflect the water level in the aquifer during the test. Redevelop piezometers with unusually sluggish response.

7.1.5 *Measuring Pre-Testing Water-Level Trends*—Measure water levels in all observation wells prior to start of pumping for a period long enough to establish the pre-pumping trend. This period is at least equal to the length of the test. The trend in all observation wells should be similar. A well with an unusual trend may reflect effects of local disturbances in the hydrologic system, or may be inadequately developed.

7.1.6 *Selecting of Pumping Rate*—Select the pumping rate, on the basis of the preliminary test (see 7.1.3), at which the well is to be pumped, such that, the rate can be sustained by the pump for the duration of the test. The rate should not be so large that the water level is drawn down below the perforations in the control well, causing cascading water and entrained air in the well. Under no circumstances should the rate be so large that the water level is drawn down to the water-entry section of the pump or tailpipe.

8. Procedure

8.1 *Withdrawing or Injecting Water from the Aquifer*—Regulate the rate at which water is withdrawn from, or injected into, the control well throughout the test. The short-term discharge should not vary more than 10 % about the mean discharge. For constant-discharge tests, long-term variation of discharge from the beginning to end of test generally should be less than 5 %.

8.2 Measure discharge frequently, for example every 5 min, and if necessary adjust discharge during the beginning of the test. When the discharge becomes more stable, reduce the frequency of adjustments and check discharge at least once every 2 h throughout the test. Variations in electric line load throughout the day will cause variations in discharge of pumps equipped with electric motors. Changes in air temperature and barometric pressure will likewise affect diesel motors. Late in a lengthy test, measure and adjust discharge much more frequently than the water levels are measured.

8.3 *Measuring Water Level; Frequency of Measurement*—Measure water levels in each observation well at approximately logarithmic intervals of time. Measure at least ten data points throughout each logarithmic interval. A typical measurement schedule is listed in Table 1.

8.4 *Duration of Pumping Phase of Test*—Make preliminary analysis of the aquifer-test data during the test using the appropriate test method (such as Test Methods D 4105 and D 4106). Continue the test until the analysis shows adequate test duration.

TABLE 1 Typical Measurement Frequency

Frequency, One Measurement Every:	Elapsed Time, For the First:
30 s	3 min
1 min	3 to 15 min
5 min	15 to 60 min
10 min	60 to 120 min
20 min	2 to 3 h
1 h	3 to 15 h
5 h	15 to 60 h

8.5 *Measuring Recovery of Water Levels*:

8.5.1 If the recovery data are to be analyzed completely as a part of the test and used to determine long-term background water-level changes, the recovery of water levels following pumping phase should be measured and recorded for a period of time equal to the pumping time. Analyze the recovery data to determine the hydraulic parameters of the system. The frequency of measuring water levels should be similar to the frequency during the pumping phase (see Table 1).

8.5.2 If water level data during the early part of the recovery phase are to be used from the control well, the pump should be equipped with a foot valve to prevent the column pipe fluid from flowing back into the well when the pump is turned off.

8.6 *Post-Testing Procedures*:

8.6.1 Tabulate water levels, including, pre-pumping water levels, for each well or piezometer, date, clock time, time since pumping started or stopped, and measurement point (Test Method D 4750).

8.6.2 Tabulate measurements of the rate of discharge or injection at the control well, date, clock time, time since pumping started, and method of measurement.

8.6.3 Prepare a written description of each well, describing the measuring point, giving its altitude and the method of obtaining the altitude, and the distance of the measuring point above the mean land surface.

8.6.4 Make plots of water-level changes and discharge measurements as follows:

8.6.4.1 Plot water levels in the control well and each observation well against the logarithm of time since pumping began. Plot the rate of discharge, Q, of the control well on arithmetic paper.

8.6.4.2 Prepare a plot of the log of drawdown, s, versus the log of the ratio of time since pumping began, t, to the square of the distance from the control well to the observation well, r, that is $\log_{10} s$ versus $\log_{10} t/r^2$, on a single graph and maintain the graph as the test progresses. Unexpected, rapid deviations of the data from the type curves may be caused by variations in discharge of the control well, or by other wells in the vicinity starting, stopping or changing discharge rates, or by other changes in field conditions. Such interfering effects may need to be measured, and adjustments made in the final data, or it may be necessary to abort the test.

8.6.4.3 *Plot Recovery of Water Levels*—Plot recovery data, consisting of plots of water level versus log of the ratio of time since pumping started (t) to the time since pumping stopped (t'). Prepare mass plots of log of recovery versus log of the quantity: ratio of time since pumping stopped (t') to the square of the distance from the control well to the observation well (r^2), that is $\log_{10} t$ versus $\log_{10} t'/r^2$.

9. Report

9.1 Prepare a report containing field data including a description of the field site, plots of water level and discharge with time, and preliminary analysis of data.

9.1.1 An introduction stating purpose of the test, dates and times water-level measurements were begun, dates and times discharge or injection was begun and ended, and the average rate of discharge or injection.

9.1.2 The "as built" description and diagrams of all control wells, observation wells, and piezometers.

9.1.3 A map of the site showing all well locations, the distances between wells, and location of all geologic boundaries or surface-water bodies which might effect the test.

9.1.3.1 The locations of wells and boundaries that would affect the aquifer tests need to be known with sufficient accuracy to provide a valid analysis. For most analyses, this means the locations must provide data points within plotting accuracy on the semilog or log-log graph paper used in the analysis. Radial distances from the control well to the observation wells usually need to be known within ±0.5 %. For prolonged, large-scale testing it may be sufficient to locate wells from maps or aerial photographs. However, for small-scale tests, the well locations should be surveyed. All faults, streams, and canals or other potential boundaries should be located. When test wells are deep relative to their spacing it may be necessary to conduct well-deviation surveys to determine the true horizontal distance between well screens in the aquifer.

9.1.4 Include tabulated field data collected during the test.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; discharging wells; drawdown; ground water; hydraulic conductivity; injection wells; recovery; storage coefficient; transmissivity

Designation: D 4104 – 96

Standard Test Method
(Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Tests)[1]

This standard is issued under the fixed designation D 4104; 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 the determination of transmissivity from the measurement of force-free (overdamped) response of a well-aquifer system to a sudden change of water level in a well. Force-free response of water level in a well to a sudden change in water level is characterized by recovery to initial water level in an approximate exponential manner with negligible inertial effects.

1.2 The analytical procedure in this test method is used in conjunction with the field procedure in Test Method D 4044 for collection of test data.

1.3 *Limitations*—Slug tests are considered to provide an estimate of transmissivity. Although the assumptions of this test method prescribe a fully penetrating well (a well open through the full thickness of the aquifer), the slug test method is commonly conducted using a partially penetrating well. Such a practice may be acceptable for application under conditions in which the aquifer is stratified and horizontal hydraulic conductivity is much greater than vertical hydraulic conductivity. In such a case the test would be considered to be representative of the average hydraulic conductivity of the portion of the aquifer adjacent to the open interval of the well.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining of Hydraulic Properties by Well Techniques[2]

D 4044 Test Method (Field Procedure) for Instantaneous Change in Head (Slug Test) for Determining Hydraulic Properties of Aquifers[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

D 5912 Test Method (Analytical Procedure) for Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response in Instantaneous Change in Head (Slug Test)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.1.4 *head, static*—the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

3.1.5 *hydraulic conductivity*—*(field aquifer tests)*, the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.6 *observation well*—a well open to all or part of an aquifer.

3.1.7 *overdamped-well response*—characterized by the water level returning to the static level in an approximately exponential manner following a sudden change in water level. (See for comparison *underdamped-well response*.)

3.1.8 *slug*—a volume of water or solid object used to induce a sudden change of head in a well.

3.1.9 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

3.1.10 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.11 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.12 *underdamped-well response*—response characterized by the water level oscillating about the static water level following a sudden change in water level. (See for comparison *overdamped-well response*.)

3.1.13 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:*

3.2.1 J_0 [nd]—zero-order Bessel function of the first kind.

3.2.2 J_1 [nd]—first-order Bessel function of the first kind.

3.2.3 K [LT^{-1}]—hydraulic conductivity.

3.2.4 T [L^2T^{-1}]—transmissivity.

3.2.5 S [nd]—storage coefficient.

3.2.6 Y_0 [nd]—zero order Bessel function of the second kind.

3.2.7 Y_1 [nd]—first order Bessel function of the second kind.

3.2.8 r_c [*L]*—radius of control-well casing or open hole in interval where water level changes.

3.2.9 r_w [L]—radius of control well screen or open hole adjacent to water bearing unit.

3.2.10 u—variable of integration.

3.2.11 H *[L]*—change in head in control well.

3.2.12 H_o *[L]*—initial head rise (or decline) in control well.

3.2.13 t—time.

3.2.14 β—Tt/r_c^2.

3.2.15 α—r_w^2S/r_c^2.

4. Summary of Test Method

4.1 This test method describes the analytical procedure for analyzing data collected during an instantaneous head (slug) test using an overdamped well. The field procedures in conducting a slug test are given in Test Method D 4044. The analytical procedure consists of analyzing the recovery of water level in the well following the change in water level induced in the well.

4.2 *Solution*—The solution given by Cooper et al **(1)**[4] is as follows:

$$H = \frac{2H_o}{\pi}\int_0^\infty [[\exp(-\beta u^2/\alpha)[J_0(ur/r_w) \quad (1)$$

$$[uY_0(u) - 2\alpha Y_1(u)] - Y_0(ur/r_w)$$

$$[uJ_0(u) - 2\alpha J_1(u)]]/\Delta(u)]]du$$

where:

$$\alpha = r_w{}^2S/r_c{}^2,$$

$$\beta = Tt/r_c{}^2,$$

and:

$$\Delta(u) = [uJ_0(u) - 2\alpha J_1(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2$$

NOTE 1—See D 5912 and Hvorslev **(2)** Bouwer and Rice **(3)**, and Bouwer **(4)**.

5. Significance and Use

5.1 *Assumptions of Solution of Cooper et al* **(1)**:

5.1.1 The head change in the control well is instantaneous at time $t = 0$.

5.1.2 Well is of finite diameter and fully penetrates the aquifer.

5.1.3 Flow in the nonleaky aquifer is radial.

5.2 *Implications of Assumptions*:

5.2.1 The mathematical equations applied ignore inertial effects and assume the water level returns the static level in an approximate exponential manner. The geometric configuration of the well and aquifer are shown in Fig. 1.

5.2.2 Assumptions are applicable to artesian or confined conditions and fully penetrating wells. However, this test method is commonly applied to partially penetrating wells and in unconfined aquifers where it may provide estimates of hydraulic conductivity for the aquifer interval adjacent to the open interval of the well if the horizontal hydraulic conductivity is significantly greater than the vertical hydraulic conductivity.

5.2.3 As pointed out by Cooper et al **(1)** the determination of storage coefficient by this test method has questionable reliability because of the similar shape of the curves, whereas, the determination of transmissivity is not as sensitive to choosing the correct curve. However, the curve selected should not imply a storage coefficient unrealistically large or small.

6. Procedure

6.1 The overall procedure consists of conducting the slug test field procedure (see Test Method D 4044) and analysis of the field data, that is addressed in this test method.

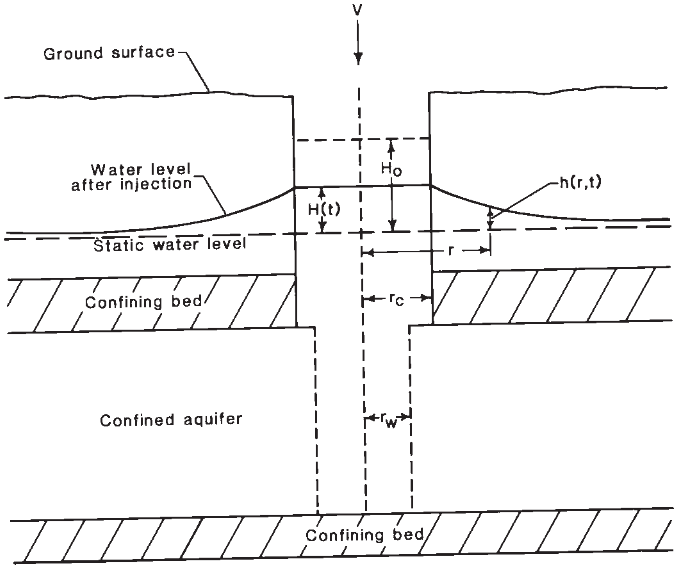

FIG. 1 Cross Section Through a Well in Which a Slug of Water is Suddenly Injected

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

6.2 The integral expression in the solution given in (Eq 1) cannot be evaluated analytically. A graphical solution for determination of transmissivity and coefficient of storage can be made using a set of type curves that can be drawn from the values in Table 1.

7. Calculation

7.1 Prepare a semilogarithmic plot of a set of type curves of values of $F(\beta, \alpha) = H/H_o$, on the arithmetic scale, as a function of β, on the logarithmic scale from the values of the functions in Table 1.

TABLE 1 Values of H/H_o

From Cooper, Bredehoeft, and Papadopulos **(1)**

$\beta = Tt/r_c^2$	α	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
10^{-3}	1.00	0.9771	0.9920	0.9969	0.9985	0.9992
	2.15	0.9658	0.9876	0.9949	0.9974	0.9985
	4.64	0.9490	0.9807	0.9914	0.9954	0.9970
10^{-2}	1.00	0.9238	0.9693	0.9853	0.9915	0.9942
	2.15	0.8860	0.9505	0.9744	0.9841	0.9883
	4.64	0.8293	0.9187	0.9545	0.9701	0.9781
10^{-1}	1.00	0.7460	0.8655	0.9183	0.9434	0.9572
	2.15	0.6289	0.7782	0.8538	0.8935	0.9167
	4.64	0.4782	0.6436	0.7436	0.8031	0.8410
10^{0}	1.00	0.3117	0.4598	0.5729	0.6520	0.7080
	2.15	0.1665	0.2597	0.3543	0.4364	0.5038
	4.64	0.07415	0.1086	0.1554	0.2082	0.2620
	7.00	0.04625	0.06204	0.08519	0.1161	0.1521
10^{1}	1.00	0.03065	0.03780	0.04821	0.06355	0.08378
	1.40	0.02092	0.02414	0.02844	0.03492	0.04426
	2.15	0.01297	0.01414	0.01545	0.01723	0.01999
	3.00	0.009070	0.009615	0.01016	0.01083	0.01169
	4.64	0.005711	0.004919	0.006111	0.006319	0.006554
	7.00	0.003722	0.003809	0.003884	0.003962	0.004046
10^{2}	1.00	0.002577	0.002618	0.002653	0.002688	0.002725
	2.15	0.001179	0.001187	0.001194	0.001201	0.001208

From Papadopulos, Bredehoeft, and Cooper **(5)**

$\beta = Tt/r_c^2$	α	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}
10^{-3}	1	0.9994	0.9996	0.9996	0.9997	0.9997
	2	0.9989	0.9992	0.9993	0.9994	0.9995
	4	0.9980	0.9985	0.9987	0.9989	0.9991
	6	0.9972	0.9978	0.9982	0.9984	0.9986
	8	0.9964	0.9971	0.9976	0.9980	0.9982
10^{-2}	1	0.9956	0.9965	0.9971	0.9975	0.9978
	2	0.9919	0.9934	0.9944	0.9952	0.9958
	4	0.9848	0.9875	0.9894	0.9908	0.9919
	6	0.9782	0.9819	0.9846	0.9866	0.9881
	8	0.9718	0.9765	0.9799	0.9824	0.9844
10^{-1}	1	0.9655	0.9712	0.9753	0.9784	0.9807
	2	0.9361	0.9459	0.9532	0.9587	0.9631
	4	0.8828	0.8995	0.9122	0.9220	0.9298
	6	0.8345	0.8569	0.8741	0.8875	0.8984
	8	0.7901	0.8173	0.8383	0.8550	0.8686
10^{0}	1	0.7489	0.7801	0.8045	0.8240	0.8401
	2	0.5800	0.6235	0.6591	0.6889	0.7139
	3	0.4554	0.5033	0.5442	0.5792	0.6096
	4	0.3613	0.4093	0.4517	0.4891	0.5222
	5	0.2893	0.3351	0.3768	0.4146	0.4487
	6	0.2337	0.2759	0.3157	0.3525	0.3865
	7	0.1903	0.2285	0.2655	0.3007	0.3337
	8	0.1562	0.1903	0.2243	0.2573	0.2888
	9	0.1292	0.1594	0.1902	0.2208	0.2505
10^{1}	1	0.1078	0.1343	0.1620	0.1900	0.2178
	2	0.02720	0.03343	0.04129	0.05071	0.06149
	3	0.01286	0.01448	0.01667	0.01956	0.02320
	4	0.008337	0.008898	0.009637	0.01062	0.01190
	5	0.006209	0.006470	0.006789	0.007192	0.007709
	6	0.004961	0.005111	0.005283	0.005487	0.005735
	8	0.003547	0.003617	0.003691	0.003773	0.003863
10^{2}	1	0.002763	0.002803	0.002845	0.002890	0.002938
	2	0.001313	0.001322	0.001330	0.001339	0.001348

7.2 Prepare a semilogarithmic plot of the same scale as that of the type-curve. Plot the water level data in the control well, expressed as a fraction, H/H_o, on the arithmetic scale, versus time, t, on the logarithmic scale.

NOTE 2—If the water level rise is very rapid with a small disparity between the calculated and measured change in water level, then time = 0 can be used as the instant the change was initiated and H_o can be the calculated rise. If there is a significant time lag between initiation of the head change and the peak rise or decline is significantly less than the calculated change use $t = 0$ as the time of maximum observed change and take H_o as the maximum observed change.

7.3 Overlay the data plot on the set of type curve plots and, with the arithmetic axes coincident, shift the data plot to match one curve or an interpolated curve of the type curve set. A match point for beta, t, and alpha picked from the two graphs.

7.4 Using the coordinates of the match line, determine the transmissivity and storage coefficient from the following equations:

$$T = \beta r_c^2/t$$

and:

$$S = \alpha r_c^2/r_w^2$$

8. Report

8.1 Prepare a report including the information described in this section. The final report of the analytical procedure will include information from the report on test method selection (see Guide D 4043) and the field testing procedure (see Test Method D 4044).

8.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the slug test method for determining transmissivity and storage coefficient. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well, and the method of measurement and of effecting a change in head. Discuss the rationale for selecting the method used (see Guide D 4043).

8.1.2 *Hydrogeologic Setting*—Review information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the method selected for conducting and analyzing an aquifer test. Compare hydrogeologic characteristics of the site as it conforms and differs from assumptions made in the solution to the aquifer test method.

8.1.3 *Equipment*—Report the field installation and equipment for the aquifer test. Include in the report, well construction information, diameter, depth, and open interval to the aquifer, and location of control well.

8.1.3.1 Report the techniques used for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturers name, model number, and basic specifications for each major item, and the name and date of the last calibration, if applicable.

8.1.4 *Testing Procedures*—Report the steps taken in conducting the pretest and test phases. Include the frequency of head measurements made in the control well, and other environmental data recorded before and during the testing procedure.

8.1.5 *Presentation and Interpretation of Test Results*:

8.1.5.1 *Data*—Present tables of data collected during the test.

8.1.5.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

8.1.5.3 Show calculation of transmissivity and storage coefficient.

8.1.5.4 Evaluate the overall quality of the test on the basis of the adequacy of instrumentation and observations of stress and response and the conformance of the hydrogeologic conditions and the performance of the test to the assumptions (see 5.1).

9. Precision and Bias

9.1 It is not practical to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

10. Keywords

10.1 aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient storativity; transmissivity

REFERENCES

(**1**) Cooper, H. H., Jr., Bredehoeft, J. D., and Papadopulos, I. S., "Response of a Finite-Diameter Well to an Instantaneous Charge of Water," *Water Resources Research*, Vol 3, No. 1, 1967, pp. 263–269.

(**2**) Hvorslev, M. J., "Time Lag and Soil Permeability in Ground-Water Observations," Waterways Experiment Station, Corps of Engineers, U.S. Army, Bulletin No. 36, 1951, p. 50.

(**3**) Bouwer, H., and Rice, R. C., "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells," *Water Resources Research*, Vol 12, No. 3, 1976, pp. 423–423.

(**4**) Bouwer, H., "The Bouwer-Rice Slug Test—An Update," *Ground Water*, Vol 27, No. 3, 1989, pp. 304–309.

(**5**) Papadopulos, I. S., Bredehoeft, J. D., and Cooper, H. H., Jr.," On the Analysis of Slug Test Data," *Water Resources Research*, Vol 9, No. 4, 1973, pp. 1087–1089.

Designation: D 4105 – 96 (Reapproved 2002)

Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[1]

This standard is issued under the fixed designation D 4105; 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 transmissivity and storage coefficient of a nonleaky confined aquifer under conditions of radial flow to a fully penetrating well of constant flux. This test method is a shortcut procedure used to apply the Theis nonequilibrium method. The Theis method is described in Test Method D 4106.

1.2 This test method is used in conjunction with the field procedure given in Test Method D 4050.

1.3 *Limitations*—The limitations of this test method are primarily related to the correspondence between the field situation and the simplifying assumptions of this test method (see 5.1). Furthermore, application is valid only for values of u less than 0.01 (u is defined in Eq 2, in 8.6).

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *aquifer, unconfined*—an aquifer that has a water table.

3.1.3 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.4 *control well*—well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.1.5 *drawdown*—vertical distance the static head is lowered due to the removal of water.

3.1.6 *hydraulic conductivity—(field aquifer tests)*, the volume of water at the existing kinematic viscosity that will move in a unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.7 *observation well*—a well open to all or part of an aquifer.

3.1.8 *piezometer*—use to measure static head at a point in the subsurface.

3.1.9 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.10 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, it is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.11 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.12 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 K [LT^{-1}]—hydraulic conductivity.

3.2.2 K_{xy}—hydraulic conductivity in the horizontal direction.

3.2.3 K_z—hydraulic conductivity in the vertical direction.

3.2.4 T [L^2T^{-1}]—transmissivity.

3.2.5 S [nd]—storage coefficient.

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.6 *Ss* [L^{-1}]—specific storage.
3.2.7 *s* [L]—drawdown.
3.2.8 *Q* [L^3T^{-1}]—discharge.
3.2.9 *r* [L]—radial distance from control well.
3.2.10 *t* [T]—time.
3.2.11 *b* [L]—thickness of the aquifer.

4. Summary of Test Method

4.1 This test method describes an analytical procedure for analyzing data collected during a withdrawal or injection well test. The field procedure (see Test Method D 4050) involves pumping a control well at a constant rate and measuring the water level response in one or more observation wells or piezometers. The water-level response in the aquifer is a function of the transmissivity and coefficient of storage of the aquifer. Alternatively, the test can be performed by injecting water at a constant rate into the aquifer through the control well. Analysis of buildup of water level in response to injection is similar to analysis of drawdown of water level in response to withdrawal in a confined aquifer. Drawdown of water level is analyzed by plotting drawdown against factors incorporating either time or distance from the control well, or both, and matching the drawdown response with a straight line.

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

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy \qquad (1)$$

where:

$$u = \frac{r^2 S}{4Tt} \qquad (2)$$

and:

$$\int_u^\infty \frac{e^{-y}}{y}\,dy = W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2!2} + \frac{u^3}{3!3} - \frac{u^4}{4!4} + \ ... \qquad (3)$$

4.3 The sum of the terms to the right of $\log_e u$ in the series of Eq 3 is not significant when *u* becomes small.

NOTE 1—The errors for small values of *u*, from Kruseman and DeRidder **(1)** are as follows:

Error less than, %:	1	2	5	10
For *u* smaller than:	0.03	0.05	0.1	0.15

The value of *u* decreases with increasing time, *t*, and decreases as the radial distance, *r*, decreases. Therefore, for large values of *t* and reasonably small values of *r*, the terms to the right of $\log_e u$ in Eq 3 may be neglected as recognized by Theis **(2)** and Jacob **(3)**. The Theis equation can then be written as follows:

$$s = \frac{Q}{4\pi T}\left[-0.577216 - \ln\left(r^2\frac{S}{4Tt}\right)\right] \qquad (4)$$

from which it has been shown by Lohman **(4)** that

$$T = \frac{2.3Q}{4\pi\Delta s/\Delta\log_{10} t} \qquad (5)$$

and:

$$T = -\frac{2.3Q}{2\pi\Delta s/\Delta\log_{10} r} \qquad (6)$$

where:
$\Delta s/\Delta\log_{10} t$ = the drawdown (measured or projected) over one log cycle of time, and
$\Delta s/\Delta\log_{10} r$ = the drawdown (measured or projected) over one log cycle of radial distance from the control well.

5. Significance and Use

5.1 *Assumptions*:

5.1.1 Well discharges at a constant rate, *Q*.

5.1.2 Well is of infinitesimal diameter and fully penetrates the aquifer, that is, the well is open to the full thickness of the aquifer.

5.1.3 The nonleaky aquifer is homogeneous, isotropic, and areally extensive. A nonleaky aquifer receives insignificant contribution of water from confining beds.

5.1.4 Discharge from the well is derived exclusively from storage in the aquifer.

5.1.5 The geometry of the assumed aquifer and well conditions are shown in Fig. 1.

5.2 *Implications of Assumptions*:

5.2.1 Implicit in the assumptions are the conditions of radial flow. Vertical flow components are induced by a control well that partially penetrates the aquifer, that is, not open to the aquifer through its full thickness. If the control well does not fully penetrate the aquifer, the nearest piezometer or partially penetrating observation well should be located at a distance, *r*, beyond which vertical flow components are negligible, where according to Reed **(5)**

$$r = \frac{1.5b}{\sqrt{\dfrac{K_z}{K_{xy}}}} \qquad (7)$$

This section applies to distance-drawdown calculations of transmissivity and storage coefficient and time-drawdown calculations of storage coefficient. If possible, compute transmissivity from time-drawdown data from wells located within a distance, *r*, of the pumped well using data measured after the effects of partial penetration have become constant. The time at which this occurs is given by Hantush **(6)** by:

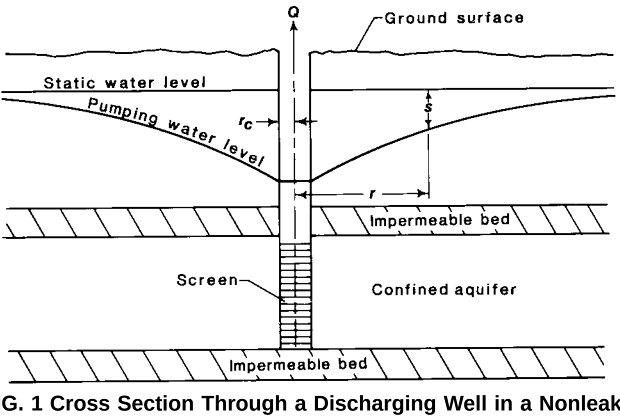

FIG. 1 Cross Section Through a Discharging Well in a Nonleaky Confined Aquifer

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

$$t = b^2 s/2T\,(K_z/K_r) \tag{8}$$

Fully penetrating observation wells may be placed at less than distance r from the control well. Observation wells may be on the same or on various radial lines from the control well.

5.2.2 The Theis method assumes the control well is of infinitesimal diameter. Also, it assumes that the water level in the control well is the same as in the aquifer contiguous to the well. In practice these assumptions may cause a difference between the theoretical drawdown and field measurements of drawdown in the early part of the test and in and near the control well. Control well storage is negligible after a time, t, given by the following equation after weeks **(7)**.

$$t = \frac{25\, r_c^{\,2}}{T} \tag{9}$$

where:

r_c = the radius of the control well in the interval that includes the water level changes.

5.2.3 *Application of Theis Nonequilibrium Method to Unconfined Aquifers*:

5.2.3.1 Although the assumptions are applicable to confined conditions, the Theis solution may be applied to unconfined aquifers if drawdown is small compared with the saturated thickness of the aquifer or if the drawdown is corrected for reduction in thickness of the aquifer and the effects of delayed gravity yield are small.

5.2.3.2 *Reduction in Aquifer Thickness*—In an unconfined aquifer, dewatering occurs when the water levels decline in the vicinity of a pumping well. Corrections in drawdown need to be made when the drawdown is a significant fraction of the aquifer thickness as shown by Jacob **(8)**. The drawdown, s, needs to be replaced by s', the drawdown that would occur in an equivalent confined aquifer, where:

$$s' = s - \frac{s^2}{2b} \tag{10}$$

5.2.3.3 *Gravity Yield Effects*—In unconfined aquifers, delayed gravity yield effects may invalidate measurements of drawdown during the early part of the test for application to the Theis method. Effects of delayed gravity yield are negligible in partially penetrating observation wells at a distance, r, from the control well, where:

$$r = \frac{b}{\sqrt{\dfrac{K_z}{K_{xy}}}} \tag{11}$$

after the time, t, as given in the following equation from Neuman **(9)**:

$$t = 10 S_y \frac{r^2}{T} \tag{12}$$

where:

S_y = the specific yield.

For fully penetrating observation wells, the effects of delayed yield are negligible at the distance, r, in Eq 11 after one tenth of the time given in the Eq 12.

6. Apparatus

6.1 Analysis of data from the field procedure (see Test Method D 4050) by this test method requires that the control well and observation wells meet the requirements specified in 6.2-6.4.

6.2 *Control Well*—Screen 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. Preferably, screen the control well throughout the full thickness of the aquifer. If the control well partially penetrates the aquifer, take special precaution in the placement or design of observation wells (see 5.2.1).

6.3 *Construction of Observation Wells*—Construct one or more observation wells or piezometers at a distance from the control well. Observation wells may be partially open or fully open throughout the thickness of the aquifer.

6.4 *Location of Observation Wells*—Locate observation wells at various distances from the control well within the area of influence of pumping. However, if vertical flow components are significant and if partially penetrating observation wells are used, locate them at a distance beyond the effect of vertical flow components (see 5.2.1). If the aquifer is unconfined, constraints are imposed on the distance to partially penetrating observation wells and the validity of early time measurements (see 5.2.3).

7. Procedure

7.1 The overall procedure consists of conducting the field procedure for withdrawal or injection well tests described in Test Method D 4050 and analysis of the field data as addressed in this test method.

7.2 Use a graphical procedure to solve for transmissivity and coefficient of storage as described in 8.2.

8. Calculation

8.1 Plot drawdown, s, at a specified distance on the arithmetic scale and time, t, on the logarithmic scale.

8.2 Plot drawdown, s, for several observation wells at a specified time on the arithmetic scale and distance on the logarithmic scale.

8.3 For convenience in calculations, by choosing drawdown, $\Delta\, s_t$, as that which occurs over one log cycle of time:

$$\Delta \log_{10} t = \log_{10}\left(\frac{t_2}{t_1}\right) = 1 \tag{13}$$

and, similarly for convenience in calculations, by choosing the drawdown, Δs_r, as that which occurs over one log cycle of distance,

$$\Delta \log_{10} r = \log_{10}\left(\frac{r_2}{r_1}\right) = 1 \tag{14}$$

8.4 Calculate transmissivity using the semilog plot of drawdown versus time by the following equation derived from Eq 5:

$$t = 2.3Q/2\pi\Delta s_r \tag{15}$$

or calculate transmissivity using the semilog plot of drawdown versus radial distance from control well by the following equation derived from Eq 6:

$$T = -\frac{2.3Q}{2\pi\Delta s_r} \tag{16}$$

8.5 Determine the coefficient of storage from these semilog plots of drawdown versus time or distance by a method proposed by Jacob **(2)** where:

$$s = \frac{2.3Q}{4\pi T} \log_{10} \left(\frac{2.25Tt}{r^2 S} \right) \tag{17}$$

Taking $s = 0$ at the zero-drawdown intercept of the straight-line semilog plot of time or distance versus drawdown,

$$S = \frac{2.25Tt}{r^2} \tag{18}$$

where:

either r or t = the value at the zero-drawdown intercept.

8.6 To apply the modified Theis nonequilibrium method to thin unconfined aquifers, where the drawdown is a significant fraction of the initial saturated thickness, apply a correction to the drawdown in solving for T and S (see 5.2.3.2).

8.7 This test method is applicable only for values of $u <$ 0.01, that is:

$$u = \frac{r^2 S}{4Tt} < 0.01 \tag{19}$$

It is seen from Eq 13 that u decreases as time increases, other things being equal. Because S is in the numerator, the value of u is much smaller for a confined aquifer, whose storage coefficient may range from only about 10^{-5} to 10^{-3}, than for an unconfined aquifer, whose specific yield may be from 0.1 to 0.3. To compensate for this, t must be greater by several orders of magnitude in testing an unconfined aquifer than testing a confined aquifer.

8.7.1 In a drawdown-time test (s versus $\log_{10}t$ or $\log_{10}t/r^2$), data points for any particular distance will begin to fall on a straight line only after the time is sufficiently long to satisfy the above criteria. In a drawdown-distance test (s versus $\log_{10}r$), the well must be pumped long enough that the data for the most distant observation well satisfy the requirements; then only the drawdowns at or after this value of t may be analyzed on a semilogarithmic plot for one particular value of t.

NOTE 2—The analyst may also find it useful to analyze the data using the Theis nonequilibrium procedure (see Test Method D 4106).

9. Report

9.1 Report the information described below. The report of the analytical procedure will include information from the report on test method selection (see Guide D 4043) and the field testing procedure (see Test Method D 4050).

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the recovery method for determining transmissivity and storativity in a nonleaky confined aquifer. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells and piezometers, the method of measurement of discharge and water levels, and the duration of the test and pumping rate. Discuss rationale for selecting the modified Theis method.

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the selection of this method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened interval, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells.

9.1.4 Describe the methods of observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturers name, model number, and basic specifications for each major item, and the name and date and method of the last calibration, if applicable.

9.1.5 *Testing Procedures*—State the steps taken in conducting pre-test, drawdown, and recovery phases of the test. Include the date, clock time, and time since pumping started or stopped for measurements of discharge rate, water levels, and other environmental data recorded during the testing procedure.

9.1.6 *Presentation and Interpretation of Test Results*:

9.1.6.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for barometric changes and calculation of drawdown and residual drawdown.

9.1.6.2 *Data Plots*—Present data plots used in analysis of the data.

9.1.6.3 Evaluate qualitatively the determinations of transmissivity and coefficient of storage on the basis of the adequacy of instrumentation, observations of stress and response, and the conformance of the hydrogeologic conditions, and the performance of the test to the assumptions of the method.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; confined aquifers; control wells; ground water; hydraulic properties; observation wells; storage coefficient; transmissivity; unconfined aquifers

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(**1**) Kruseman, G. P., and DeRidder, N. A.,“ Analysis and Evaluation of Pumping Test Data,” *ILRI Publication 47*, 1990, p. 377.

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(**7**) Papadopulos, S. S., and Cooper, H. H., Jr., “Drawdown in a Well of Large Diameter,” *Water Resources Research*, Vol 1, 1967, pp. 241–244.

(**8**) Jacob, C. E., “Determining Permeability of Water-Table Aquifers,” in Bentall, Ray, compiler, *Methods of Determining Permeability, Transmissibility, and Drawdown*, U.S. Geological Survey Water-Supply Paper 1536-I, 1963, pp. 272–292.

(**9**) Neuman, S. P., “Effect of Partial Penetration on Flow in Unconfined Aquifers Considering Delayed Gravity Response,” *Water Resources Research*, Vol 10, No. 2, 1974, pp. 303–312.

Designation: D 4106 – 96 (Reapproved 2002)

Standard Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[1]

1. Scope

1.1 This test method covers an analytical procedure for determining the transmissivity and storage coefficient of a nonleaky confined aquifer. It is used to analyze data on water-level response collected during radial flow to or from a well of constant discharge or injection.

1.2 This analytical procedure is used in conjunction with the field procedure given in Test Method D 4050.

1.3 *Limitations*—The limitations of this test method for determination of hydraulic properties of aquifers are primarily related to the correspondence between the field situation and the simplifying assumptions of this test method (see 5.1).

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer Test Method in Determining of Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the head and flow in the aquifer is changed, for example, by pumping, injection, or imposing a constant change of head.

3.1.4 *drawdown*—vertical distance the static head is lowered due to the removal of water.

3.1.5 *head*—see *head, static*.

3.1.6 *head, static*—the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

3.1.7 *hydraulic conductivity (field aquifer tests)*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.8 *observation well*—a well open to all or part of an aquifer.

3.1.9 *piezometer*—a device so constructed and sealed as to measure hydraulic head at a point in the subsurface.

3.1.10 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.11 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.12 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.13 *unconfined aquifer*—an aquifer that has a water table.

3.1.14 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 K [LT^{-1}]—hydraulic conductivity.

3.2.2 K_{xy}—hydraulic conductivity in the horizontal plane, radially from the control well.

3.2.3 K_z—hydraulic conductivity in the vertical direction.

3.2.4 Q [L^3T^{-1}]—discharge.

3.2.5 S [nd]—storage coefficient.

3.2.6 S_s[L^{-1}]—specific storage.

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

Current edition approved Oct. 10, 1996. Published June 1997. Originally published as D 4106 – 91.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.7 T [L^2T^{-1}]—transmissivity.

3.2.8 $W(u)$ [nd]—well function of u.

3.2.9 b [L]—thickness of aquifer.

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

3.2.11 s [L]—drawdown.

4. Summary of Test Method

4.1 This test method describes an analytical procedure for analyzing data collected during a withdrawal or injection well test. The field procedure (see Test Method D 4050) involves pumping a control well at a constant rate and measuring the water level response in one or more observation wells or piezometers. The water-level response in the aquifer is a function of the transmissivity and storage coefficient of the aquifer. Alternatively, this test method can be performed by injecting water at a constant rate into the aquifer through the control well. Analysis of buildup of water level in response to injection is similar to analysis of drawdown of water level in response to withdrawal in a confined aquifer. Drawdown of water level is analyzed by plotting drawdown against factors incorporating either time or distance from the control well, or both, and matching the drawdown response with a type curve.

4.2 *Solution*—The solution given by Theis **(1)**[3] may be expressed as follows:

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy \tag{1}$$

where:

$$u = \frac{r^2S}{4Tt} \tag{2}$$

$$\int_u^\infty \frac{e^{-y}}{y}\,dy = W(u)$$

$$= -0.577216 - \log_e u + u - \frac{u^2}{2!2} + \frac{u^3}{3!3} - \frac{u^4}{4!4} + \ldots \tag{3}$$

5. Significance and Use

5.1 *Assumptions*:

5.1.1 Well discharges at a constant rate, Q.

5.1.2 Well is of infinitesimal diameter and fully penetrates the aquifer.

5.1.3 The nonleaky aquifer is homogeneous, isotropic, and aerially extensive. A nonleaky aquifer receives insignificant contribution of water from confining beds.

5.1.4 Discharge from the well is derived exclusively from storage in the aquifer.

5.1.5 The geometry of the assumed aquifer and well conditions are shown in Fig. 1.

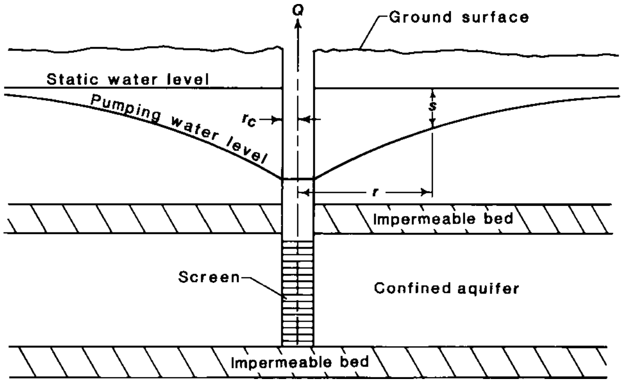

FIG. 1 Cross Section Through a Discharging Well in a Nonleaky Confined Aquifer

5.2 *Implications of Assumptions*:

5.2.1 Implicit in the assumptions are the conditions of radial flow. Vertical flow components are induced by a control well that partially penetrates the aquifer, that is, the well is not open to the aquifer through its full thickness. If the control well does not fully penetrate the aquifer, the nearest piezometer or partially penetrating observation well should be located at a distance, r, beyond which vertical flow components are negligible, where according to Reed **(2)**:

$$r = 1.5\frac{b}{\sqrt{\frac{K_z}{K_{xy}}}} \tag{4}$$

This section applies to distance-drawdown calculations of transmissivity and storage coefficient and time-drawdown calculations of storage coefficient. If possible, compute transmissivity from time-drawdown data from wells located within a distance, r, of the pumped well using data measured after the effects of partial penetration have become constant. The time at which this occurs is given by Hantush **(3)** by:

$$t = b^2s/2T\,(K_z/K_r) \tag{5}$$

Fully penetrating observation wells may be placed at less than distance r from the control well. Observation wells may be on the same or on various radial lines from the control well.

5.2.2 The Theis method assumes the control well is of infinitesimal diameter. Also, it assumes that the water level in the control well is the same as in the aquifer contiguous to the well. In practice these assumptions may cause a difference between the theoretical drawdown and field measurements of drawdown in the early part of the test and in and near the control well. Control well storage is negligible after a time, t, given by the Eq 6 after Weeks **(4)**.

$$t = 25 \times \frac{r_c^2}{T} \tag{6}$$

where:

r_c = the radius of the control well in the interval in which the water level changes.

5.2.3 *Application of Theis Method to Unconfined Aquifers*:

5.2.3.1 Although the assumptions are applicable to artesian or confined conditions, the Theis solution may be applied to unconfined aquifers if drawdown is small compared with the saturated thickness of the aquifer or if the drawdown is corrected for reduction in thickness of the aquifer, and the effects of delayed gravity yield are small.

5.2.3.2 *Reduction in Aquifer Thickness*—In an unconfined aquifer dewatering occurs when the water levels decline in the vicinity of a pumping well. Corrections in drawdown need to be made when the drawdown is a significant fraction of the

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

aquifer thickness as shown by Jacob **(5)**. The drawdown, s, needs to be replaced by s', the drawdown that would occur in an equivalent confined aquifer, where:

$$s' = s - \left(\frac{s^2}{2b}\right) \quad (7)$$

5.2.3.3 *Gravity Yield Effects*—In unconfined aquifers, delayed gravity yield effects may invalidate measurements of drawdown during the early part of the test for application to the Theis method. Effects of delayed gravity yield are negligible in partially penetrating observation wells at and beyond a distance, r, from the control well, where:

$$r = \frac{b}{\sqrt{\frac{K_z}{K_{xy}}}} \quad (8)$$

After the time, t, as given in Eq 9 from Neuman **(6)**.

$$t = 10 \times S_y (r^2/T) \quad (9)$$

where:

S_y = the specific yield. For fully penetrating observation wells, the effects of delayed yield are negligible at the distance, r, in Eq 8 after one tenth of the time given in the Eq 9.

6. Apparatus

6.1 Analysis of data from the field procedure (see Test Method D 4050) by the method specified in this test method requires that the control well and observation wells meet the specifications in the following paragraphs.

6.2 *Construction of Control Well*—Screen the control well in the aquifer to be tested and equip with a pump capable of discharging water from the well at a constant rate for the duration of the test. Preferably, screen the control well throughout the full thickness of the aquifer. If the control well partially penetrates the aquifer, take special precaution in the placement and design of observation wells (see 5.2.1).

6.3 *Construction of Observation Wells*—Construct one or more observation wells at a distance from the control well. Observation wells may be partially open or open throughout the thickness of the aquifer.

6.4 *Location of Observation Wells*—Locate observation wells at various distances from the control well within the area of influence of pumping. However, if vertical flow components are significant and if partially penetrating observation wells are used, locate them at a distance beyond the effect of vertical flow components (see 5.2.1). If the aquifer is unconfined, constraints are imposed on the distance to partially penetrating observation wells and the validity of early time measurements (see 5.2.3).

7. Procedure

7.1 The overall procedure consists of conducting the field procedure for withdrawal or injection well tests (described in Test Method D 4050) and analysis of the field data that is addressed in this test method.

7.2 The integral expression in Eq 1 and Eq 2 can not be evaluated analytically. A graphical procedure is used to solve for the two unknown parameters transmissivity and storage coefficient where:

$$s = \frac{Q}{4\pi T} \mathrm{W(u)} \quad (10)$$

and:

$$u = \frac{r^2 S}{4Tt} \quad (11)$$

8. Calculation

8.1 The graphical procedure used to calculate test results is based on the functional relations between $W(u)$ and s and between u and t or t/r^2.

8.1.1 Plot values of $W(u)$ versus $1/u$ on logarithmic-scale paper (see Table 1). This plot is referred to as the type curve plot.

8.1.2 On logarithmic tracing paper of the same scale and size as the $W(u)$ versus $1/u$ type curve, plot values of drawdown, s, on the vertical coordinate versus either time on the horizontal coordinate if one observation well is used or versus t/r^2 on the horizontal coordinate if more than one observation well is used.

8.1.3 Overlay the data plot on the type curve plot and, while the coordinate axes of the two plots are held parallel, shift the plot to align with the type curve (see Fig. 2).

8.1.4 Select and record the values of $W(u)$, $1/u$, s, and t at an arbitrary point, referred to as the match point (see Fig. 2), anywhere on the overlapping part of the plots. For convenience the point may be selected where $W(u)$ and $1/u$ are integer values.

NOTE 1—Alternatively, the type curve can be constructed by plotting $W(u)$ against u, then plotting the data as s versus r^2/t.

8.1.5 Using the coordinates of the point, determine the transmissivity and storage coefficient from Eq 12 and Eq 13:

$$T = \frac{QW(u)}{4\pi s} \quad (12)$$

$$S = 4Tu \frac{t}{r^2} \quad (13)$$

8.1.6 To apply the Theis nonequilibrium method to thin unconfined aquifers where the drawdown is a significant fraction of the initial saturated thickness, apply a correction to the drawdown in solving for transmissivity and coefficient of storage (see 5.2.3.2).

9. Report

9.1 Prepare a report including the information described in this section. The report of the analytical procedure will include information from the report on test method selection (see Guide D 4043) and the field testing procedure (see Test Method D 4050).

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the constant discharge method for determining transmissivity and storativity in a confined nonleaky aquifer under constant flux. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells or piezometers, or both, the method of measurement of discharge and water levels, and the duration of the test and pumping rate. Discuss rationale for selecting the Theis nonequilibrium method.

TABLE 1 Values of Theis Equation *W*(*u*) for values of 1/*u*, From Reed (2)

1/*u*	1/*u* × 10^{-1}	1	10	10^2	10^3	10^4	10^5	10^6
1.0	0.00000[A]	0.21938	1.82292	4.03793	6.33154	8.63322	10.93572	13.23830
1.2	0.00003	0.29255	1.98932	4.21859	6.51369	8.81553	11.11804	13.42062
1.5	0.00017	0.39841	2.19641	4.44007	6.73667	9.03866	11.34118	13.64376
2.0	0.00115	0.55977	2.46790	4.72610	7.02419	9.32632	11.62886	13.93144
2.5	0.00378	0.70238	2.68126	4.94824	7.24723	9.54945	11.85201	14.15459
3.0	0.00857	0.82889	2.85704	5.12990	7.42949	9.73177	12.03433	14.33691
3.5	0.01566	0.94208	3.00650	5.28357	7.58359	9.88592	12.18847	14.49106
4.0	0.02491	1.04428	3.13651	5.41675	7.71708	10.01944	12.32201	14.62459
5.0	0.04890	1.22265	3.35471	5.63939	7.94018	10.24258	12.54515	14.84773
6.0	0.07833	1.37451	3.53372	5.82138	8.12247	10.42490	12.72747	15.03006
7.0	0.11131	1.50661	3.68551	5.97529	8.27659	10.57905	12.88162	15.18421
8.0	0.14641	1.62342	3.81727	6.10865	8.41011	10.71258	13.01515	15.31774
9.0	0.18266	1.72811	3.93367	6.22629	8.52787	10.83036	13.13294	15.43551

1/*u*	1/*u* × 10^7	10^8	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}
1.0	15.54087	17.84344	20.14604	22.44862	24.75121	27.05379	29.36638	31.65897
1.2	15.72320	18.02577	20.32835	22.63094	24.93353	27.23611	29.53870	31.84128
1.5	15.94634	18.24892	20.55150	22.85408	25.15668	27.45926	29.76184	32.06442
2.0	16.23401	18.53659	20.83919	23.14177	25.44435	27.74693	30.04953	32.35211
2.5	16.45715	18.76974	21.06233	23.36491	25.66750	27.97008	30.27267	32.57526
3.0	16.63948	18.94206	21.24464	23.54723	25.84982	28.15240	30.45499	32.75757
3.5	16.79362	19.09621	21.39880	23.70139	26.00397	28.30655	30.60915	32.91173
4.0	16.92715	19.22975	21.53233	23.83492	26.13750	28.44008	30.74268	33.04526
5.0	17.15030	19.45288	21.75548	24.05806	26.36064	28.66322	30.96582	33.26840
6.0	17.33263	19.63521	21.93779	24.24039	26.54297	28.84555	31.14813	33.45071
7.0	17.48677	19.78937	22.09195	24.39453	26.69711	28.99969	31.30229	33.60487
8.0	17.62030	19.92290	22.22548	24.52806	26.83064	29.13324	31.43582	33.73840
9.0	17.73808	20.04068	22.34326	24.64584	26.94843	29.25102	31.55360	33.85619

[A] Value shown as 0.00000 is nonzero but less than 0.000005.

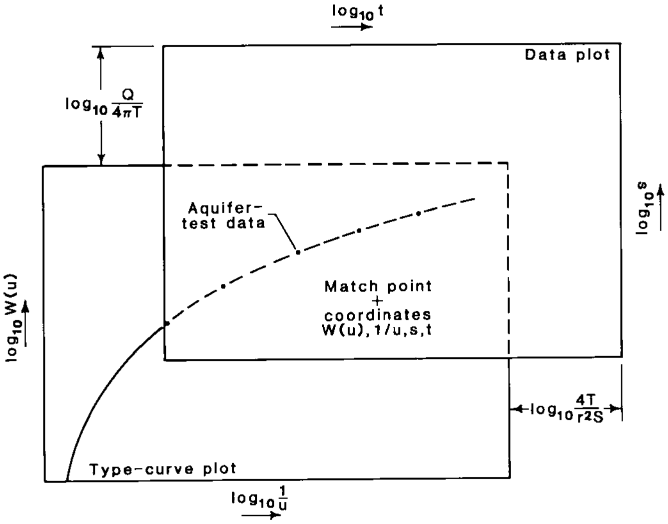

FIG. 2 Relation of 1/*u*, *W*(*u*) Type Curve and *t, s* Data Plot

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the selection of this test method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions of this test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened and gravel packed intervals, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells or piezometers.

9.1.4 Describe the methods of observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturers name, model number, and basic specifications for each major item, and the name and date and method of the last calibration, if applicable.

9.1.5 *Testing Procedures*—State the steps taken in conducting pre-test, drawdown, and recovery phases of the test. Include the date, clock time, and time since pumping started or stopped for measurements of discharge rate, water levels, and other environmental data recorded during the testing procedure.

9.2 *Presentation and Interpretation of Test Results*:

9.2.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for background water-level and barometric changes and calculation of drawdown and residual drawdown.

9.2.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.2.3 Show calculation of transmissivity and storage coefficient.

9.2.4 Evaluate qualitatively the test on the basis of the adequacy of instrumentation, observations of stress and response, the conformance of the hydrogeologic conditions, and the performance of the test to the assumptions of this test method.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient; transmissivity

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Designation: D 4630 – 96 (Reapproved 2002)

Standard Test Method for Determining Transmissivity and Storage Coefficient of Low-Permeability Rocks by In Situ Measurements Using the Constant Head Injection Test[1]

This standard is issued under the fixed designation D 4630; 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 a field procedure for determining the transmissivity and storativity of geological formations having permeabilities lower than $10^{-3}\mu m^2$ (1 millidarcy) using constant head injection.

1.2 The transmissivity and storativity values determined by this test method provide a good approximation of the capacity of the zone of interest to transmit water, if the test intervals are representative of the entire zone and the surrounding rock is fully water-saturated.

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

1.4 *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. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *transmissivity, T*—the transmissivity of a formation of thickness, *b*, is defined as follows:

$$T = K \cdot b \tag{1}$$

where:
K = hydraulic conductivity.

The hydraulic conductivity, *K*, is related to the permeability, *k*, as follows:

$$K = k\rho g/\mu \tag{2}$$

where:
ρ = fluid density,
μ = fluid viscosity, and
g = acceleration due to gravity.

2.1.2 *storage coefficient, S*—the storage coefficient of a formation of thickness, *b*, is defined as follows:

$$S = S_s \cdot b \tag{3}$$

where:
S_s = specific storage.

The ebrss is the specific storage of a material if it were homogeneous and porous over the entire interval. The specific storage is given as follows:

$$S_s = \rho g\,(C_b + nC_w) \tag{4}$$

where:
C_b = bulk rock compressibility,
C_w = fluid compressibility, and
n = formation porosity.

2.2 *Symbols:*

2.2.1 C_b—bulk rock compressibility ($M^{-1}LT^2$).

2.2.2 C_w—compressibility of water ($M^{-1}LT^2$).

2.2.3 G—dimensionless function.

2.2.4 K—hydraulic conductivity (LT^{-1}).

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

2.2.5 P—excess test hole pressure ($ML^{-1}T^{-2}$).

2.2.6 Q—excess water flow rate (L^3T^{-1}).

2.2.7 Q_o—maximum excess water flow rate (L^3T^{-1}).

2.2.8 S—storativity (or storage coefficient) (dimensionless).

2.2.9 S_s—specific storage (L^{-1}).

2.2.10 T—transmissivity (L^2T^{-1}).

2.2.11 b—formation thickness (L).

2.2.12 e—fracture aperture (L).

2.2.13 g—acceleration due to gravity (LT^{-2}).

2.2.14 k—permeability (L^2).

2.2.15 n—porosity (dimensionless).

2.2.16 r_w—radius of test hole (L).

2.2.17 t—time elapsed from start of test (T).

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

Current edition approved Oct. 10, 1996. Published June 1997. Originally published as D 4630 – 86. Last previous edition D 4630 – 86 (1991)$^{\epsilon 1}$.

2.2.18 α—dimensionless parameter.
2.2.19 μ—viscosity of water ($ML^{-1}T^{-1}$).
2.2.20 ρ—density of water (ML^{-3}).

3. Summary of Test Method

3.1 A borehole is first drilled into the rock mass, intersecting the geological formations for which the transmissivity and storativity are desired. The borehole is cored through potential zones of interest, and is later subjected to geophysical borehole logging over these intervals. During the test, each interval of interest is packed off at top and bottom with inflatable rubber packers attached to high-pressure steel tubing.

3.2 The test itself involves rapidly applying a constant pressure to the water in the packed-off interval and tubing string, and recording the resulting changes in water flow rate. The water flow rate is measured by one of a series of flow meters of different sensitivities located at the surface. The initial transient water flow rate is dependent on the transmissivity and storativity of the rock surrounding the test interval and on the volume of water contained in the packed-off interval and tubing string.

4. Significance and Use

4.1 *Test Method*—The constant pressure injection test method is used to determine the transmissivity and storativity of low-permeability formations surrounding packed-off intervals. Advantages of the method are: (*a*) it avoids the effect of well-bore storage, (*b*) it may be employed over a wide range of rock mass permeabilities, and (*c*) it is considerably shorter in duration than the conventional pump and slug tests used in more permeable rocks.

4.2 *Analysis*—The transient water flow rate data obtained using the suggested test method are evaluated by the curve-matching technique described by Jacob and Lohman **(1)**[2] and extended to analysis of single fractures by Doe *et al.* **(2).** If the water flow rate attains steady state, it may be used to calculate the transmissivity of the test interval **(3).**

4.3 *Units*:

4.3.1 *Conversions*—The permeability of a formation is often expressed in terms of the unit darcy. A porous medium has a permeability of 1 darcy when a fluid of viscosity 1 cp (1 mPa·s) flows through it at a rate of 1 cm^3/s (10−6 m^3/s)/1 cm^2 (10−4 m^2) cross-sectional area at a pressure differential of 1 atm (101.4 kPa)/1 cm (10 mm) of length. One darcy corresponds to 0.987 μm^2. For water as the flowing fluid at 20°C, a hydraulic conductivity of 9.66 μm/s corresponds to a permeability of 1 darcy.

5. Apparatus

NOTE 1—A schematic of the test equipment is shown in Fig. 1.

5.1 *Source of Constant Pressure*—A pump or pressure intensifier shall be capable of providing an additional amount of water to the water-filled tubing string and packed-off test interval to produce a constant pressure of up to 1 MPA (145 psi) in magnitude, preferably with a rise time of less than 1 % of one half of the flow rate decay ($Q/Q_o = 0.5$).

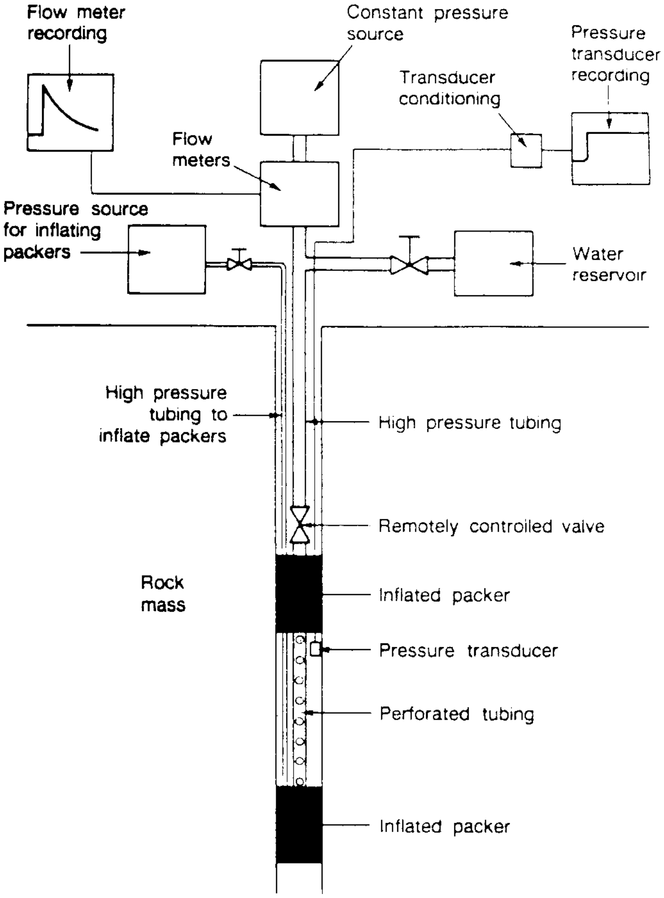

FIG. 1 Equipment Schematic

5.2 *Packers*—Hydraulically actuated packers are recommended because they produce a positive seal on the borehole wall and because of the low compressibility of water they are also comparatively rigid. Each packer shall seal a portion of the borehole wall at least 0.5 m in length, with an applied pressure at least equal to the excess constant pressure to be applied to the packed-off interval and less than the formation fracture pressure at that depth.

5.3 *Pressure Transducers*—The pressure shall be measured as a function of time, with the transducer located in the packed-off test interval. The pressure transducer shall have an accuracy of at least ±3 kPa (±0.4 psi), including errors introduced by the recording system, and a resolution of at least 1 kPa (0.15 psi).

5.4 *Flow Meters*—Suitable flow meters shall be provided for measuring water flow rates in the range from 10^3 cm^3/s to 10^{-3} cm^3/s. Commercially available flow meters are capable of measuring flow rates as low as 10^2 cm^3/s with an accuracy of ±1 % and with a resolution of 10^{-5} cm^3/s; these can test permeabilities to 10^{-3} md based on a 10-m packer spacing. Positive displacement flow meters of either the tank type (Haimson and Doe **(4)** or bubble-type (Wilson *et al.* **(3)** are capable of measuring flow rates as low as 10^{-3} cm^3/s; these can test permeabilities to 10^{-4} md based on a 10-m packer spacing.

5.5 *Hydraulic Systems*—The inflatable rubber packers shall be attached to high-pressure steel tubing reaching to the

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

surface. The packers themselves shall be inflated with water using a separate hydraulic system. The pump or pressure intensifier providing the constant pressure shall be attached to the steel tubing at the surface. A remotely controlled down-hole valve, located in the steel tubing immediately above the upper packer, shall be used for shutting in the test interval and for instantaneous starting of tests.

6. Procedure

6.1 *Drilling Test Holes*:

6.1.1 *Number and Orientation*—The number of test holes shall be sufficient to supply the detail required by the scope of the project. The test holes shall be directed to intersect major fracture sets, preferably at right angles.

6.1.2 *Test Hole Quality*—The drilling procedure shall provide a borehole sufficiently smooth for packer seating, shall contain no rapid changes in direction, and shall minimize formation damage.

6.1.3 *Test Holes Cored*—Core the test holes through zones of potential interest to provide information for locating test intervals.

6.1.4 *Core Description*—Describe the rock core from the test holes with particular emphasis on the lithology and natural discontinuities.

6.1.5 *Geophysical Borehole Logging*—Log geophysically the zones of potential interest. In particular, run electrical-induction and gamma-gamma density logs. Whenever possible, also use sonic logs and the acoustic televiewer. Run other logs as required.

6.1.6 *Washing Test Holes*—The test holes must not contain any material that could be washed into the permeable zones during testing, thereby changing the transmissivity and storativity. Flush the test holes with clean water until the return is free from cuttings and other dispersed solids.

6.2 *Test Intervals*:

6.2.1 *Selection of Test Intervals*—Determine test intervals from the core descriptions, geophysical borehole logs, and, if necessary, from visual inspection of the borehole with a borescope or TV camera.

6.2.2 *Changes in Lithology*—Test each major change in lithology that can be isolated between packers.

6.2.3 *Sampling Discontinuities*—Discontinuities are often the major permeable features in hard rock. Test jointed zones, fault zones, bedding planes, and the like, both by isolating individual features and by evaluating the combined effects of several features.

6.2.4 *Redundancy of Tests*—To evaluate variability in transmissivity and storativity, conduct three or more tests in each rock type, if homogeneous. If the rock is not homogeneous, the sets of tests should encompass similar types of discontinuities.

6.3 *Test Water*:

6.3.1 *Quality*—Water used for pressure pulse tests shall be clean, and compatible with the formation. Even small amounts of dispersed solids in the injection water could plug the rock face of the test interval and result in a measured transmissivity value that is erroneously low.

6.3.2 *Temperature*—The lower limit of the test water temperature shall be 5°C below that of the rock mass to be tested. Cold water injected into a warm rock mass causes air to come out of solution, and the resulting bubbles will radically modify the pressure transient characteristics.

6.4 *Testing*:

6.4.1 *Filling and Purging System*—Once the packers have been set, slowly fill the tubing string and packed-off interval with water to ensure that no air bubbles will be trapped in the test interval and tubing. Close the downhole valve to shut in the test interval, and allow the test section pressures (as determined from downhole pressure transducer reading) to dissipate.

6.4.2 *Constant Pressure Test*—Pressurize the tubing, typically to between 300 and 600 kPa (50 to 100 psi) above the shut-in pressure. This range of pressures is in most cases sufficiently low to minimize distortion of fractures adjacent at the test hole, but in no case should the pressure exceed the minimum principal ground stress. It is necessary to provide sufficient volume of pressurized water to maintain constant pressure during testing. Open the down-hole valve, maintain the constant pressure, and record the water flow rate as a function of time. Then close the down-hole valve and repeat the test for a higher value of constant test pressure. A typical record is shown in Fig. 2.

7. Calculation and Interpretation of Test Data

7.1 The solution of the differential equation for unsteady state flow from a borehole under constant pressure located in an extensive aquifer is given by Jacob and Lohman **(1)** as:[3]

$$Q = 2\pi TP\, G(\alpha)/\rho g, \tag{5}$$

where:

Q = water flow rate,
T = transmissivity of the test interval,
P = excess test hole pressure,
ρ = water density,
g = acceleration due to gravity, and
$G(\alpha)$ = function of the dimensionless parameter α:

$$\alpha = Tt/Sr_w^{\ 2} \tag{6}$$

where:

t = time elapsed from start of test,
S = storativity, and
r_w = radius of the borehole over the test interval.

7.1.1 In Fig. 2, the flow rate in the shut-in, packed-off interval is considered constant. In those cases where the response of the shut-in interval is time dependent, interpretation of the constant pressure test is unaffected, provided the time dependency is linear.

7.2 To determine the transmissivity, T, and storativity, S, data on the water flow rate at constant pressure as a function of time are plotted in the following manner **(1)**.

7.2.1 First, plot a type curve log of of the function $G(\alpha)$ versus α where values of $G(\alpha)$ are given in Table 1.

7.2.2 Second, on transparent logarithmic paper to the same scale, plot values of the log of flow rate, Q, versus values of the log of time, t at the same scale as the type curve.

7.2.3 Then, by placing the experimental data over the theoretical curve, the best fit of the data to the curve can be made.

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[3] For bounded aquifers the reader is referred to Hantush **(5).**

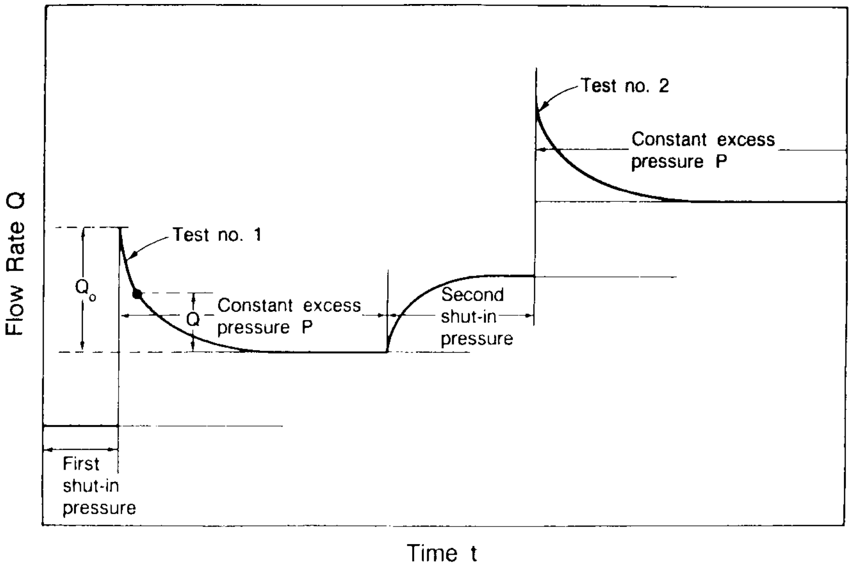

FIG. 2 Typical Flow Rate Record

TABLE 1 Values of $G(\alpha)$ for Values of α Between 10^{-4} and 10^{12} [A]

	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1	10	10^{2}	10^{3}
1	56.9	18.34	6.13	2.249	0.985	0.534	0.346	0.251
2	40.4	13.11	4.47	1.716	0.803	0.461	0.311	0.232
3	33.1	10.79	3.74	1.477	0.719	0.427	0.294	0.222
4	28.7	9.41	3.30	1.333	0.667	0.405	0.283	0.215
5	25.7	8.47	3.00	1.234	0.630	0.389	0.274	0.210
6	23.5	7.77	2.78	1.160	0.602	0.377	0.268	0.206
7	21.8	7.23	2.60	1.103	0.580	0.367	0.263	0.203
8	20.4	6.79	2.46	1.057	0.562	0.359	0.258	0.200
9	19.3	6.43	2.35	1.018	0.547	0.352	0.254	0.198
10	18.3	6.13	2.25	0.985	0.534	0.346	0.251	0.196

	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}	10^{11}
1	0.1964	0.1608	0.1360	0.1177	0.1037	0.0927	0.0838	0.0764
2	0.1841	0.1524	0.1299	0.1131	0.1002	0.0899	0.0814	0.0744
3	0.1777	0.1479	0.1266	0.1106	0.0982	0.0883	0.0801	0.0733
4	0.1733	0.1449	0.1244	0.1089	0.0968	0.0872	0.0792	0.0726
5	0.1701	0.1426	0.1227	0.1076	0.0958	0.0864	0.0785	0.0720
6	0.1675	0.1408	0.1213	0.1066	0.0950	0.0857	0.0779	0.0716
7	0.1654	0.1393	0.1202	0.1057	0.0943	0.0851	0.0774	0.0712
8	0.1636	0.1380	0.1192	0.1049	0.0937	0.0846	0.0770	0.0709
9	0.1621	0.1369	0.1184	0.1043	0.0932	0.0842	0.0767	0.0706
10	0.1608	0.1360	0.1177	0.1037	0.0927	0.0838	0.0764	0.0704

[A] From Jacob and Lohman **(1)**.

7.2.4 Determine the values of transmissivity, T, and storativity, S, using Eq 5 and Eq 6 from the coordinates of any point in both coordinate systems.

8. Report

8.1 The report shall include the following:

8.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the constant pressure test program, and the characteristics of rock mass tested.

8.1.1.1 *Scope of Testing Program*:

8.1.1.1.1 Report the location and orientation of the boreholes and test intervals. For tests in many boreholes or in a variety of rock types, present the matrix in tabular form.

8.1.1.1.2 Rationale for test location selection, including the reasons for the number, location, and size of test intervals.

8.1.1.1.3 Discuss in general terms limitations of the testing program, stating the areas of interest which are not covered by the testing program and the limitations of the data within the areas of application.

8.1.1.2 *Brief Description of the Test Intervals*—Describe rock type, structure, fabric, grain or crystal size, discontinuities, voids, and weathering of the rock mass in the test intervals. A more detailed description may be needed for certain applications. In a heterogeneous rock mass or for several rock types, many intervals may be described; a tabular presentation is then recommended for clarity.

8.1.2 *Test Method*:

8.1.2.1 *Equipment and Apparatus*—Include a list of the equipment used for the test, the manufacturer's name, model number, and basic specifications for each major item, and the date of last calibration, if applicable.

8.1.2.2 *Procedure*—State the steps actually followed in the procedure for the test.

8.1.2.3 *Variations*—If the actual equipment or procedure deviates from this test method, note each variation and the reasons. Discuss the effects of any deviations upon the test results.

8.1.3 *Theoretical Background*:

8.1.3.1 *Data Reduction Equations*—Clearly present and fully define all equations and type curves used to reduce the data. Note any assumptions inherent in the equations and type curves and any limitations in their applications and discuss their effects on the results.

8.1.3.2 *Site Specific Influences*—Discuss the degree to which the assumptions contained in the data reduction equations pertain to the actual test location and fully explain any factors or methods applied to the data to correct for departures from the assumptions of the data reduction equations.

8.1.4 *Results*:

8.1.4.1 *Summary Table*—Present a table of results, including the types of rock and discontinuities, the average values of the transmissivity and storativity, and their ranges and uncertainties.

8.1.4.2 *Individual Results*—Present a table of results for individual tests, including test number, interval length, rock types, value of constant pressure transmissivity and storativity, and flow rate as a function of time.

8.1.4.3 *Graphic Data*—Present water flow rate versus time curves for each test, together with the appropriate type curves used for their interpretation.

8.1.4.4 *Other*—Other analyses or presentations may be included as appropriate, for example: (*a*) discussion of the characteristic of the permeable zones, (*b*) histograms of results, and (*c*) comparison of results to other studies or previous work.

8.1.5 *Appended Data*—Include in an appendix a completed data form (Fig. 3) for each test.

9. Precision and Bias

9.1 *Error Estimate*:

9.1.1 Analyze the results using standard statistical methods. Calculate all uncertainties using a 95 % confidence interval.

9.1.2 *Measurement Error*—Evaluate the errors in transmissivity and storativity associated with a single test. This includes the combined effects of flow rate determination, measurement of time, and type curve matching.

9.1.3 *Sample Variability*—For each rock or discontinuity type, calculate, as a minimum, the mean transmissivity and storativity and their ranges, standard deviations, and 95 % confidence limits for the means. Compare the uncertainty associated with the transmissivity and storativity for each rock type with the measurement uncertainty to determine whether measurement error or sample variability is the dominant factor in the results.

10. Keywords

10.1 borehole; constant head testing; flow; in situ; fault-zones; field testing; flow and flow rate; permeability; pressure testing; rock; saturation; storativity; transmissivity; viscosity; water; water saturation

Data Sheet

Project
Test Location
Rock Type
Date
Testing by

Test No.
Borehole No.
Borehole Dip and Dip Direction
Measured Depth of Test to Top Packer, m
Borehole Diameter, mm
Rock Temperature, °C

Equipment Description	Serial No.	Date of last Calibration

Length of Packed-off Interval, m
Length of Tubing Above Top Packer, m
Water Temperature, °C

Packer Pressure, kPa
Tubing ID, mm
Shut-in Borehole Pressure, kPa
Constant Water Pressure, kPa

FIG. 3 Data Sheet for In Situ Measurement of Transmissivity and Storativity Using the Constant Head Injection Test

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Designation: D 4631 – 95 (Reapproved 2000)

Standard Test Method for Determining Transmissivity and Storativity of Low Permeability Rocks by In Situ Measurements Using Pressure Pulse Technique[1]

This standard is issued under the fixed designation D 4631; 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 a field procedure for determining the transmissivity and storativity of geological formations having permeabilities lower than 10^{-3} µm^2 (1 millidarcy) using the pressure pulse technique.

1.2 The transmissivity and storativity values determined by this test method provide a good approximation of the capacity of the zone of interest to transmit water, if the test intervals are representative of the entire zone and the surrounding rock is fully water saturated.

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

1.4 *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. Terminology

2.1 *Definitions of Terms Specific to This Standard:*

2.1.1 *transmissivity, T*—the transmissivity of a formation of thickness, *b*, is defined as follows:

$$T = K \cdot b \tag{1}$$

where:
K = equivalent formation hydraulic conductivity (efhc).

The efhc is the hydraulic conductivity of a material if it were homogeneous and porous over the entire interval. The hydraulic conductivity, *K*, is related to the equivalent formation, *k*, as follows:

$$K = k\rho g/\mu \tag{2}$$

where:
ρ = fluid density,
μ = fluid viscosity, and
g = acceleration due to gravity.

2.1.2 *storativity, S*—the storativity (or storage coefficient) of a formation of thickness, *b*, is defined as follows:

$$S = S_s \cdot b \tag{3}$$

where:
S_s = equivalent bulk rock specific storage (ebrss).

The ebrss is defined as the specific storage of a material if it were homogeneous and porous over the entire interval. The specific storage is given as follows:

$$S_s = \rho g(C_b + nC_w) \tag{4}$$

where:
C_b = bulk rock compressibility,
C_w = fluid compressibility, and
n = formation porosity.

2.2 *Symbols:*

2.2.1 C_b—bulk rock compressibility [$M^{-1}LT^2$].

2.2.2 C_w—compressibility of water [$M^{-1}LT^2$].

2.2.3 K—hydraulic conductivity [LT^{-1}].

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

2.2.4 L—length of packed-off zone [L].

2.2.5 P—excess test hole pressure [$ML^{-1}T^{-2}$].

2.2.6 P_o—initial pressure pulse [$ML^{-1}T^{-2}$].

2.2.7 S—storativity (or storage coefficient) (dimensionless).

2.2.8 S_s—specific storage [L^{-1}].

2.2.9 T—transmissivity [L^2T^{-1}].

2.2.10 V_w—volume of water pulsed [L^3].

2.2.11 b—formation thickness [L].

2.2.12 e—fracture aperture [L].

2.2.13 g—acceleration due to gravity [LT^{-2}].

2.2.14 k—permeability [L^2].

2.2.15 n—porosity (dimensionless).

2.2.16 r_w—radius of test hole [L].

2.2.17 t—time elapsed from pulse initiation [T].

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

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2.2.18 α—dimensionless parameter.

2.2.19 β—dimensionless parameter.

2.2.20 μ—viscosity of water [$ML^{-1}T^{-1}$].

2.2.21 ρ—density of water [ML^{-3}].

3. Summary of Test Method

3.1 A borehole is first drilled into the rock mass, intersecting the geological formations for which the transmissivity and storativity are desired. The borehole is cored through potential zones of interest, and is later subjected to geophysical borehole logging over these intervals. During the test, each interval of interest is packed off at top and bottom with inflatable rubber packers attached to high-pressure steel tubing. After inflating the packers, the tubing string is completely filled with water.

3.2 The test itself involves applying a pressure pulse to the water in the packed-off interval and tubing string, and recording the resulting pressure transient. A pressure transducer, located either in the packed-off zone or in the tubing at the surface, measures the transient as a function of time. The decay characteristics of the pressure pulse are dependent on the transmissivity and storativity of the rock surrounding the interval being pulsed and on the volume of water being pulsed. Alternatively, under non-artesian conditions, the pulse test may be performed by releasing the pressure on a shut-in well, thereby subjecting the well to a negative pressure pulse. Interpretation of this test method is similar to that described for the positive pressure pulse.

4. Significance and Use

4.1 *Test Method*—The pulse test method is used to determine the transmissivity and storativity of low-permeability formations surrounding the packed-off intervals. This test method is considerably shorter in duration than the pump and slug tests used in more permeable rocks. To obtain results to the desired accuracy, pump and slug tests in low-permeability formations are too time consuming, as indicated in Fig. 1 (from Bredehoeft and Papadopulos **(1)**).[2]

4.2 *Analysis*—The transient pressure data obtained using the suggested method are evaluated by the curve-matching technique described by Bredehoeft and Papadopulos **(1)**, or by an analytical technique proposed by Wang et al **(2)**. The latter is particularly useful for interpreting pulse tests when only the early-time transient pressure decay data are available.

4.3 *Units*:

4.3.1 *Conversions*—The permeability of a formation is often expressed in terms of the unit darcy. A porous medium has a permeability of 1 darcy when a fluid of viscosity 1 cP (1 mPa·s) flows through it at a rate of 1 cm^3/s (10^{-6} m ^{3}/s)/1 cm^2 (10^{-4} m^2) cross-sectional area at a pressure differential of 1 atm (101.4 kPa)/1 cm (10 mm) of length. One darcy corresponds to 0.987 μm^2. For water as the flowing fluid at 20°C, a hydraulic conductivity of 9.66 μm/s corresponds to a permeability of 1 darcy.

4.3.2 *Viscosity of Water*—Table 1 shows the viscosity of water as a function of temperature.

5. Apparatus

NOTE 1—A schematic of the test equipment is shown in Fig. 2.

5.1 *Source of Pressure Pulse*—A pump or pressure intensifier shall be capable of injecting an additional amount of water to the water-filled tubing string and packed-off test interval to produce a sharp pressure pulse of up to 1 MPa (145 psi) in magnitude, preferably with a rise time of less than 1 % of one half of the pressure decay ($P/P_o = 0.5$).

5.2 *Packers*—Hydraulically actuated packers are recommended because they produce a positive seal on the borehole wall and because of the low compressibility of water they are also comparatively rigid. Each packer shall seal a portion of the borehole wall at least 0.5 m in length, with an applied pressure at least equal to the excess maximum pulse pressure to be applied to the packed-off interval and less than the formation fracture pressure at that depth.

5.3 *Pressure Transducers*—The test pressure may be measured directly in the packed-off test interval or between the fast-acting valve and the test interval with an electronic pressure transducer. In either case the pressure shall be recorded at the surface as a function of time. The pressure transducer shall have an accuracy of at least ±3 kPa (±0.4

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

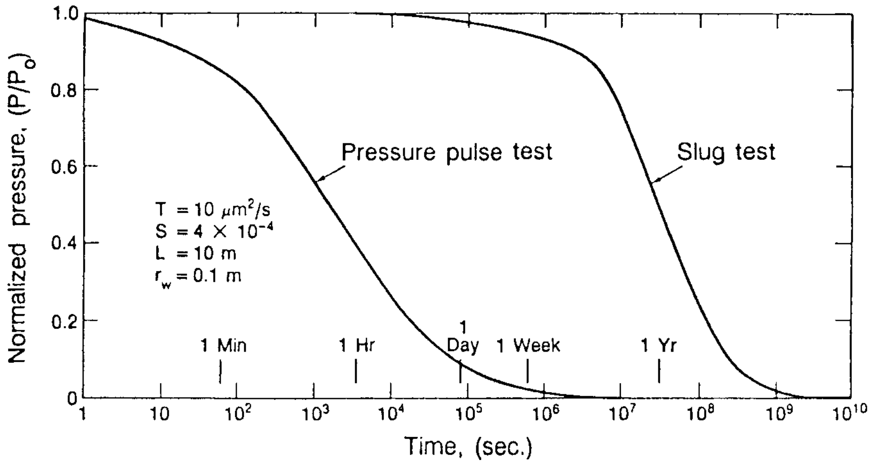

FIG. 1 Comparative Times for Pressure Pulse and Slug Tests

TABLE 1 Viscosity of Water as a Function of Temperature

Temperature, °C	Absolute Viscosity, mPa·s
0	1.79
2	1.67
4	1.57
6	1.47
8	1.39
10	1.31
12	1.24
14	1.17
16	1.11
18	1.06
20	1.00
22	0.96
24	0.91
26	0.87
28	0.84
30	0.80
32	0.77
34	0.74
36	0.71
38	0.68
40	0.66

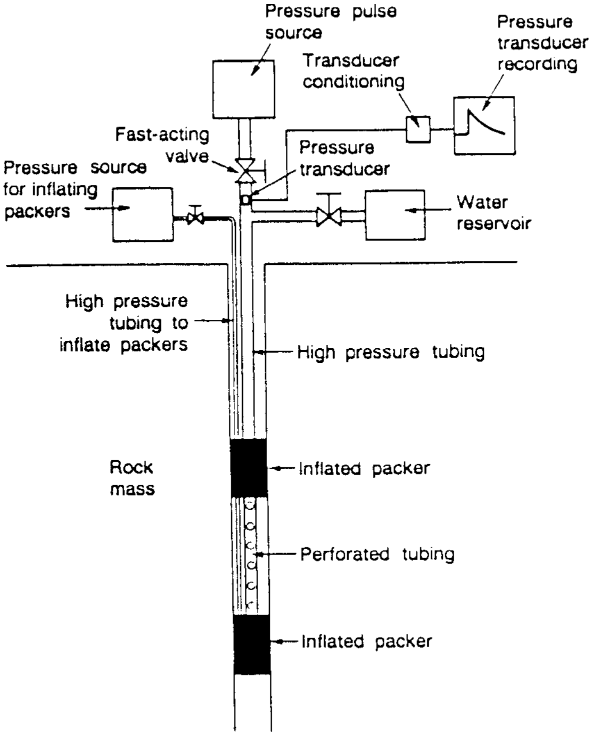

FIG. 2 Schematic of Test Equipment

psi), including errors introduced by the recording system, and a resolution of at least 1 kPa (0.15 psi).

5.4 *Hydraulic Systems*—The inflatable rubber packers shall be attached to high-pressure steel tubing reaching to the surface. The packers themselves shall be inflated with water using a separate hydraulic system. The pump or pressure intensifier providing the pressure pulse shall be attached to the steel tubing at the surface. If the pump is used, a fast-operating valve shall be located above, but as near as practical to the upper packer. That valve should be located less than 10 m above the anticipated equilibrium head in the interval being tested to avoid conditions in the tubing changing during the test from a full water column to a falling water-level column because of formation of a free surface at or near zero absolute pressure (Neuzil **(3)**).

6. Procedure

6.1 *Drilling Test Holes*:

6.1.1 *Number and Orientation*—The number of test holes shall be sufficient to supply the detail required by the scope of the project. The test holes shall be directed to intersect major fracture sets, preferable at right angles.

6.1.2 *Test Hole Quality*—The drilling procedure shall provide a borehole sufficiently smooth for packer seating, shall contain no rapid changes in direction, and shall minimize formation damage.

6.1.3 *Test Holes Cored*—Core the test holes through zones of potential interest to provide information for locating test intervals.

6.1.4 *Core Description*—Describe the rock core from the test holes with particular emphasis on the lithology and natural discontinuities.

6.1.5 *Geophysical Borehole Logging*—Log geophysically the zones of potential interest. In particular, run electrical-induction and gamma-gamma density logs. Run other logs as required.

6.1.6 *Washing Test Holes*—The test holes must not contain any material that could be washed into the permeable zones during testing, thereby changing the transmissivity and storativity. Flush the test holes with clean water until the return is free from cuttings and other dispersed solids.

6.2 *Test Intervals*:

6.2.1 *Selection of Test Intervals*—Test intervals are determined from the core descriptions, geophysical borehole logs, and, if necessary, from visual inspection of the borehole with a borescope or television camera.

6.2.2 *Changes in Lithology*—Test each major change in lithology that can be isolated between packers.

6.2.3 *Sampling Discontinuities*—Discontinuities are often the major permeable features in hard rock. Test jointed zones, fault zones, bedding planes, and the like, both by isolating individual features and by evaluating the combined effects of several features.

6.2.4 *Redundancy of Tests*—To evaluate variability in transmissivity and storativity, conduct several tests in each rock type, if homogeneous. If the rock is not homogeneous, each set of tests should encompass similar types of discontinuities.

6.3 *Test Water*:

6.3.1 *Quality*—Water used for pressure pulse tests shall be clean and compatible with the formation. Even small amounts of dispersed solids in the injection water could plug the rock face of the test interval and result in a measured transmissivity value that is erroneously low.

6.3.2 *Temperature*—The lower limit of the test water temperature shall be 5°C below that of the rock mass to be tested. Cold water injected into a warm rock mass causes air to come out of solution, and the resulting bubbles will radically modify the pressure transient characteristics.

6.4 *Testing*:

6.4.1 *Filling and Purging System*—Allow sufficient time after washing the test hole for any induced formation pressures to dissipate. Once the packers have been set, slowly fill the tubing string and packed-off interval with water to ensure that no air bubbles will be trapped in the test interval and tubing.

6.4.2 *Pressure Pulse Test*—This range of pressures is in most cases sufficiently low to minimize distortion of fractures adjacent to the test hole, but in no case should the pressure exceed the minimum principal ground stress. Record the resulting pressure pulse and decay transient detected by the pressure transducer as a function of time. A typical record is shown in Fig. 3.

6.4.2.1 Before the pressure pulse test can be started it is necessary to reliably estimate the natural pressure in the test interval. See 7.1.1 and Fig. 3 for a description of a method to prepare the system for the pulse test. After the pressure is at, or estimated to be approaching at a predictable rate, near-equilibrium conditions, then rapidly pressurize the tubing, typically to between 300 and 600 kPa (50 to 100 psi), and then shut in.

7. Calculation and Interpretation of Test Data

7.1 The type of matching technique developed by Bredehoeft and Papadopulos **(1)** involves plotting normalized pressure (the ratio of the excess borehole pressure, P, at a given time to the initial pressure pulse, P_o) against the logarithm of time, as indicated in Fig. 1 and Fig. 3. The pulse decay is given as follows:

$$\frac{P}{P_o} = F(\alpha,\beta) \qquad (5)$$

where:
α and β = dimensionless parameters given by: to:

$$\alpha = \pi r_w^2 S/V_w C_w \rho g \qquad (6)$$

and:

$$\beta = \pi T t/V_w C_w \rho g \qquad (7)$$

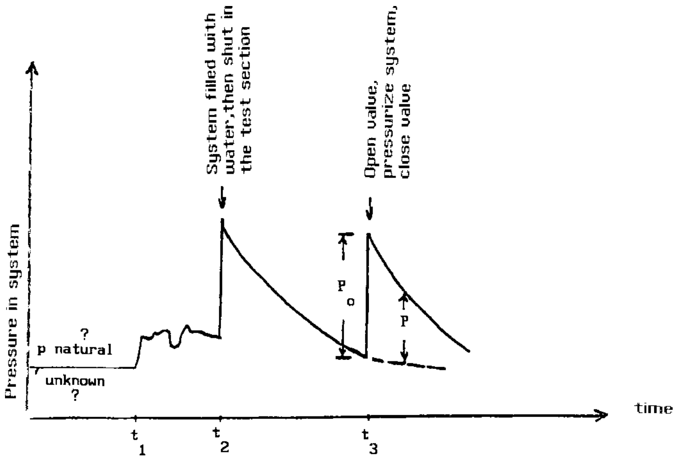

FIG. 3 Typical Pressure Record

where:
V_w = volume of water being pulsed,
r_w = well radius,
t = time elapsed from pulse initiation,
C_w = compressibility of water,
T = transmissivity,
S = storage coefficient,
ρ = density of water, and
g = gravitational acceleration.

Tables of the function F (α β) have been provided by Cooper, et al **(4)**, Papadopulos **(5)**, and Bredehoeft and Papadopulos **(1)**.

7.1.1 In Fig. 3 the pressure, p, shown before (to the left of) Time t_1 represents the unknown natural pressure in the interval eventually to be tested. The drill hole encounters that interval at Time t_1 and from then until Time t_2 the pressure variation reflects the effects of drilling and test hole development. If the interval consists of rocks or sediments of low hydraulic conductivity, there might be a long time period before the water level in an open hole would stabilize to the equilibrium level. For that reason before a pulse test can be conducted we want to establish a condition that provides a reasonable estimate of the undisturbed pressure for the interval. The following procedure is intended to provide that condition. At Time t_2 the packers are inflated, and then the system is filled with water and shut in. By this operation the change in pressure in the packed-off interval will reflect a compressive system and should approach the pressure in the interval being tested much more rapidly than would the water level in an open test hole. Monitoring the pressure changes should indicate when near-equilibrium conditions are approached. At Time t_3 the value is opened, the system is subjected to the Pulse P_o, and the valve is closed. Monitoring the heads after Time t_3 gives the data needed to use the calculation procedure of Bredehoeft and Papadopulos.

7.1.1.1 Neuzil **(3)** points out the necessity of measuring the amount of water used to create the pulse to account for the fact that the compressibility of the shut-in test system can be larger than C_w, the compressibility of water. Neuzil **(3)** suggests that the larger compressibility reflects "give" in the downhole test equipment and in the tubing, and possibly air trapped in the system. The direct computation of the observed test system compressibility can be expressed as

$$C_{obs} = \frac{dv/v}{dp} \qquad (8)$$

where:
v = total fluid volume of the test system,
dv = injected volume (the pulse), and
dp = pressure pulse.

7.2 The method for analyzing pulse decay data depends on whether the parameter, α, is larger or smaller than 0.1. Since the value ofα is not known *a priori*, the test data are first analyzed by the method applicable to $\alpha < 0.1$. If this analysis indicates that $\alpha > 0.1$, then that method is used.

7.2.1 For $\alpha < 0.1$, the data are analyzed by the method described by Cooper et al **(4)**, in which the family of curves shown in Fig. 4 for F (α, β) as a function of β for various values of α are used. Observed values of P/P_o are plotted as a

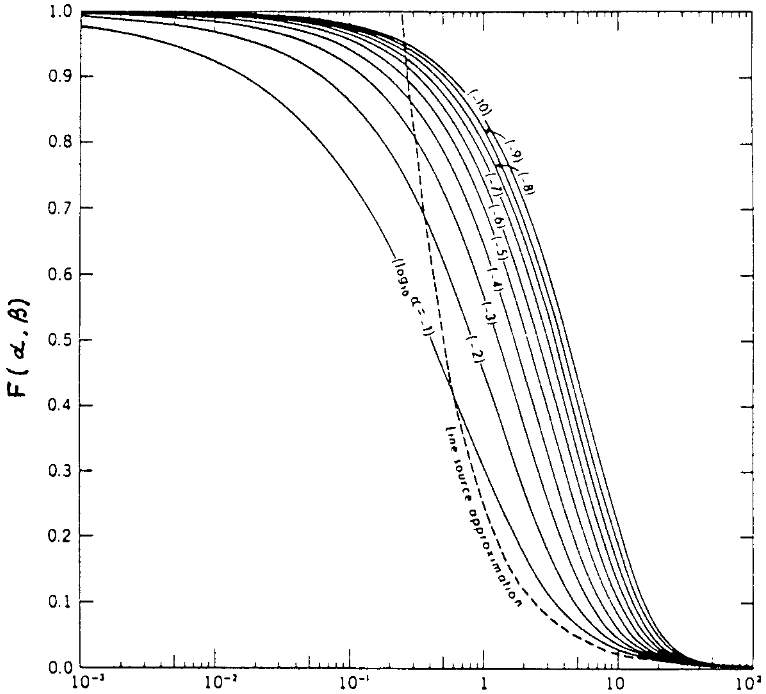

FIG. 4 Type Curves of the Function *F*(α, β) Against the Parameter β for Different Values of α

function of time, *t*, on semilogarithmic paper of the same scale, and are matched with a type curve by keeping the β and *t* axes coincident and moving the plots horizontally.

7.2.2 The expressions corresponding to α and β in Eq 5 and Eq 6, the α value of the matched type curve, and the β and *t* values from a match point are used to determine the transmissivity, *T*, and the storage coefficient, *S*, of the tested interval. Bredehoeft and Papadopulos **(1)** indicate that this procedure yields good estimates of the transmissivity when ≤ 0.1, but that the storage coefficient could be of questionable reliability for values of $\alpha < 10^{-5}$.

7.2.3 For $\alpha > 0.1$, Bredehoeft and Papadopulos **(1)** recommend the use of the family of curves shown in Fig. 5 for *F* (α, β) as a function of the product $\alpha\beta = \left(\frac{\pi^2 r_w{}^2 TSt}{(V_w C_w{}^{\rho} g)^2}\right)$ to interpret the data. Matching of the observed values of P/P_o plotted as a function of *t* with a type curve is performed in the same manner as indicated previously for $\alpha \leq 0.1$. In this way, the product *TS* and *S* are determined. Analysis with the type curves shown in Fig. 5 provides an indication as to whether the data are adequate for identifying both α and β and, hence, determining both *S* and *T*, or whether the data fall in the range where only the product *TS* can be determined.

7.3 Wang et al **(2)** present an alternative method of analyzing pressure pulse data involving analytical solutions for pulse decay in single fractures of both infinite and finite extent. Recognizing that finite fracture geometry introduces errors in the interpretation of the pulse decay data, Wang suggests a method that uses data from elapsed times before the fracture

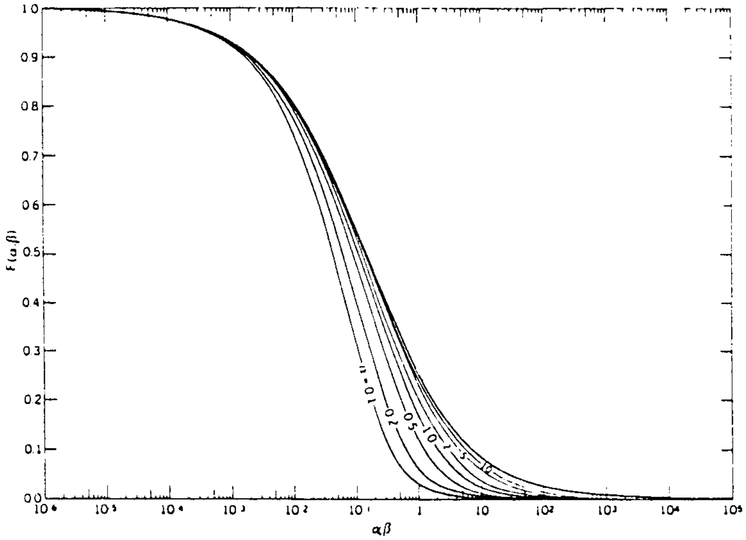

FIG. 5 Type Curves of the Function *F*(α, β) Against the Product Parameter αβ

boundaries begin to influence the pressure data. Wang found by linear regression of calculated decay pressure versus time an empirical expression for the fracture aperture of the following form:

$$\log (e/10^6) = -0.32 \log (t) + C + 0.32 [2 \log (r_w/0.04) + \log (2.394\mu C_w \times 10^{12})] + 0.333 \log (L/2). \quad (9)$$

where:

e = parallel-plate equivalent aperture, m,
t = time, s,
r_w = borehole radius, m,
μ = water viscosity, mPa·s,
C_w = water compressibility, 1/Pa,
L = length of the packed-off interval, m, and
C = constant that depends on the fraction of pulse decay, as follows:

Fraction of pulse decay, $(P_o - P)/P_o$	0.05	0.10	0.15
Wang constant, C:	1.09	1.20	1.27

7.3.1 Wang shows that in test zones containing two fractures of different apertures, the wider fracture dominates the early time behavior. The early pressure pulse decay therefore reflects the major fracture only. Doe et al **(6)** view individual fractures as confined aquifers whose transmissivities are given by the cubic relationship:

$$T = \rho g e^3/12\mu \quad (10)$$

Thus, Eq 10 provides transmissivity in terms of a parallel-plate equivalent fracture aperture calculated from Eq 9.

7.3.2 Eq 9 and Eq 10 can be solved for the early-time pressure pulse decay data to provide a transmissivity value for the test interval from the calculated parallel-plate equivalent aperture.

8. Report

8.1 Report the following information:

8.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the pressure pulse test program, and the characteristics of the rock mass tested.

8.1.2 *Scope of Testing Program*:

8.1.2.1 Report the location and orientation of the boreholes and test intervals. For tests in many boreholes or in a variety of rock types, present the test matrix in tabular form.

8.1.2.2 Rationale for test location selection, including the reasons for the number, location, and size of test intervals.

8.1.2.3 Discuss in general terms the limitations of the testing program, stating the areas of interest which are not covered by the testing program and the limitations of the data within the areas of application.

8.1.3 *Brief Description of the Test Intervals*—Describe rock type, structure, fabric, grain or crystal size, discontinuities, voids, and weathering of the rock mass in the test intervals. A more detailed description may be needed for certain applications. In a heterogeneous rock mass or for several rock types, many intervals may be described; a tabular presentation is then recommended for clarity.

8.1.4 *Test Method*:

8.1.4.1 *Equipment and Apparatus*—Include a list of the equipment used for the test, the manufacturer's name, model number, and basic specifications for each major item, and the date of last calibration, if applicable.

8.1.4.2 *Procedure*—State the steps actually followed in the procedure for the test.

8.1.4.3 *Variations*—If the actual equipment or procedure deviates from this test method, note each variation and the reasons. Discuss the effects of the deviations upon the test results.

8.1.5 *Theoretical Background*:

8.1.5.1 *Data Reduction Equations*—Clearly present and fully define all equations and type curves used to reduce the data. Note any assumptions inherent in the equations and type curves and any limitations in their applications and discuss their effects on the results.

8.1.5.2 *Site Specific Influences*—Discuss the degree to which the assumptions contained in the data reduction equations pertain to the actual test location and fully explain any factors or methods applied to the data to correct for departures from the assumptions of the data reduction equations.

8.1.6 *Results*:

8.1.6.1 *Summary Table*—Present a table of results, including the types of rock and discontinuities, the average values of the transmissivity and storativity, and their ranges and uncertainties.

8.1.6.2 *Individual Results*—Present a table of results for individual tests, including test number, interval length, rock types, transmissivity and storativity, and pressure pulse amplitude and decay time (or recording time, if the decay is incomplete).

8.1.6.3 *Graphic Data*—Present pressure pulse decay versus time curves for each test, together with the appropriate type curves used for their interpretation.

8.1.6.4 *Other*—Other analysis or presentations may be included as appropriate, for example: (*1*) discussion of the characteristics of the permeable zones, (*2*) histograms of results, and (*3*) comparison of results to other studies or previous work.

8.1.7 *Appended Data*—Include in an appendix a completed data form (Fig. 6) for each test.

9. Precision and Bias

9.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

10. Keywords

10.1 borehole drilling; discontinuities; fault zones; field testing flow and flow rate; ground water; permeability; pressure testing; pulse testing; rock; saturation; storativity; transmissivity; viscosity; water; water saturation

Data Sheet

Project

Test No.

Test Location

Borehole No.

Rock Type

Borehole Dip and Dip Direction

Date

Measured Depth of Test to Top Packer, m

Testing by

Borehole Diameter, mm

Rock Temperature, °C

Equipment Description	Serial No.	Date of Last Calibration

Length of Packed-off Interval, m

Packer Pressure, kPa

Length of Tubing Above Top Packer, m

Tubing ID, mm

Water Temperature, °C

Maximum Pulse Pressure, kPa

Pulse Decay Time, s

FIG. 6 Data Sheet for In Situ Measurement of Transmissivity and Storativity Using the Pressure Pulse Technique

REFERENCES

(**1**) Bredehoeft, J. D., and Papadopulos, S. S., "A Method for Determining the Hydraulic Properties of Tight Formations," *Water Resources Research*, Vol 16, 1980, pp. 233–238.

(**2**) Wang, J. S. Y., Narasimhan, T. N., Tsang, C. F., and Witherspoon, P. A., "Transient Flow in Tight Fractures," *Proceedings of the First Invitational Well Testing Symposium*, Berkeley, 1977, pp. 103–116.

(**3**) Neuzil, C. E., "On Conducting the Modified ′Slug Test' in Tight Formations," *Water Resources Research*, Vol 18, 1982, pp. 439–441.

(**4**) Cooper, H. H., Bredehoeft, J. D., and Papadopulos, S. S., "Response of a Finite Diameter Well to an Instantaneous Charge of Water," *Water Resources Research*, Vol 3, 1967, pp. 263–269.

(**5**) Papadopulos, S. S., Bredehoeft, J. D., and Cooper, H. H., "On the Analysis of ′Slug Test' Data," *Water Resources Research*, Vol 9,1973, pp. 1087–1089.

(**6**) Doe, T. W., Long, J. C. S., Endo, H. K., and Wilson, C. R., "Approaches to Evaluating the Permeability and Porosity of Fractured Rock Masses," *Proceedings of the Twenty-Third U.S. Symposium on Rock Mechanics*, Berkeley, 1982, pp. 30–38.

(**7**) Earlougher, R. C., "Advances in Well Test Analysis," *Society of Petroleum Engineers of AIME*, New York, NY, 1977.

(**8**) Freeze, R. A., and Cherry, J. A., *Groundwater*, Prentice-Hall, Englewood Cliffs, NJ, 1979.

(**9**) Shuri, F. S., Feves, M. L., Peterson, G. L., Foster, K. M., and Kienle, C. F., Public Draft: "Field and In Situ Rock Mechanics Testing Manual," Office of Nuclear Waste Isolation, Document ONWI-310, Section F: "In Situ Fluid Properties," GT-F.1 In Situ Permeability Measurement of Rock Using Borehole Packers, 1981.

Designation: D 4750 – 87 (Reapproved 2001)

Standard Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[1]

This standard is issued under the fixed designation D 4750; 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 describes the procedures for measuring the level of liquid in a borehole or well and determining the stabilized level of liquid in a borehole.

1.2 The test method applies to boreholes (cased or uncased) and monitoring wells (observation wells) that are vertical or sufficiently vertical so a flexible measuring device can be lowered into the hole.

1.3 Borehole liquid-level measurements obtained using this test method will not necessarily correspond to the level of the liquid in the vicinity of the borehole unless sufficient time has been allowed for the level to reach equilibrium position.

1.4 This test method generally is not applicable for the determination of pore-pressure changes due to changes in stress conditions of the earth material.

1.5 This test method is not applicable for the concurrent determination of multiple liquid levels in a borehole.

1.6 The values stated in inch-pound units are to be regarded as the standard.

1.7 *This standard does not purport to address all of the safety problems, 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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *borehole*—a hole of circular cross-section made in soil or rock to ascertain the nature of the subsurface materials. Normally, a borehole is advanced using an auger, a drill, or casing with or without drilling fluid.

3.1.2 *earth material*—soil, bedrock, or fill.

3.1.3 *ground-water level*—the level of the water table surrounding a borehole or well. The ground-water level can be represented as an elevation or as a depth below the ground surface.

3.1.4 *liquid level*—the level of liquid in a borehole or well at a particular time. The liquid level can be reported as an elevation or as a depth below the top of the land surface. If the liquid is ground water it is known as water level.

3.1.5 *monitoring well (observation well)*—a special well drilled in a selected location for observing parameters such as liquid level or pressure changes or for collecting liquid samples. The well may be cased or uncased, but if cased the casing should have openings to allow flow of borehole liquid into or out of the casing.

3.1.6 *stabilized borehole liquid level*—the borehole liquid level which remains essentially constant with time, that is, liquid does not flow into or out of the borehole.

3.1.7 *top of borehole*—the surface of the ground surrounding the borehole.

3.1.8 *water table (ground-water table)*—the surface of a ground-water body at which the water pressure equals atmospheric pressure. Earth material below the ground-water table is saturated with water.

3.2 *Definitions:*

3.2.1 For definitions of other terms used in this test method, see Terminology D 653.

4. Significance and Use

4.1 In geotechnical, hydrologic, and waste-management investigations, it is frequently desirable, or required, to obtain information concerning the presence of ground water or other liquids and the depths to the ground-water table or other liquid surface. Such investigations typically include drilling of exploratory boreholes, performing aquifer tests, and possibly completion as a monitoring or observation well. The opportunity exists to record the level of liquid in such boreholes or wells, as the boreholes are being advanced and after their completion.

4.2 Conceptually, a stabilized borehole liquid level reflects the pressure of ground water or other liquid in the earth material exposed along the sides of the borehole or well. Under suitable conditions, the borehole liquid level and the ground-water, or other liquid, level will be the same, and the former can be used to determine the latter. However, when earth materials are not exposed to a borehole, such as material which is sealed off with casing or drilling mud, the borehole water

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

Current edition approved Nov. 27, 1987. Published January 1988.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

levels may not accurately reflect the ground-water level. Consequently, the user is cautioned that the liquid level in a borehole does not necessarily bear a relationship to the ground-water level at the site.

4.3 The user is cautioned that there are many factors which can influence borehole liquid levels and the interpretation of borehole liquid-level measurements. These factors are not described or discussed in this test method. The interpretation and application of borehole liquid-level information should be done by a trained specialist.

4.4 Installation of piezometers should be considered where complex ground-water conditions prevail or where changes in intergranular stress, other than those associated with fluctuation in water level, have occurred or are anticipated.

5. Apparatus

5.1 Apparatus conforming to one of the following shall be used for measuring borehole liquid levels:

5.1.1 *Weighted Measuring Tape*—A measuring tape with a weight attached to the end. The tape shall have graduations that can be read to the nearest 0.01 ft. The tape shall not stretch more than 0.05% under normal use. Steel surveying tapes in lengths of 50, 100, 200, 300, and 500 ft (20, 30, 50 or 100 m) and widths of ¼ in. (6 mm) are commonly used. A black metal tape is better than a chromium-plated tape. Tapes are mounted on hand-cranked reels up to 500 ft (100 m) lengths. Mount a slender weight, made of lead, to the end of the tape to ensure plumbness and to permit some feel for obstructions. Attach the weight to the tape with wire strong enough to hold the weight but not as strong as the tape. This permits saving the tape in the event the weight becomes lodged in the well or borehole. The size of the weight shall be such that its displacement of water causes less than a 0.05-ft (15-mm) rise in the borehole water level, or a correction shall be made for the displacement. If the weight extends beyond the end of the tape, a length correction will be needed in measurement Procedure C (see 7.2.3).

5.1.2 *Electrical Measuring Device*—A cable or tape with electrical wire encased, equipped with a weighted sensing tip on one end and an electric meter at the other end. An electric circuit is completed when the tip contacts water; this is registered on the meter. The cable may be marked with graduations similar to a measuring tape (as described in 5.1.1).

5.1.3 *Other Measuring Devices*—A number of other recording and non-recording devices may be used. See Ref. **(1)** for more details.[3]

6. Calibration and Standardization

6.1 Calibrate measuring apparatus in accordance with the manufacturers' directions.

7. Procedure

7.1 Liquid-level measurements are made relative to a reference point. Establish and identify a reference point at or near the top of the borehole or a well casing. Determine and record the distance from the reference point to the top of the borehole (land surface). If the borehole liquid level is to be reported as an elevation, determine the elevation of the reference point or the top of borehole (land surface). Three alternative measurement procedures (A, B, and C) are described.

NOTE 1—In general, Procedure A allows for greater accuracy than B or C, and B allows for greater accuracy than C; other procedures have a variety of accuracies that must be determined from the referenced literature **(2-5).**

7.2 *Procedure A—Measuring Tape*:

7.2.1 Chalk the lower few feet of tape by drawing the tape across a piece of colored carpenter's chalk.

7.2.2 Lower a weighted measuring tape slowly into the borehole or well until the liquid surface is penetrated. Observe and record the reading on the tape at the reference point. Withdraw the tape from the borehole and observe the lower end of the tape. The demarcation between the wetted and unwetted portions of the chalked tape should be apparent. Observe and record the reading on the tape at that point. The difference between the two readings is the depth from the reference point to the liquid level.

NOTE 2—Submergence of the weight and tape may temporarily cause a liquid-level rise in wells or boreholes having very small diameters. This effect can be significant if the well is in materials of very low hydraulic conductivity.

NOTE 3—Under dry surface conditions, it may be desirable to pull the tape from the well or borehole by hand, being careful not to allow it to become kinked, and reading the liquid mark before rewinding the tape onto the reel. In this way, the liquid mark on the chalked part of the tape is rapidly brought to the surface before the wetted part of the tape dries. In cold regions, rapid withdrawal of the tape from the well is necessary before the wet part freezes and becomes difficult to read. The tape must be protected if rain is falling during measurements.

NOTE 4—In some pumped wells, or in contaminated wells, a layer of oil may float on the water. If the oil layer is only a foot or less thick, read the tape at the top of the oil mark and use this reading for the water-level measurement. The measurement will not be greatly in error because the level of the oil surface in this case will differ only slightly from the level of the water surface that would be measured if no oil was present. If several feet of oil are present in the well, or if it is necessary to know the thickness of the oil layer, a water-detector paste for detecting water in oil and gasoline storage tanks is available commercially. The paste is applied to the lower end of the tape that is submerged in the well. It will show the top of the oil as a wet line and the top of the water as a distinct color change.

7.2.3 As a standard of good practice, the observer should make two measurements. If two measurements of static liquid level made within a few minutes do not agree within about 0.01 or 0.02 ft (generally regarded as the practical limit of precision) in boreholes or wells having a depth to liquid of less than a couple of hundred feet, continue to measure until the reason for the lack of agreement is determined or until the results are shown to be reliable. Where water is dripping into the hole or covering its wall, it may be impossible to get a good water mark on the chalked tape.

7.2.4 After each well measurement, in areas where polluted liquids or ground water is suspected, decontaminate that part of the tape measure that was wetted to avoid contamination of other wells.

7.3 *Procedure B—Electrical Measuring Device*:

7.3.1 Check proper operation of the instrument by inserting the tip into water and noting if the contact between the tip and

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

the water surface is registered clearly.

NOTE 5—In pumped wells having a layer of oil floating on the water, the electric tape will not respond to the oil surface and, thus, the liquid level determined will be different than would be determined by a steel tape. The difference depends on how much oil is floating on the water. A miniature float-driven switch can be put on a two-conductor electric tape that permits detection of the surface of the uppermost fluid.

7.3.2 Dry the tip. Slowly lower the tip into the borehole or well until the meter indicates that the tip has contacted the surface of the liquid.

7.3.3 For devices with measurement graduations on the cable, note the reading at the reference point. This is the liquid-level depth below the reference point of the borehole or well.

7.3.4 For measuring devices without graduations on the cable, mark the cable at the reference point. Withdraw the cable from the borehole or well. Stretch out the cable and measure and record the distance between the tip and the mark on the cable by use of a tape. This distance is the liquid-level depth below the reference point.

7.3.5 A second or third check reading should be taken before withdrawing the electric tape from the borehole or well.

7.3.6 Decontaminate the submerged end of the electric tape or cable after measurements in each well.

NOTE 6—The length of the electric line should be checked by measuring with a steel tape after the line has been used for a long time or after it has been pulled hard in attempting to free the line. Some electric lines, especially the single line wire, are subject to considerable permanent stretch. In addition, because the probe is usually larger in diameter than the wire, the probe can become lodged in a well. Sometimes the probe can be attached by twisting the wires together by hand and using only enough electrical tape to support the weight of the probe. In this manner, the point of probe attachment is the weakest point of the entire line. Should the probe become "hung in the hole," the line may be pulled and breakage will occur at the probe attachment point, allowing the line to be withdrawn.

7.4 *Procedure C—Measuring Tape and Sounding Weight*:

7.4.1 Lower a weighted measuring tape into the borehole or well until the liquid surface is reached. This is indicated by an audible splash and a noticeable decrease in the downward force on the tape. Observe and note the reading on the tape at the reference point. Repeat this process until the readings are consistent to the accuracy desired. Record the result as the liquid-level depth below the reference point.

NOTE 7—The splash can be made more audible by using a "plopper," a lead weight with a concave bottom surface.

7.4.2 If the liquid level is deep, or if the measuring tape adheres to the side of the borehole, or for other reasons, it may not be possible to detect the liquid surface using this method. If so, use Procedure A or Procedure B.

8. Determination of a Stabilized Liquid Level

8.1 As liquid flows into or out of the borehole or well, the liquid level will approach, and may reach, a stabilized level. The liquid level then will remain essentially constant with time.

NOTE 8—The time required to reach equilibrium can be reduced by removing or adding liquid until the liquid level is close to the estimated stabilized level.

8.2 Use one of the following two procedures to determine the stabilized liquid level.

8.2.1 *Procedure 1*—Take a series of liquid-level measurements until the liquid level remains constant with time. As a minimum, two such constant readings are needed (more readings are preferred). The constant reading is the stabilized liquid level for the borehole or well.

NOTE 9—If desired, the time and level data could be plotted on graph paper in order to show when equilibrium is reached.

8.2.2 *Procedure 2*—Take at least three liquid-level measurements at approximately equal time intervals as the liquid level changes during the approach to a stabilized liquid level.

8.2.2.1 The approximate position of the stabilized liquid level in the well or borehole is calculated using the following equation:

$$h_o = \frac{{y_1}^2}{y_1 - y_2} \qquad (1)$$

where:

h_o = distance the liquid level must change to reach the stabilized liquid level,

y_1 = distance the liquid level changed during the time interval between the first two liquid-level readings, and

y_2 = distance the liquid level changed during the time interval between the second and the third liquid level readings.

8.2.2.2 Repeat the above process using successive sets of three measurements until the h_o computed is consistent to the accuracy desired. Compute the stabilized liquid level in the well or borehole.

NOTE 10—The time span required between readings for Procedures 1 and 2 depends on the permeability of the earth material. In material with comparatively high permeability (such as sand), a few minutes may be sufficient. In materials with comparatively low permeability (such as clay), many hours or days may be needed. The user is cautioned that in clayey soils the liquid in the borehole or well may never reach a stabilized level equivalent to the liquid level in the earth materials surrounding the borehole or well.

9. Report

9.1 For borehole or well liquid-level measurements, report, as a minimum, the following information:

9.1.1 Borehole or well identification.

9.1.2 Description of reference point.

9.1.3 Distance between reference point and top of borehole or land surface.

9.1.4 Elevation of top of borehole or reference point (if the borehole or well liquid level is reported as an elevation).

9.1.5 Description of measuring device used, and graduation.

9.1.6 Procedure of measurement.

9.1.7 Date and time of reading.

9.1.8 Borehole or well liquid level.

9.1.9 Description of liquid in borehole or well.

9.1.10 State whether borehole is cased, uncased, or contains a monitoring (observation) well standpipe and give description of, and length below top of borehole of, casing or standpipe.

9.1.11 Drilled depth of borehole, if known.

9.2 For determination of stabilized liquid level, report:

9.2.1 All pertinent data and computations.

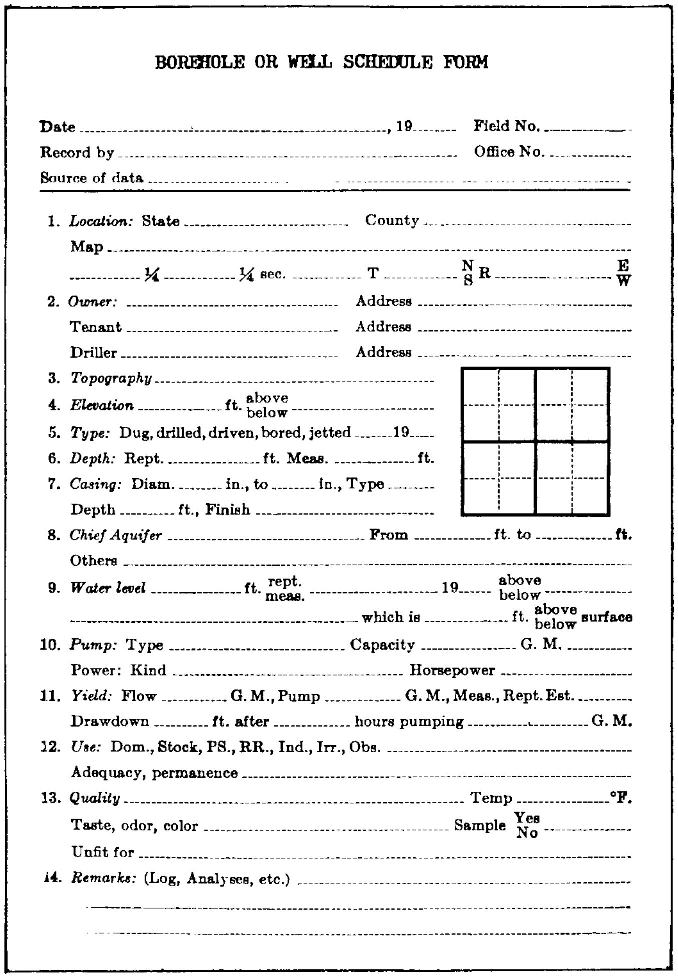
9.2.2 Procedure of determination.

9.2.3 The stabilized liquid level.

9.3 *Report Forms*—An example of a borehole or well-schedule form is shown in Fig. 1. An example of a liquid-level measurement form, for recording continuing measurements for a borehole or well, is shown in Fig. 2. An example of a borehole or well schedule form designed to facilitate computer data storage is shown in Fig. 3.

10. Precision and Bias

10.1 Borehole liquid levels shall be measured and recorded to the accuracy desired and consistent with the accuracy of the measuring device and procedures used. Procedure A multiple measurements by wetted tape should agree within 0.02 ft (6 mm). Procedure B multiple measurements by electrical tape should agree within 0.04 ft (12 mm). Procedure C multiple measurements by tape and sounding weight should agree within 0.04 ft (12 mm). Garber and Koopman **(2)** describe corrections that can be made for effects of thermal expansion of tapes or cables and of stretch due to the suspended weight of tape or cable and plumb weight when measuring liquid levels at depths greater than 500 ft (150 m).

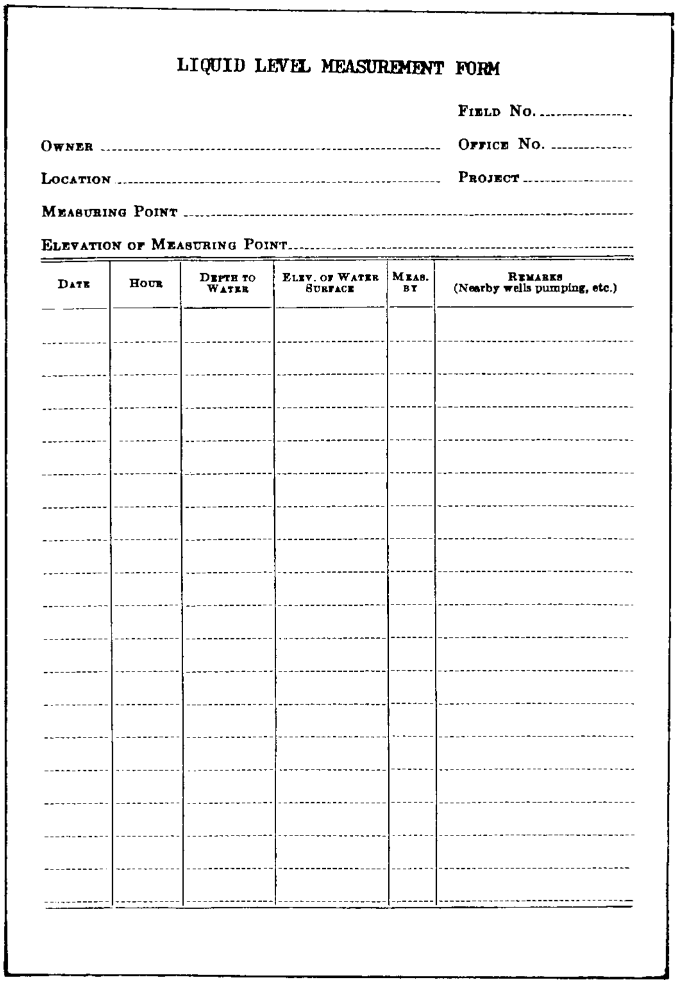


BOREHOLE OR WELL SCHEDULE FORM

Date ...., 19...... Field No. ....
Record by .... Office No. ....
Source of data ....

1. *Location:* State .... County ....
Map ....
.... ¼ .... ¼ sec. .... T .... N/S R .... E/W
2. *Owner:* .... Address ....
Tenant .... Address ....
Driller .... Address ....
3. *Topography* ....
4. *Elevation* .... ft. above/below ....
5. *Type:* Dug, drilled, driven, bored, jetted ......19....
6. *Depth:* Rept. .... ft. Meas. .... ft.
7. *Casing:* Diam. ...... in., to ...... in., Type ......
Depth ...... ft., Finish ....
8. *Chief Aquifer* .... From .... ft. to .... ft.
Others ....
9. *Water level* .... ft. rept./meas. .... 19..... above/below ....
.... which is .... ft. above/below surface
10. *Pump:* Type .... Capacity .... G. M. ....
Power: Kind .... Horsepower ....
11. *Yield:* Flow .... G. M., Pump .... G. M., Meas., Rept. Est. ....
Drawdown .... ft. after .... hours pumping .... G. M.
12. *Use:* Dom., Stock, PS., RR., Ind., Irr., Obs. ....
Adequacy, permanence ....
13. *Quality* .... Temp .... °F.
Taste, odor, color .... Sample Yes/No ....
Unfit for ....
14. *Remarks:* (Log, Analyses, etc.) ....

FIG. 1 Example of a Borehole or Well Schedule Form



LIQUID LEVEL MEASUREMENT FORM

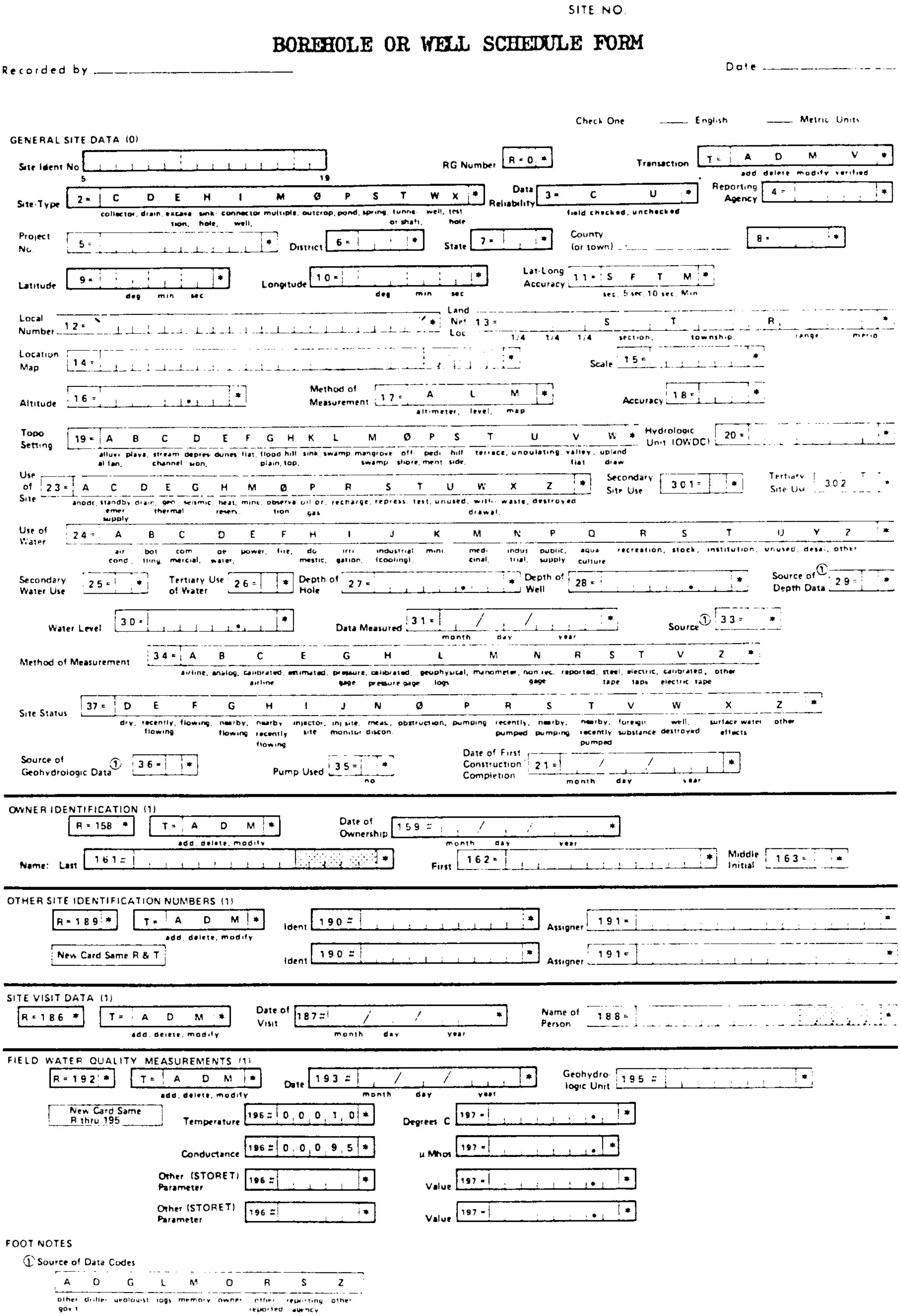
Field No. ....
Owner .... Office No. ....
Location .... Project ....
Measuring Point ....
Elevation of Measuring Point ....

Date	Hour	Depth to Water	Elev. of Water Surface	Meas. by	Remarks (Nearby wells pumping, etc.)

FIG. 2 Example of a Liquid Level Measurement Form

11. Keywords

11.1 borehole; electrical measuring device; ground water; liquid level; measuring tape; well



SITE NO.

BOREHOLE OR WELL SCHEDULE FORM

Recorded by ____________________ Date ____________

Check One ____ English ____ Metric Units

GENERAL SITE DATA (0)

Site Ident No [ ] 5 19 — RG Number R = 0 * — Transaction T = A D M V * (add, delete, modify, verified)

Site-Type 2 = C D E H I M 0 P S T W X * (collector, drain, excavation, sink hole, connector well, multiple, outcrop, pond, spring, tunnel or shaft, well, test hole) — Data Reliability 3 = C U * (field checked, unchecked) — Reporting Agency 4 = *

Project No. 5 = * — District 6 = * — State 7 = * — County (or town) ______ 8 = *

Latitude 9 = * (deg min sec) — Longitude 10 = * (deg min sec) — Lat-Long Accuracy 11 = S F T M * (sec, 5 sec, 10 sec, Min)

Local Number 12 = * — Land Net Loc 13 = S T R * (1/4 1/4 1/4 section, township, range, merid)

Location Map 14 = * — Scale 15 = *

Altitude 16 = * — Method of Measurement 17 = A L M * (altimeter, level, map) — Accuracy 18 = *

Topo Setting 19 = A B C D E F G H K L M 0 P S T U V W * (alluvial fan, playa, stream channel, depression, dunes, flat, flood plain, hill top, sink, swamp, mangrove swamp, off shore, pediment, hill side, terrace, undulating, valley flat, upland draw) — Hydrologic Unit (OWDC) 20 = *

Use of Site 23 = A C D E G H M 0 P R S T U W X Z * (anode, standby emer supply, drain, geothermal, seismic, heat reservoir, mine, observation, oil or gas, recharge, repress, test, unused, withdrawal, waste, destroyed) — Secondary Site Use 301 = * — Tertiary Site Use 302 *

Use of Water 24 = A B C D E F H I J K M N P Q R S T U Y Z * (air cond, bottling, commercial, dewater, power, fire, domestic, irrigation, industrial (cooling), mining, medicinal, industrial, public supply, aquaculture, recreation, stock, institution, unused, desal, other)

Secondary Water Use 25 = * — Tertiary Use of Water 26 = * — Depth of Hole 27 = * — Depth of Well 28 = * — Source of ① Depth Data 29 = *

Water Level 30 = * — Data Measured 31 = / / * (month day year) — Source ① 33 = *

Method of Measurement 34 = A B C E G H L M N R S T V Z * (airline, analog, calibrated airline, estimated, pressure gage, calibrated pressure gage, geophysical logs, manometer, non rec. gage, reported, steel tape, electric tape, calibrated electric tape, other)

Site Status 37 = D E F G H I J N 0 P R S T V W X Z * (dry, recently flowing, flowing, nearby flowing, nearby recently flowing, injector site, inj site monitor, meas. discon., obstruction, pumping, recently pumped, nearby pumping, nearby recently pumped, foreign substance, well destroyed, surface water effects, other)

Source of Geohydrologic Data ① 36 = * — Pump Used 35 = * (no) — Date of First Construction Completion 21 = / / * (month day year)

OWNER IDENTIFICATION (1)

R = 158 * — T = A D M * (add, delete, modify) — Date of Ownership 159 = / / * (month day year)

Name: Last 161 = * — First 162 = * — Middle Initial 163 = *

OTHER SITE IDENTIFICATION NUMBERS (1)

R = 189 * — T = A D M * (add, delete, modify) — Ident 190 = * — Assigner 191 = *

New Card Same R & T — Ident 190 = * — Assigner 191 = *

SITE VISIT DATA (1)

R = 186 * — T = A D M * (add, delete, modify) — Date of Visit 187 = / / * (month day year) — Name of Person 188 = *

FIELD WATER QUALITY MEASUREMENTS (1)

R = 192 * — T = A D M * (add, delete, modify) — Date 193 = / / * (month day year) — Geohydrologic Unit 195 = *

New Card Same R thru 195

Temperature 196 = 0 0 0 1 0 * — Degrees C 197 = . *

Conductance 196 = 0 0 0 9 5 * — µ Mhos 197 = . *

Other (STORET) Parameter 196 = * — Value 197 = . *

Other (STORET) Parameter 196 = * — Value 197 = . *

FOOT NOTES

① Source of Data Codes

A D G L M O R S Z (other gov't, driller, geologist, logs, memory, owner, other reported, reporting agency, other)

FIG. 3 Example of a Borehole or Well Schedule Form

REFERENCES

(**1**) "*National Handbook of Recommended Methods for Water Data Acquisition—Chapter 2—Ground Water*", Office of Water Data Coordination, Washington, DC, 1980.

(**2**) Garber, M. S., and Koopman, F. C., "Methods of Measuring Water Levels in Deep Wells," *U.S. Geologic Survey Techniques for Water Resources Investigations*, Book 8, Chapter A-1, 1968.

(**3**) Hvorslev, M. J., "Ground Water Observations," in *SubsurfaceExploration and Sampling of Soils for Civil Engineering Purposes*, American Society Civil Engineers, New York, NY, 1949.

(**4**) Zegarra, E. J., "Suggested Method for Measuring Water Level in Boreholes," *Special Procedures for Testing Soil and Rock for Engineering Purposes, ASTM STP 479*, ASTM, 1970.

(**5**) "Determination of Water Level in a Borehole," CSA Standard A 119.6 – 1971, Canadian Standards Association, 1971.

Designation: D 5269 – 96 (Reapproved 2002)

Standard Test Method for Determining Transmissivity of Nonleaky Confined Aquifers by the Theis Recovery Method[1]

This standard is issued under the fixed designation D 5269; 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 of a confined aquifer. This test method is used to analyze data from the recovery of water levels following pumping or injection of water to or from a control well at a constant rate.

1.2 The analytical procedure given in this test method is used in conjunction with the field procedure in Test Method D 4050.

1.3 *Limitations*—The valid use of the Theis recovery method is limited to determination of transmissivities for aquifers in hydrogeologic settings with reasonable correspondence to the assumptions of the Theis theory (see 5.1).

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:*

D 653 Terminology Relating to Soil, Rock and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—a well by which the aquifer is stressed, for example, by pumping, injection, or change of head.

3.1.4 *drawdown*—vertical distance the static head is lowered due to the removal of water.

3.1.5 *hydraulic conductivity (field aquifer tests)*—the volume of water at the existing kinematic viscosity that will move in a unit time under unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.6 *observation well*—a well open to all or part of an aquifer.

3.1.7 *piezometer*—a device used to measure head at a point in the subsurface.

3.1.8 *residual drawdown*—The difference between the projected prepumping water-level trend and the water level in a well or piezometer after pumping or injection has stopped.

3.1.9 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.10 *step-drawdown test*—a test in which a control well is pumped at constant rates in "steps" of increasing discharge. Each step is approximately equal in duration, although the last step may be prolonged.

3.1.11 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer it is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.12 *transmissivity*—the volume of water of the prevailing kinematic viscosity transmitted in a unit time through a unit width of the aquifer under a unit hydraulic gradient.

3.2 *Symbols:*Symbols and Dimensions:

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

Current edition approved Oct. 10, 1996. Published June 1997. Originally published as D 5269 – 92.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.1 b [L]—aquifer thickness.

3.2.2 K [LT^{-1}]—hydraulic conductivity.

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

3.2.3 K_r—hydraulic conductivity in the plane of the aquifer, radially from the control well.

3.2.4 K_z—hydraulic conductivity in the vertical direction.

3.2.5 ln—natural logarithm.

3.2.6 $\log_{10}$—logarithm to the base 10.

3.2.7 Q [L^3T^{-1}]—discharge.

3.2.8 r [L]—radial distance from control well.

3.2.9 r_c [L]—equivalent inside radius of control well.

3.2.10 S [nd]—storage coefficient.

3.2.11 s [L]—drawdown.

3.2.12 s_c [L]—drawdown corrected for the effects of reduction in saturated thickness.

3.2.13 S_y [nd]—specific yield.

3.2.14 s' *[L]*—residual drawdown.

3.2.15 $\Delta s'$ [L]—change in residual drawdown over one log cycle of t/t'.

3.2.16 T [L^2T^{-1}]—transmissivity.

3.2.17 t [T]—time since pumping or injection began.

3.2.18 t' [T]—time since pumping or injection stopped.

3.2.19 u—dimensionless parameter, equal to $r^2S/4Tt$.

3.2.20 u'—dimensionless parameter, equal to $r^2S/4Tt'$.

4. Summary of Test Method

4.1 This test method describes an analytical procedure for determining transmissivity using data collected during the recovery phase of a withdrawal or injection well test. The field test (see Test Method D 4050) requires pumping or injecting a control well that is open to the entire thickness of a confined aquifer at a constant rate for a specified period. The water-levels in the control well, observation wells, or piezometers are measured after pumping is stopped and used to calculate the transmissivity of the aquifer using the procedures in this test method. Alternatively, this test method can be performed by injecting water into the control well at a constant rate. With some modification, this test method can also be used to analyze the residual drawdown following a step test. This test method is used by plotting residual drawdown against either a function of time or a function of time and discharge and determining the slope of a straight line fitted to the points.

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

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy \qquad (1)$$

and:

$$u = \frac{r^2S}{4Tt} \qquad (2)$$

4.3 At a control well, observation well, or piezometer, for large values of time, t, and small values of radius, r, the Theis equation reduces, as shown by Cooper and Jacob **(2)** and Jacob **(3)** to the following:

$$s' = \frac{Q}{4\pi T}\,ln(t/t') \qquad (3)$$

where:

t = the time after pumping began and

t' = the time after pumping ceases. From which it can be shown that:

$$T = \frac{2.3Q}{4\pi\Delta s'} \qquad (4)$$

where:

$\Delta s'$ = the measured or projected residual drawdown over one $\log_{10}$ cycle of t/t'.

4.4 A similar analysis (see 4.3) may also be used for a step-drawdown test in which a well is pumped at a constant rate for an initial period, and then the pumping rate is increased through several new constant rates in a series of steps. Harrill **(4)** shows that:

$$s' = \frac{2.3\Delta Q_1}{4\pi T}\left(\log_{10}\frac{t_1}{t'}\right) + \frac{2.3\Delta Q_2}{4\pi T}\left(\log_{10}\frac{t_2}{t'}\right) + \ldots \frac{2.3\Delta Q_n}{4\pi T}\left(\log_{10}\frac{t_n}{t'}\right) \qquad (5)$$

where:

$t_1, t_2, \ldots t_n$ = the elapsed times since either pumping was begun or the discharge rate was increased,

$Q_1, Q_2, \ldots Q_n$ = the well discharge rates, and

$\Delta Q_1, \Delta Q_2 \ldots \Delta Q_n$ = the incremental increases in discharge.

Eq 5 can be rewritten as follows:

$$T = \frac{2.3Q_n}{4\pi s'}\log_{10}f(t, Q) \qquad (6)$$

where:

$$f(t, Q) = \frac{t_1^{\Delta Q_1/Q_n}t_2^{\Delta Q_2/Q_n}t_3^{\Delta Q_3/Q_n}\ldots t_n^{\Delta Q_n/Q_n}}{t'} \qquad (7)$$

and:

$$T = \frac{2.3Q_n}{4\pi\Delta s'_h} \qquad (8)$$

where:

$\Delta s'_h$ = the residual drawdown over one log cycle of the expression $f(t, Q)$ in Eq 6.

Eq 8 can also be used to analyze the residual drawdown following a test in which discharge varies significantly, so long as the discharge can be generalized as a series of constant-discharge steps.

5. Significance and Use

5.1 *Assumptions*:

5.1.1 The well discharges at a constant rate, Q, or at steps of

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

constant rate Q_1, Q_2... Q_n.

5.1.2 Well is of infinitesimal diameter and is open through the full thickness of the aquifer.

5.1.3 The nonleaky aquifer is homogeneous, isotropic, and areally extensive.

5.1.4 Discharge from the well is derived exclusively from storage in the aquifer.

5.1.5 The geometry of the assumed aquifer and well are shown in Fig. 1.

5.2 *Implications of Assumptions*:

5.2.1 Implicit in the assumptions are the conditions of radial flow. Vertical flow components are induced by a control well that partially penetrates the aquifer, that is, not open to the aquifer through the full thickness of the aquifer. If vertical flow components are significant, the nearest partially penetrating observation well should be located at a distance, *r*, beyond which vertical flow components are negligible. See 5.2.1 of Test Method D 4106 for assistance in determining the minimum distance to partially penetrating observation wells and piezometers.

5.2.2 The Theis 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 D 4106 for assistance in determining the duration of the effects of well-bore storage on drawdown.

5.2.3 *Application of Theis Recovery Method for Unconfined Aquifers*:

5.2.3.1 Although the assumptions are applicable to artesian or confined conditions, the Theis solution may be applied to unconfined aquifers if (*A*) drawdown is small compared with the saturated thickness of the aquifer or if the drawdown is corrected for reduction in thickness of the aquifer and (*B*) the effects of delayed gravity yield are small. See 5.2.3 of Test Method D 4106 for guidance in treating reduction in saturated thickness and delayed gravity drainage in unconfined aquifers.

6. Apparatus

6.1 Analysis of data by this test method from the field procedure given in Test Method D 4050 requires that the control well and observation wells meet the requirements specified in the following subsections.

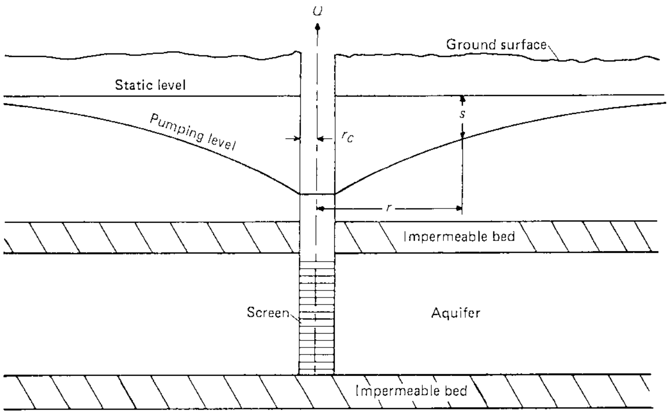

FIG. 1 Cross Section Through a Discharging Well in a Nonleaky Aquifer

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, or several steps at constant rate, for the duration of the test. Preferably, the control well should be open throughout the full thickness of the aquifer. If the control well partially penetrates the aquifer, take special precautions in the placement or design of observation wells (see 5.2.1).

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

6.4 *Location of Observation Wells and Piezometers*—Wells may be located at any distance from the control well within the area of influence of pumping. However, if vertical flow components are significant and if piezometers or partially penetrating observation wells are used, locate them at a distance beyond the effect of vertical flow components. If the aquifer is unconfined, constraints are imposed on the distance to partially penetrating observation wells and the validity of early time measurements (see 5.2.1).

7. Procedure

7.1 The overall procedure consists of conducting the field procedure for withdrawal or injection well tests (described in Test Method D 4050) and analysis of the field data, which is addressed in Section 8.

8. Calculation and Interpretation of Results

8.1 The Theis recovery method gives satisfactory results when properly used. However, the method is valid only for small values of *u*, that is:

for confined aquifers:

$$u' = \frac{r^2 S}{4Tt'} \tag{9}$$

or for unconfined aquifers:

$$u' = \frac{r^2 S_y}{4Tt'} \tag{10}$$

NOTE 1—The limiting value for *u* of less than 0.01 may be excessively restrictive in some applications. The errors for small values of *u*, from Kruseman and De Ridder **(5)** are:

Error less than, %	1	2	5	10
For *u* smaller than	0.03	0.05	0.1	0.15

8.1.1 This test method allows only the calculation of transmissivity, *T*, not storage coefficient, *S*, or specific yield, S_y. Therefore, to determine whether the assumption in Eq 9 or Eq 10 has been violated it is necessary to estimate a value for storage coefficient for confined aquifers or specific yield for unconfined aquifers. If data are available during the pumping period, the storage may be computed using the procedures in Test Method D 4105. Storage coefficients can be estimated as about $3 \times 10^{-5}b$, where *b* is aquifer thickness in meters. Whereas the specific yield of unconfined aquifers averages about 0.2 according to Lohman **(6)**. After calculating *T*, substitute the appropriate values into Eq 9 or Eq 10 and solve for u'. It is not adequate to simply note that the data described a straight line on semi-log graph paper.

8.2 Plot either residual drawdown, s', or water level, on the arithmetic axis of semilogarithmic graph paper versus either t/t' (for recovery from a constant-discharge test) (see Fig. 2) or $f(t, Q)$ (for recovery from a step-drawdown test) (see Fig. 3) on the logarithmic axis. Fit a straight line to the linear part of the data plot, usually at smaller values of t/t'. Extend the straight line to intercept the $t/t' = 1$ axis. At $t/t' = 1$, residual drawdown should be approximately equal to zero, or if water levels were plotted, the intercept should be equal to the prepumping water levels corrected for prepumping water-level trends. Substitute the values for $\Delta s'$ or $\Delta s'_h$ in Eq 4 or Eq 8 and solve for transmissivity. Check that all values of t' for the points used in defining the straight line meet the criterion that $u' < 0.01$ (Eq 9 and Eq 10), as described in 8.1.

9. Report

9.1 Prepare a report including the information described below. The report of the analysis will include information from the field testing procedure.

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the Theis recovery method for determining transmissivity in a confined nonleaky aquifer. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells and piezometers, the method of measurement of discharge and water levels, and the duration of the test and pumping rates. Discuss rationale for selecting the Theis recovery method.

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site. Include driller's logs and geologist's description of drill cuttings. Interpret and describe the hydrogeology of the site as it pertains to the selection of this method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Scope of Aquifer Test*:

9.1.3.1 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened interval, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells or piezometers.

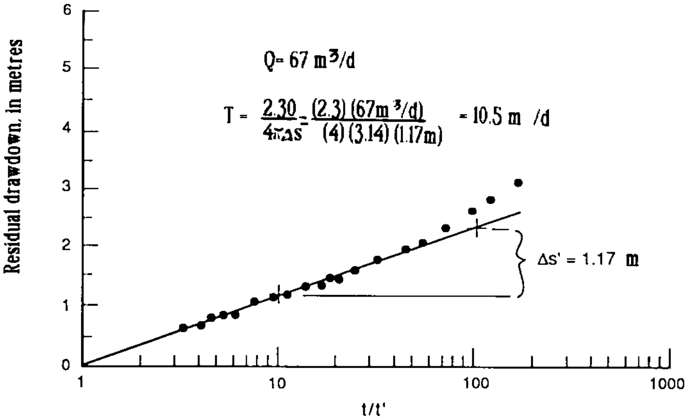

FIG. 2 Example Analysis Using the Theis Recovery Method

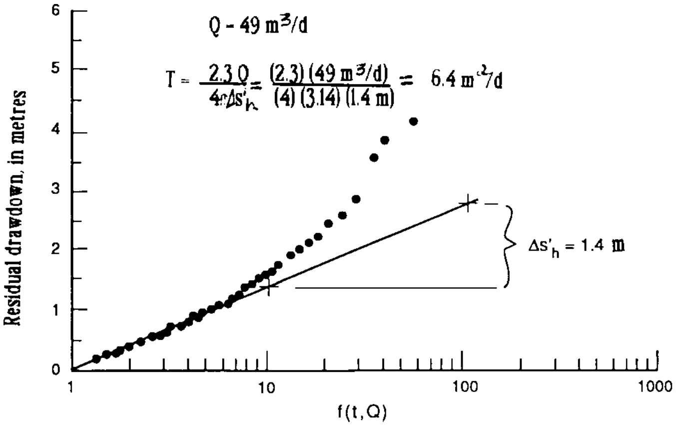

FIG. 3 Example Analysis Using Harrill's Method

9.1.3.2 *Instrumentation*—Report the field instrumentation for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturer's name, model number, and basic specifications for each major item, and the name and date of the last calibration, if applicable.

9.1.3.3 *Testing Procedures*—State the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.4 *Presentation of Interpretation of Test Results*:

9.1.4.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for barometric changes and calculation of drawdown and residual drawdown.

9.1.4.2 *Data Plots*—Present data plots used in analysis of the data. Show data plots with straight line segments and intercepts of the $t/t' = 1$ axis.

9.1.4.3 Evaluate qualitatively the overall accuracy of the test on the basis of the adequacy of instrumentation and observations of stress end response, and the conformance of the hydrogeologic conditions and the performance of the test to the assumptions of the test method (see 5.1) and the implications of the assumptions (see 5.2).

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; confined aquifers; control wells; ground water; hydraulic properties; observation wells; step tests; transmissivity; unconfined aquifers

REFERENCES

(**1**) Theis, C. V., "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage," *American Geophysical Union Transactions*, Vol 16, Part 2, 1935, p. 519–524.

(**2**) Cooper, H. H., and Jacob, C. E., "A Generalized Graphical Method for Evaluating Formation Constants and Summarizing Well-Field History," *Trans. Amer. Geophys. Union*, Vol 27, 1946, pp. 526–534.

(**3**) Jacob, C. E., "The Recovery Method for Determining the Coefficient of Transmissibility," *in* Bentall, Ray, Compiler, "Methods of Determining Permeability, Transmissibility, and Drawdown," *U.S. Geological Survey Water-Supply Paper 1536-I*, 1963, pp. 288–292.

(**4**) Harrill, J. R., "Determining Transmissivity from Water-Level Recovery of a Step-Drawdown Test," *U.S. Geological Survey Professional Paper 700-C*, 1970.

(**5**) Kruseman, G. P., and DeRidder, N. S., "Analysis and Evaluation of Pumping Test Data," Intern. Inst. for Land and Reclamation and Improvement, Bull. 47 Wageningen, The Netherlands, 1990.

(**6**) Lohman, S. W., "Ground-Water Hydraulics," *U.S. Geological Survey Professional Paper 708*, 1970.

Designation: D 5270 – 96 (Reapproved 2002)

Standard Test Method for Determining Transmissivity and Storage Coefficient of Bounded, Nonleaky, Confined Aquifers[1]

1. Scope

1.1 This test method covers an analytical procedure for determining the transmissivity, storage coefficient, and possible location of boundaries for a confined aquifer with a linear boundary. This test method is used to analyze water-level or head data from one or more observation wells or piezometers during the pumping of water from a control well at a constant rate. This test method also applies to flowing artesian wells discharging at a constant rate. With appropriate changes in sign, this test method also can be used to analyze the effects of injecting water into a control well at a constant rate.

1.2 The analytical procedure in this test method is used in conjunction with the field procedure in Test Method D 4050.

1.3 *Limitations*—The valid use of this test method is limited to determination of transmissivities and storage coefficients for aquifers in hydrogeologic settings with reasonable correspondence to the assumptions of the Theis nonequilibrium method (see Test Method D 4106) (see 5.1), except that the aquifer is limited in areal extent by a linear boundary that fully penetrates the aquifer. The boundary is assumed to be either a constant-head boundary (equivalent to a stream or lake that hydraulically fully penetrates the aquifer) or a no-flow (impermeable) boundary (equivalent to a contact with a significantly less permeable rock unit). The Theis nonequilibrium method is described in Test Methods D 4105 and D 4106.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *constant-head boundary*—the conceptual representation of a natural feature such as a lake or river that effectively fully penetrates the aquifer and prevents water-level change in the aquifer at that location.

3.1.2 *equipotential line*—a line connecting points of equal hydraulic head. A set of such lines provides a contour map of a potentiometric surface.

3.1.3 *image well*—an imaginary well located opposite a control well such that a boundary is the perpendicular bisector of a straight line connecting the control and image wells; used to simulate the effect of a boundary on water-level changes.

3.1.4 *impermeable boundary*—the conceptual representation of a natural feature such as a fault or depositional contact that places a boundary of significantly less-permeable material laterally adjacent to an aquifer.

3.1.5 See Terminology D 653 for other terms.

3.2 *Symbols and Dimensions*:

3.2.1 K_l [nd]—constant of proportionality, r_i / r_r.

3.2.2 Q [L^3T^{-1}]—discharge.

3.2.3 r [L]—radial distance from control well.

3.2.4 r_i [L]—distance from observation well to image well.

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.5 r_r [L]—distance from observation well to control well.
3.2.6 S [nd]—storage coefficient.
3.2.7 s [L]—drawdown.
3.2.8 s_i [L]—component of drawdown due to image well.
3.2.9 s_o [L]—drawdown at an observation well.
3.2.10 s_r [L]—component of drawdown due to control well.
3.2.11 T [L^2T^{-1}]—transmissivity.
3.2.12 t [T]—time since pumping or injection began.
3.2.13 t_o [T]—time at projection of zero drawdown.

4. Summary of Test Method

4.1 This test method prescribes two analytical procedures for analysis of a field test. This test method requires pumping water from, or injecting water into, a control well that is open to the entire thickness of a confined bounded aquifer at a constant rate and measuring the water-level response in one or more observation wells or piezometers. The water-level response in the aquifer is a function of the transmissivity and storage coefficient of the aquifer, and the location and nature of the aquifer boundary or boundaries. Drawdown or build up of the water level is analyzed as a departure from the type curve defined by the Theis nonequilibrium method (see Test Method D 4106) or from straight-line segments defined by the modified Theis nonequilibrium method (see Test Method D 4105).

4.2 A constant-head boundary such as a lake or stream that fully penetrates the aquifer prevents drawdown or build up of head at the boundary, as shown in Fig. 1. Likewise, an impermeable boundary provides increased drawdown or build up of head, as shown in Fig. 2. These effects are simulated by treating the aquifer as if it were infinite in extent and introducing an imaginary well or "image well" on the opposite side of the boundary a distance equal to the distance of the control well from the boundary. A line between the control well and the image well is perpendicular to the boundary. If the boundary is a constant-head boundary, the flux from the image well is opposite in sign from that of the control well; for example, the image of a discharging control well is an injection well, whereas the image of an injecting well is a discharging well. If the boundary is an impermeable boundary, the flux from the image well has the same sign as that from the control well. Therefore, the image of a discharging well across an impermeable boundary is a discharging well. Because the effects are symmetrical, only discharging control wells will be described in the remainder of this test method, but this test method is equally applicable, with the appropriate change in sign, to control wells into which water is injected.

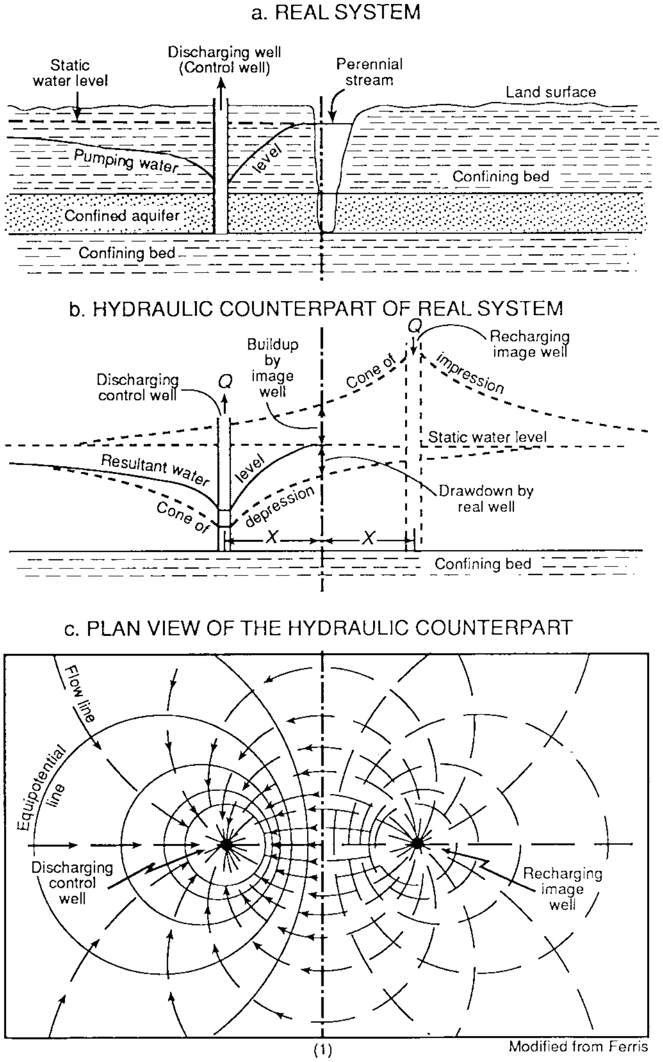
4.3 *Solution*—The solution given by Theis **(1)**[3] can be expressed as follows:

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-y}}{y}\,dy \tag{1}$$

and:

$$u = \frac{r^2S}{4Tt} \tag{2}$$

where:



NOTE 1—Modified from Ferris and others **(6)** and Heath **(7)**.

FIG. 1 Diagram Showing Constant-Head Boundary

$$\int_u^\infty \frac{e^{-y}}{y}\,dy = W(u) = -0.577216 - \log_e u + u - \frac{u^2}{2!2} + \frac{u^3}{3!3} - \frac{u^4}{4!4} + ... \tag{3}$$

4.4 According to the principle of superposition, the drawdown at any point in the aquifer is the sum of the drawdown due to the real and image wells **(1)** and **(2)**:

$$s_o = s_r \pm s_i \tag{4}$$

Equation **(4)** can be rewritten as follows:

$$s_o = \frac{Q}{4\pi T}[W(u_r) \pm W(u_i)] = \frac{Q}{4\pi T}\Sigma\, W(u) \tag{5}$$

where:

$$u_r = \frac{{r_r}^2S}{4Tt},\ u_i = \frac{{r_i}^2S}{4Tt} \tag{6}$$

so that:

$$u_i = \left(\frac{r_i}{r_r}\right)^2 u_r,\ u_i = {K_l}^2u_r \tag{7}$$

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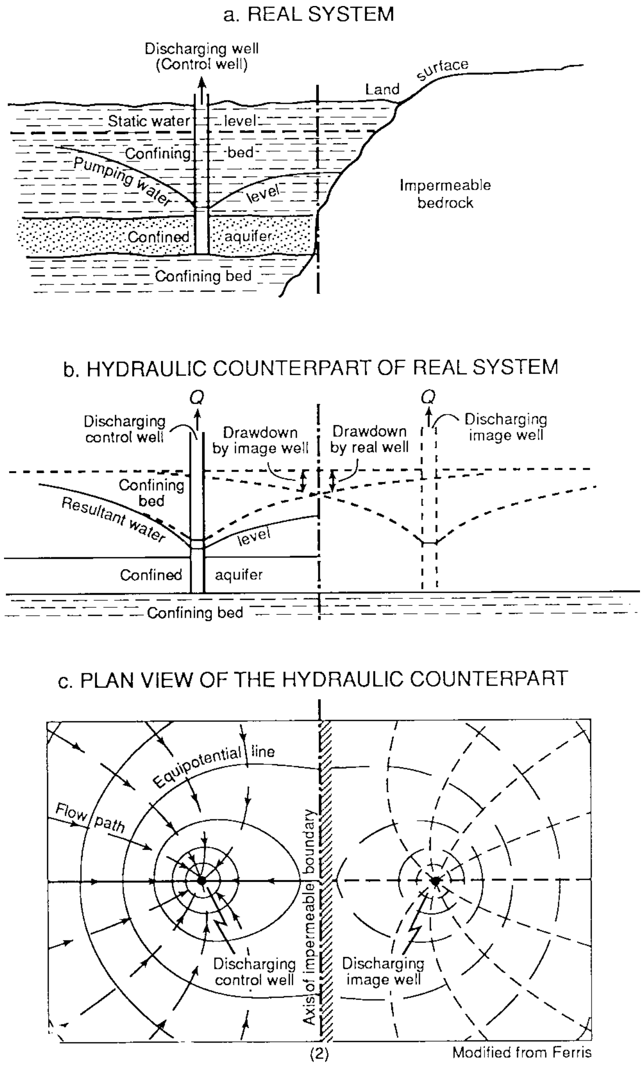
[3] The boldface numbers given in parentheses refer to a list of references at the end of the text.



NOTE 1—Modified from Ferris and others **(6)** and Heath **(7)**.

FIG. 2 Diagram Showing Impermeable Boundary

where:

$$K_l = \frac{r_i}{r_r} \qquad (8)$$

NOTE 1—K_l is a constant of proportionality between the radii, not to be confused with hydraulic conductivity.

5. Significance and Use

5.1 *Assumptions*:

5.1.1 The well discharges at a constant rate.

5.1.2 Well is of infinitesimal diameter and is open through the full thickness of the aquifer.

5.1.3 The nonleaky confined aquifer is homogeneous, isotropic, and areally extensive except where limited by linear boundaries.

5.1.4 Discharge from the well is derived initially from storage in the aquifer; later, movement of water may be induced from a constant-head boundary into the aquifer.

5.1.5 The geometry of the assumed aquifer and well are shown in Fig. 1 or Fig. 2.

5.1.6 Boundaries are vertical planes, infinite in length that fully penetrate the aquifer. No water is yielded to the aquifer by impermeable boundaries, whereas recharging boundaries are in perfect hydraulic connection with the aquifer.

5.1.7 Observation wells represent the head in the aquifer; that is, the effects of wellbore storage in the observation wells are negligible.

5.2 *Implications of Assumptions*:

5.2.1 Implicit in the assumptions are the conditions of a fully-penetrating control well and observation wells of infinitesimal diameter in a confined aquifer. Under certain conditions, aquifer tests can be successfully analyzed when the control well is open to only part of the aquifer or contains a significant volume of water or when the test is conducted in an unconfined aquifer. These conditions are discussed in more detail in Test Method D 4105.

5.2.2 In cases in which this test method is used to locate an unknown boundary, a minimum of three observation wells is needed. If only two observation wells are available, two possible locations of the boundary are defined, and if only one observation well is used, a circle describing all possible locations of the image well is defined.

5.2.3 The effects of a constant-head boundary are often indistinguishable from the effects of a leaky, confined aquifer. Therefore, care must be taken to ensure that a correct conceptual model of the system has been created prior to analyzing the test. See Guide D 4043.

6. Apparatus

6.1 Analysis of the data from the field procedure (see Test Method D 4050) 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. Preferably, the control well should be open throughout the full thickness of the aquifer. If the control well partially penetrates the aquifer, take special precautions in the placement or design of observation wells (see 5.2.1).

6.3 *Construction of Observation Wells and Piezometers*—Construct one or more observation wells or piezometers at specified distances from the control well.

6.4 *Location of Observation Wells and Piezometers*—Wells may be located at any distance from the control well within the area of influence of pumping. However, if vertical flow components are expected to be significant near the control well and if partially penetrating observation wells are to be used, the observation wells should be located at a distance beyond the effect of vertical flow components. If the aquifer is unconfined, constraints are imposed on the distance to partially penetrating observation wells and on the validity of early time measurements (see Test Method D 4106).

NOTE 2—To ensure that the effects of the boundary may be observed during the tests, some of the wells should be located along lines parallel to the suspected boundary, no farther from the boundary than the control well.

7. Procedure

7.1 The general procedure consists of conducting the field procedure for withdrawal or injection wells tests (see Test

Method D 4050) and analyzing the field data, as addressed in this test method.

7.2 Analysis of the field data consists of two steps: determination of the properties of the aquifer and the nature and distance to the image well from each observation well, and determination of the location of the boundary.

7.3 Two methods of analysis can be used to determine the aquifer properties and the nature and distance to the image well. One method is based on the Theis nonequilibrium method; the other method is based on the modified Theis nonequilibrium method.

7.3.1 *Theis Nonequilibrium Method*—Expressions in Eq 5-8 are used to generate a family of curves of $1/u_r$ versus $\Sigma\ W\ (u)$ for values of K_l for recharging and discharging image wells as shown in Fig. 3 **(2)**. Table 1 gives values of $W\ (u)$ versus $1/u$. This table may be used to create a table of $\Sigma W\ (u)$ versus $1/u$ for each value of K_l by picking values for $W\ (u_r)$ and $W\ (u_i)$, and computing the $\Sigma\ W\ (u)$ for the each value of 1/u.

7.3.1.1 Transmissivity, storage coefficient, and the possible location of one or more boundaries are calculated from parameters determined from the match point and a curve selected from a family of type curves.

7.3.2 *Modified Theis Nonequilibrium Method*—The sum of the terms to the right of $\log_e u$ in Eq 3 is not significant when u becomes small, that is, equal to or less than 0.01.

NOTE 3—The limiting value for u of less than 0.01 may be excessively restrictive in some applications. The errors for small values of u, from Kruseman and DeRidder **(3)** are as follows:

Error less than, %:	1	2	5	10
For u smaller than:	0.03	0.05	0.1	0.15

7.3.2.1 The value of u decreases as time, t, increases and decreases as radial distance, r, decreases. Therefore, for large values of t and small values of r, the terms to the right of $\log_e u$ in Eq 3 may be neglected, as recognized by Theis **(1)**. The modified Theis equation can then be written as follows:

$$s = \frac{Q}{4\pi T}\left(-0.577216 - \log_e\left(\frac{r^2S}{4Tt}\right)\right) \qquad (9)$$

from which it has been shown by Lohman **(4)** that:

$$T = \frac{2.3Q}{4\pi\Delta s} \qquad (10)$$

where:

Δs = the drawdown (measured or projected) over one log cycle of time.

8. Calculation and Interpretation of Results

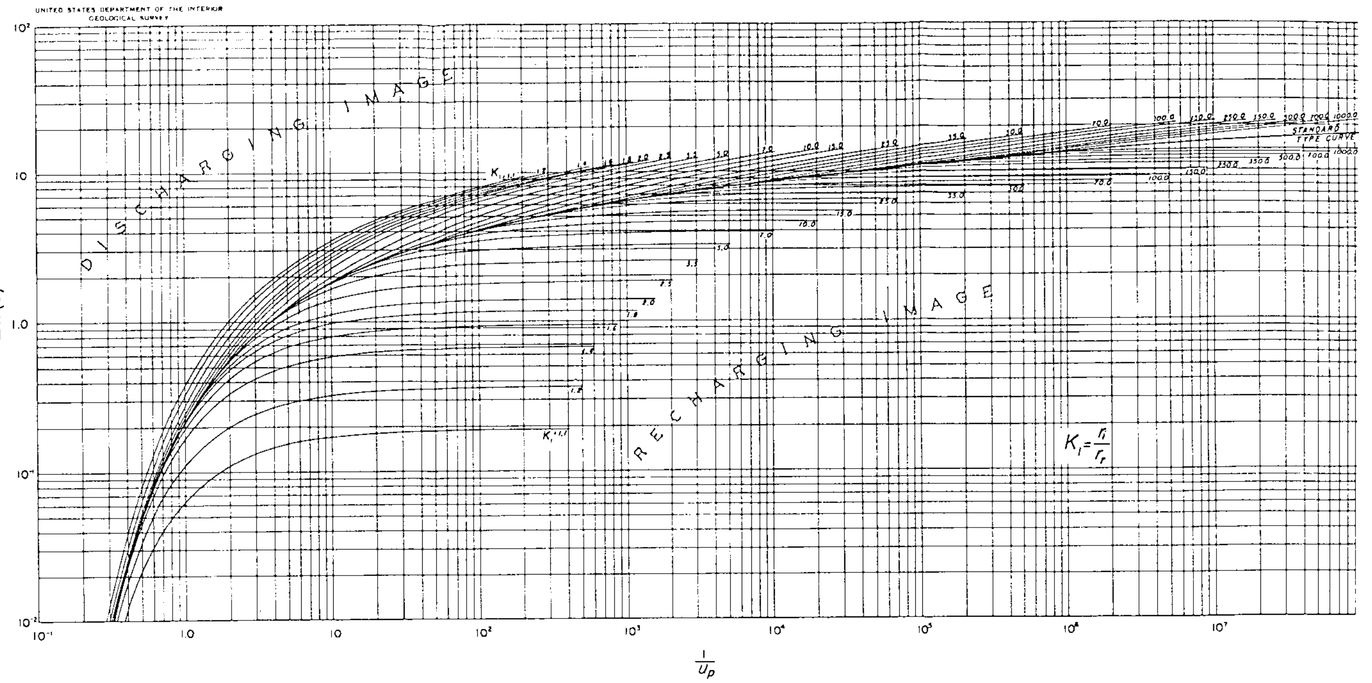
8.1 Determine the aquifer properties and the nature and distance to the image well by either the Theis nonequilibrium method or the modified Theis method.

8.1.1 *Theis Nonequilibrium Method*—The graphical procedure for solution by the Theis nonequilibrium method is based on the relationship between $\Sigma W\ (u)$ and s, and between $1/u$ and t/r^2.

8.1.1.1 Plot the log of values of $\Sigma W\ (u)$ on the vertical coordinate and $1/u$ on the horizontal coordinate. Plot a family of curves for several values of K_l, for both recharging and discharging images. This plot (see Fig. 3) is referred to as a family of type curves. Plots of the family of type curves are contained in **(2)** and **(4)**.

8.1.1.2 Plot values of the log of drawdown, s, on the vertical coordinate versus the log of t/r^2 on the horizontal coordinate. Use a different symbol for data from each observation well.

8.1.1.3 Overlay the data plot on the type curve plot and, while the coordinate axes are held parallel, shift the plot to



NOTE 1—From Stallman **(2)**.

FIG. 3 Family of Type Curves for the Solution of the Modified Theis Formula

TABLE 1 Values of Theis equation *W(u)* for values of *1/u* (8)

1/u	*1/u* × 10^{-1}	1	10	10^2	10^3	10^4	10^4	10^4
1.0	0.00000[A]	0.21938	1.82292	4.03793	6.33154	8.63322	10.93572	13.23830
1.2	0.00003	0.29255	1.98932	4.21859	6.51369	8.81553	11.11804	13.42062
1.5	0.00017	0.39841	2.19641	4.44007	6.73667	9.03866	11.34118	13.64376
2.0	0.00115	0.55977	2.46790	4.72610	7.02419	9.32632	11.62886	13.93144
2.5	0.00378	0.70238	2.68126	4.94824	7.24723	9.54945	11.85201	14.15459
3.0	0.00857	0.82889	2.85704	5.12990	7.42949	9.73177	12.03433	14.33691
3.5	0.01566	0.94208	3.00650	5.28357	7.58359	9.88592	12.18847	14.49106
4.0	0.02491	1.04428	3.13651	5.41675	7.71708	10.01944	12.32201	14.62459
5.0	0.04890	1.22265	3.35471	5.63939	7.94018	10.24258	12.54515	14.84773
6.0	0.07833	1.37451	3.53372	5.82138	8.12247	10.42490	12.72747	15.03006
7.0	0.11131	1.50661	3.68551	5.97529	8.27659	10.57905	12.88162	15.18421
8.0	0.14641	1.62342	3.81727	6.10865	8.41011	10.71258	13.01515	15.31774
9.0	0.18266	1.72811	3.93367	6.22629	8.52787	10.83036	13.13294	13.43551
1/u	*1/u* × 10^1	10^1	10^9	10^{10}	10^{11}	10^{12}	10^{13}	10^{14}
1.0	15.54087	17.84344	20.14604	22.44862	24.75121	27.05379	29.35638	31.65897
1.2	15.72320	18.02577	20.32835	22.63094	24.93353	27.23611	29.53870	31.84128
1.5	15.94634	18.24892	20.55150	22.85408	25.15668	27.45926	29.76184	32.06442
2.0	16.23401	18.53659	20.83919	23.14177	25.44435	27.74693	30.04953	32.35211
2.5	16.45715	18.75974	21.06233	23.36491	25.66750	27.97008	30.27267	32.57526
3.0	16.63948	18.94206	21.24464	23.54723	25.84982	28.15240	30.45499	32.75757
3.5	16.79362	19.09621	21.39880	23.70139	26.00397	28.30655	30.60915	32.91173
4.0	16.92715	19.22975	21.53233	23.83492	26.13750	28.44008	30.74268	33.04526
5.0	17.15030	19.45288	21.75548	24.05806	26.36054	23.66322	30.96582	33.26840
6.0	17.33263	19.63521	21.93779	24.24039	26.54297	28.84555	31.14813	33.45071
7.0	17.48677	19.78937	22.09195	24.39453	26.69711	28.99969	31.30229	33.60487
8.0	17.62030	19.92290	22.22548	24.52806	26.83064	29.13324	31.43582	33.73840
9.0	17.73808	20.04068	22.34326	24.64584	29.94843	29.25102	31.55360	33.85619

[A] Value shown as 0.00000 is nonzero but less than 0.000005.

align the data with the type curve. The data points for small values of t/r^2 should fall on or near the central (standard) type curve, and larger values of t/r^2 should fall on curves representing different values of K_l, ordinarily a different value of K_l for each observation well.

8.1.1.4 Select and record the values of $\Sigma W(u)$, $1/u$, s, and t/r^2 for a point (called the match point) common to both the type curve and the data plot. For convenience, the point may be selected where $\Sigma W(u)$ and $1/u$ are major axes, that is, 0.1, 1.0, 10.0, etc. Record a value of K_l for each observation well.

8.1.1.5 Using the match point coordinates, determine the transmissivity and storage coefficient from the following equations:

$$T = \frac{Q}{4\pi s} \Sigma\, W(u) \tag{11}$$

and:

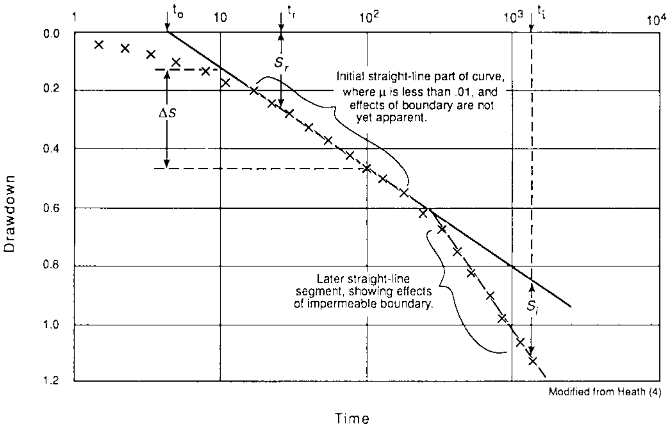
$$S = 4T(t/r^2)u \tag{12}$$

8.1.1.6 For each observation well, determine the distance to the image well, r_i, using the following:

$$r_i = K_l r_r \tag{13}$$

8.1.2 *Modified Theis Method*—The graphical procedure for solution by the modified Theis nonequilibrium method is based on the relationship between s and $\log_{10} t$ using Eq 10.

8.1.2.1 Plot values of s for each observation well or piezometer on the vertical (arithmetic) coordinate and values of the log of t on the horizontal (logarithmic) coordinate. For values of t that are sufficiently large such that u is less than 0.01, the points should fall on a straight line. At larger values of t, the points will begin to diverge from the straight line due to the effects of the nearest boundary (see Fig. 4). A constant-head boundary will cause decreased drawdown, and measurements will fall above the projected straight line, whereas an impermeable boundary will cause increased drawdown and points will fall below the projected line. Note that an impermeable boundary doubles the slope of the drawdown plot.



Modified from Heath (4)

FIG. 4 Semilogarithmic Plot of Drawdown Versus Time Showing Effects of an Impermeable Boundary

8.1.2.2 Draw a straight line through the initial straight-line part of the data where $u < 0.01$ and the effects of boundary are not yet apparent. The drawdown over one log cycle of time (measured or projected) Δs, is used to calculate transmissivity from Eq 10. This method of calculating hydraulic properties is prescribed in more detail in Test Method D 4105.

8.1.2.3 Determine the storage coefficient from the semilogarithmic plot of drawdown versus $\log_{10}$ time by a method proposed by Jacob **(5)**, where:

$$s = \frac{2.3Q}{4\pi T} \log_{10} \left(\frac{2.25Tt}{r^2 S} \right) \tag{14}$$

Project the initial straight-line part of the curve to the left until it intercepts the line of zero drawdown. Taking $s = 0$ atthe zero-drawdown intercept of the straight-line plot of drawdown versus $\log_{10}$ time:

$$S = \frac{2.25\,Tt_0}{r^2} \tag{15}$$

where:
t_o = the value of time at the projection of zero.

Additional discussion of the limits of the modified Theis nonequilibrium method is found in Test Method D 4105.

8.1.2.4 Select a convenient value of s within the initial straight-line part of the plot. Because the drawdown has not yet been affected by the boundary, $s = s_r$. Note the value of t_r that corresponds to this value of s_r.

8.1.2.5 Graphically extend the initial straight-line part of the curve to the right. The departure of the measured drawdown from the extended straight line is the drawdown due to the presence of the boundary, the image-well drawdown, s_i. Select a point within the second straight-line part of the curve such that $s_i = s_r$ and note the value of time, t_i, at which s_i is found.

8.1.2.6 Because t_r and t_i were selected such that $s_r = s_i$, u_r is equal to u_i and $r_r^2S/4Tt_r = r_i^2S/4Tt_i$, so that:

$$K_l = \frac{r_i}{r_r} = \sqrt{\frac{t_i}{t_r}} \tag{16}$$

Determine the radius to the image well using Eq 13.

8.2 *Determine Location of Boundary*:

8.2.1 On a map showing the locations of the control and observation wells, with a compass describe a circle around each observation well. The radius of the circle should be the radius to the image well, r_i, from that observation well.

8.2.2 The image well is located at the intersection of the circles. If the circles do not intersect exactly, the most probable location is the centroid of the intersections.

8.2.3 Draw a straight line between the control well and the image well. The boundary is represented by the perpendicular bisector of this line.

9. Report

9.1 Prepare a report including the following information:

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of this test method for determining transmissivity, storage coefficient, and boundary location in a confined nonleaky aquifer. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells, the method of measurement of discharge and water levels, and the duration of the test and pumping rates. Discuss the rationale for selecting a method that incorporates the effects of boundaries.

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site. Include driller's logs and geologist's description of drill cuttings. Interpret and describe the hydrogeology of the site as it pertains to the selection of this test method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as they conform and differ from those assumed in the solution to the aquifer test method. In particular, locate all possible boundaries and describe their characteristics.

9.1.3 *Scope of Aquifer Test*:

9.1.3.1 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened interval, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells or piezometers.

9.1.3.2 *Instrumentation*—Report the field instrumentation for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturer's name, model number, and basic specifications for each major item, and the name and date of the last calibration, if applicable.

9.1.3.3 *Testing Procedures*—State the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.4 *Presentation of Interpretation of Test Results*:

9.1.4.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for barometric changes or other background water level changes and calculation of drawdown.

9.1.4.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curves with match points and corresponding values of parameters at match points. Show values of K_l, selected for each observation well.

9.1.4.3 *Calculation*—Show calculation of transmissivity, storage coefficient, radius to image well and radius to boundary.

9.1.5 Evaluate qualitatively the overall accuracy of the test on the basis of the adequacy of instrumentation and observations of stress and response, and the conformance of the hydrogeologic conditions and the performance of the test to the model assumptions.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer boundaries; aquifer tests; confined aquifers; control wells; ground water; hydraulic properties; image wells; observation wells; storage coefficient; transmissivity

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(**1**) Theis, C. V., “The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage,” *American Geophysical Union Transactions*, Vol 16, part 2, 1935, pp. 519–524.

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Designation: D 5472 – 93 (Reapproved 1999)$^{\epsilon 1}$

Standard Test Method for Determining Specific Capacity and Estimating Transmissivity at the Control Well[1]

This standard is issued under the fixed designation D 5472; 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.

ϵ^1 NOTE—Section 10.2.1 was corrected editorially in August 1999.

1. Scope

1.1 This test describes a procedure for conducting a specific capacity test, computing the specific capacity of a control well, and estimating the transmissivity in the vicinity of the control well. Specific capacity is the well yield per unit drawdown at an identified time after pumping started.

1.2 This test method is used in conjunction with Test Method D 4050 for conducting withdrawal and injection well tests.

1.3 The method of determining transmissivity from specific capacity is a variation of the nonequilibrium method of Theis **(1)** for determining transmissivity and storage coefficient of an aquifer. The Theis nonequilibrium method is given in Test Method D 4106.

1.4 *Limitations*—The limitations of the technique for determining transmissivity are primarily related to the correspondence between the field situation and the simplifying assumptions of the Theis method.

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

1.6 This standard may involve hazardous materials, operations, and equipment. This standard does not address safety problems 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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4106 Test Method for Analytical Procedure for Determining Transmissivity and Storativity of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *aquifer, unconfined*—an aquifer that has a water table.

3.1.3 *control well*—well by which the head and flow in the aquifer is changed by pumping, injecting, or imposing a constant change of head.

3.1.4 *head, static*—the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

3.1.5 *hydraulic conductivity*—(field aquifer test) the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.6 *observation well*—a well open to all or part of an aquifer, and used to make measurements.

3.1.7 *specific capacity*—well yield per unit drawdown at an identified time after pumping started.

3.1.8 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.1.9 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.10 For definitions of other terms used in this method see Terminology, D 653.

3.2 *Symbols:*Symbols and Dimensions:

3.2.1 K—hydraulic conductivity [LT^{-1}]

3.2.2 m—saturated thickness [L]

3.2.3 Q—discharge [L^3T^{-1}]

3.2.4 Q/s—specific capacity [$(L^3T^{-1})L^{-1}$]

3.2.5 r—well radius [L]

3.2.6 s—drawdown [L]

3.2.7 S—storage coefficient [dimensionless]

3.2.8 T—transmissivity [L^2T^{-1}]

3.2.9 T'—provisional value of transmissivity [L^2T^{-1}]

3.2.10 t—elapsed time of pumping [T]

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved Nov. 15, 1993. Published January 1994.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.11 u—$r^2S/4Tt$ [dimensionless]
3.2.12 $W(u)$—well function of "u" [dimensionless]
3.2.13 c_1— $[W(u)/4\pi]$

4. Significance and Use

4.1 Assumptions of the Theis **(1)** equation affect specific capacity and transmissivity estimated from specific capacity. These assumptions are given below:

4.1.1 Aquifer is homogeneous and isotropic.

4.1.2 Aquifer is horizontal, of uniform thickness, and infinite in areal extent.

4.1.3 Aquifer is confined by impermeable strata on its upper and lower boundaries.

4.1.4 Density gradient in the flowing fluid must be negligible and the viscous resistance to flow must obey Darcy's Law.

4.1.5 Control well penetrates and receives water equally from the entire thickness of the aquifer.

4.1.6 Control well has an infinitesimal diameter.

4.1.7 Control well discharges at a constant rate.

4.1.8 Control well operates at 100 percent efficiency.

4.1.9 Aquifer remains saturated throughout the duration of pumping.

4.2 *Implications of Assumptions and Limitations of Method.*

4.2.1 The simplifying assumptions necessary for solution of the Theis equation and application of the method are never fully met in a field test situation. The satisfactory use of the method may depend upon the application of one or more empirical correction factors being applied to the field data.

4.2.2 Generally the values of transmissivity derived from specific capacity vary from those values determined from aquifer tests utilizing observation wells. These differences may reflect 1) that specific-capacity represents the response of a small part of the aquifer near the well and may be greatly influenced by conditions near the well such as a gravel pack or graded material resulting from well development, and 2) effects of well efficiency and partial penetration.

4.2.3 The values of transmissivity estimated from specific capacity data are considered less accurate than values obtained from analysis of drawdowns that are observed some distance from the pumped well.

5. Apparatus

5.1 Apparatus required for specific capacity testing includes control well, control well pump, discharge measuring equipment and water-level measuring equipment. The description and function requirements of this equipment is given in Test Method D 4050.

6. Conditioning Procedures

6.1 Conditioning procedures are conducted before the test to ensure that the control well is properly equipped and that the well discharge and water-level measuring equipment is operational.

6.1.1 Equip the control well with a calibrated accumulating water meter or another type of calibrated well yield measuring device.

6.1.2 Provide the control well with a system for maintaining a constant discharge.

6.1.3 Equip control well for measuring the pretest water level (prepumping water level) and pumping water levels during the specific capacity test.

6.1.4 Measure static water level immediately before starting the pump.

6.1.5 Start pump and simultaneously measure elapsed time with a stop watch or data recorder. After 3 to 5 minutes well yield and drawdown should be measured and recorded.

6.1.6 If all the equipment is working properly, drawdown measurements can be obtained, and constant discharge maintained, the equipment check can be ended.

6.1.7 Cease pumping and allow the water level to recover to its prepumping level before the specific capacity test procedure (Section 5) is initiated.

7. Test Procedure

7.1 Initiate well discharge.

7.2 Measure the well yield and pumping water level in the control well at predetermined time intervals, for example, 2-, 5-, 10-, 20-, 30-, minutes after discharge is initiated. Adjust the discharge rate during the test to maintain discharge within 5 % of the rate planned.

7.3 While test continues make the following calculations:

7.3.1 Adjust drawdown for effects of desaturation of the aquifer, if applicable (see Section 8).

7.3.2 Determine the specific capacity (see Section 10) and estimate transmissivity (see Section 11). If well bore storage effects are negligible (see Section 9), compare the new value of T' to the value used to calculate c_1, if the value is within 10 %, the test can be terminated.

7.3.3 If control well is not screened through the entire thickness of the aquifer, estimate the transmissivity of the aquifer following procedure in Sections 11 and 12.

8. Correction of Drawdown in an Unconfined Aquifer

8.1 The Theis equation is directly applicable to confined aquifers and is suitable for use with limitations in unconfined aquifers. If the aquifer is unconfined and drawdown is less than 10 percent of the prepumping saturated thickness, little error will be introduced. If drawdown exceeds 25 percent of the prepumping saturated thickness, this test should not be used to estimate transmissivity. For unconfined aquifers with drawdown equal to 10 to 25 percent of the original saturated thickness, correct the drawdown for the effects of reduced saturated thickness by the following formula given by Jacob **(2)**:

$$s' = s - \frac{(s^2)}{2m} \tag{1}$$

where:
s = measured drawdown in the control well,
s' = corrected drawdown, and
m = saturated thickness of the aquifer prior to pumping.

9. Well Bore Storage Effects

9.1 Evaluate the time criterion to determine if well-bore storage affects drawdown at the current duration of the test. Weeks **(3)** gives a time criterion modified after Papadopulos and Cooper **(4)** of $t > 25\ r^2/T$ after which drawdown in the control well is not affected by well-bore storage. For example, a well with a radius of 1 foot and a T of 1000 ft^2/day has a time criterion of $t > 25\ r^2/T = t > 25\ (1)^2/1000 = t > 0.025$ days $= t > 36$ min.

10. Computation of Specific Capacity

10.1 Record the drawdown and the time since pumping started.

10.2 Compute the specific capacity of the control well from the average well yield (Q) and the drawdown (s):

$$\text{Specific Capacity} = Q/s[(L^3T^{-1})L^{-1}] \quad (2)$$

10.2.1 An example of specific capacity where discharge is given in American Standard Units (1000 gallons per minute) and drawdown in feet (50):

Specific Capacity =
[1000 gpm (1440 min/day/7.48 gal/ft^3)]/50 ft =
3850 [(ft^3/day)]ft

11. Estimate Transmissivity from Specific Capacity

11.1 A modification of the Theis **(1)** nonequilibrium equation is used to evaluate transmissivity data derived from specific capacity as follows:

$$T = [W(u)/4\pi]Q/s \quad (3)$$

11.1.1 A general form of the equation is:

$$T' = c_1Q/s \quad (4)$$

where:
$c_1 = W(u)/4\pi$.

11.1.2 Calculate the value of c_1 from a provisional value of transmissivity, T', estimated storage coefficient, S, well radius, r, and duration of the test, t. An example of the computation of c_1 using field values of discharge in American units is as follows:

where:
$T' = 11\,000\ ft^2$/day,
$S = 2 \times 10^{-5}$
$r = 0.67$ ft (16-in. diameter pipe),
$t = 0.50$ days

$$C_1 = W(u)/4\pi$$
$$W(u) = (-0.5772 - \mathrm{L}n[u])$$

where:
$u = (r^2S)/(4Tt) = 4.0809 \times 10^{-10}$
$C_1 = (-0.5772 - \mathrm{L}\,n[4.0809 \times 10^{-10})/4\pi]$
$C_1 = (-0.5772 - \mathrm{L}n[4.0809 \times 10^{-10}])/12.5664$
$C_1 = (-0.5772 - [-21.6195])/12.5664$
$C_1 = 21.0423/12.5664 = 1.6745$

11.1.3 Calculate transmissivity from Eq 4;

$T = c_1Q/s$,
Assume $Q/s = 3850$ [(ft^3/day)/ft]
$T = 1.6745 \times 3850 = 6450\ ft^2$/day (rounded)

11.1.4 If transmissivity calculated in 11.1.3 is not within 10 % of the provisional transmissivity, T', recalculate c_1 from the new value of transmissivity and recalculate transmissivity by formula. In the example, because 6450 ft^2/day is 59 percent of the initial T' value of the 11 000 ft^2/day, a more accurate c_1 can be computed to match the new T' value.

$$T' = 6450\ ft^2/\text{day}$$
$$S = 2 \times 10^{-5}$$
$$c_1 = W(u)/4\pi$$
$$W(u) = (-0.5772 - \mathrm{L}n[u])$$

where:
$u = (r^2S)/(4Tt) = 8.9780 \times 10^{-6} = 6.9597 \times 10^{-10}$
$C_1 = (-0.5772 - \mathrm{L}n\ 6.9597 \times 10^{-10})/4\pi$
$C_1 = (-0.5772 - \mathrm{L}\ n\ 6.9597 \times 10^{-10})/12.5664$
$C_1 = (-0.5772 - (-21.0857)/12.5664$
$C_1 = 20.5085/12.5664 = 1.6320$

thus:
$T' = C_1(Q/s) = 1.6320 \times 3850 = 6300\ ft^2$/day (rounded). The new value of transmissivity is within 10 % of the value used to compute transmissivity.

11.1.5 To obtain SI units, multiply American units by 9.290×10^{-2} for m^2/day.

NOTE 1—The initial estimates of transmissivity can be based on values of transmissivity and storage of the aquifer determined at other locations or from a general knowledge of the aquifer properties. The transmissivity could be estimated from driller's logs using methods described by Gutentag and others **(5)**. The storage coefficient can be estimated for unconfined aquifer as 0.2 and for confined aquifers as b × 10^{-6}, where b is the thickness of the aquifer in feet. In areas where aquifer properties are not known and drillers log data are lacking, the following values, modified from Harlan, Kolm, and Gutentag **(6)** can be used as initial estimates of c_1:

Confined aquifers	1.6
Unconfined aquifers	0.8

12. Correction of Transmissivity for Partially Penetrating Well

12.1 If the full aquifer thickness is not screened, the value of T' represents the transmissivity of the screened section of the aquifer. To estimate the transmissivity of the full thickness of the aquifer, divide estimated transmissivity by the length of the screened interval to compute the hydraulic conductivity (K). After computing (K) the hydraulic conductivity value is multiplied by the entire thickness of the saturated thickness (m) of the aquifer to compute an estimate of transmissivity as: $T = Km$.

13. Report

13.1 Prepare a report containing all data, including a description of the field site, well construction, plots of pumping water level and well discharge with time.

13.2 Present analysis of data, using iteration techniques for c, when results differ from initial input values of T and S.

13.3 Compare estimated test conditions with the test method assumptions listed in 4.1.

14. Precision and Bias

14.1 It is not practicable to specify the precision of this procedure because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

15. Keywords

15.1 aquifers; aquifer tests; control wells; hydraulic conductivity; observation wells; specific capacity; storage coefficient; transmissivity; unconfined aquifers

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(**1**) Theis, C. V., 1935, The Relation Between the Lowering of Duration of Discharge of a Well Using Ground-Water Storage: *American Geophysical Union Transactions*, v. 16. pt. 2, p. 519–524.

(**2**) Jacob, C. E., "Determining the Permeability of Water-Table Aquifers," in Bentall, Ray, Compiler, "Methods of Determining Permeability, Transmissibility, and Drawdown," U.S. Geological Survey Water-Supply Paper 1536-I, 1963, pp. 245–271.

(**3**) Weeks, E. P., 1978, Aquifer Tests—the State of the Art in Hydrology: in Proceedings Invitational Well-Testing Symposium, October 19–21, 1977, Lawrence Berkeley Laboratory, University of California, LBL-7027, UC-66, TID 4500-R66, p. 14–26.

(**4**) Papadopulos, I. S., and Cooper, H. H., Jr., 1967, Drawdown in a Well of Large Diameter: Water Resources Research, v. 3, no. 1, p. 241–244.

(**5**) Gutentag, E. D., Heimes, F. J., Krothe, N. C., Luckey, R. R., and Weeks, J. B., 1984, Geohydrology of the High Plains Aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

(**6**) Harlan, R. L., Kolm, K. E., and Gutentag, E. D., 1989, Water-Well Design and Construction: Elsevier, Amsterdam, 205, p.

Designation: D 5473 – 93 (Reapproved 2000)

Standard Test Method for (Analytical Procedure for) Analyzing the Effects of Partial Penetration of Control Well and Determining the Horizontal and Vertical Hydraulic Conductivity in a Nonleaky Confined Aquifer[1]

1. Scope

1.1 This test method covers an analytical solution for determining the horizontal and vertical hydraulic conductivity of an aquifer by analysis of the response of water levels in the aquifer to the discharge from a well that partially penetrates the aquifer.

1.2 *Limitations*—The limitations of the technique for determination of the horizontal and vertical hydraulic conductivity of aquifers are primarily related to the correspondence between the field situation and the simplifying assumption of this test method.

1.3 The values stated in either inch-pound or SI units are to be regarded separately as the standard. The values given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety problems, 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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4050 Test Method for (Field Procedure for) Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method for (Analytical Procedure for) Determining Transmissivity and Storativity of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the head and flow in the aquifer is changed, for example, by pumping, injection, or imposing a constant change of head.

3.1.4 *drawdown*—vertical distance the static head is lowered due to the removal of water.

3.1.5 *hydraulic conductivity*—(field aquifer tests), the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.6 *observation well*—a well open to all or part of an aquifer.

3.1.7 *piezometer*—a device so constructed and sealed as to measure hydraulic head at a point in the subsurface.

3.1.8 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

3.1.9 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.1.10 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 *unconfined aquifer*—an aquifer that has a water table.

3.1.12 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions*:

3.2.1 a [nd]—$(K_z/K_r)^{1/2}$.

3.2.2 b [L]—thickness of aquifer.

3.2.3 d [L]—distance from top of aquifer to top of screened interval of control well.

3.2.4 d' [L]—distance from top of aquifer to top of screened interval of observation well.

3.2.5 f_s [nd]—dimensionless drawdown factor.

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

Current edition approved Nov. 15, 1993. Published January 1994.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.6 K [LT^{-1}]—hydraulic conductivity.

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

3.2.8 K_z [LT^{-1}]—hydraulic conductivity normal to the plane of the aquifer.

3.2.9 K_0— modified Bessel function of the second kind and zero order.

3.2.10 l [L]—distance from top of aquifer to bottom of screened interval of control well.

3.2.11 l' [L]—distance from top of aquifer to bottom of screened interval of observation well.

3.2.12 Q [L^3T^{-1}]—discharge.

3.2.13 r [L]—radial distance from control well.

3.2.14 r_c— distance from pumped well at which an observed drawdown deviation, δs, would occur in the equivalent isotropic aquifer.

3.2.15 S [nd]—storage coefficient.

3.2.16 s [L]—drawdown.

3.2.17 S_s [L^{-1}]—specific storage.

3.2.18 T [L^2T^{-1}]—transmissivity.

3.2.19 u [nd]—$(r^2S)/(4\ Tt)$.

3.2.20 $W(u)$ [nd]—an exponential integral known in hydrology as the well function of u.

3.2.21 $W(u, f_s)$—partial-penetration control well function.

3.2.22 δs [L]—drawdown deviation due to partial penetration from that given by equations for purely radial flow.

3.2.23 z [L]—distance from top of aquifer to bottom of piezometer.

4. Summary of Test Method

4.1 This test method uses the deviations in drawdown near a partially penetrating control well from those that would occur near a control well fully penetrating the aquifer. These deviations occur when a well partially penetrating the aquifer is pumped because water levels are drawn down more near the level of the screen, and less at levels somewhat above or below the screened interval, than they would be if the pumped well fully penetrated the aquifer. These effects are shown in Fig. 1 by comparing drawdown and flow lines for fully penetrating and partially penetrating control wells in an isotropic aquifer. Drawdown deviations due to partial penetration are amplified when the vertical permeability is less than the horizontal permeability, as often occurs in stratified sediments **(1)**.[3] Hantush **(2)** has shown that at a distance, r, from the control well the drawdown deviation due to pumping a partially penetrating well at a constant rate is the same as that at a distance $r\ (K_z/K_r)^{1/2}$ if the aquifers were transformed into an equivalent isotropic aquifer.

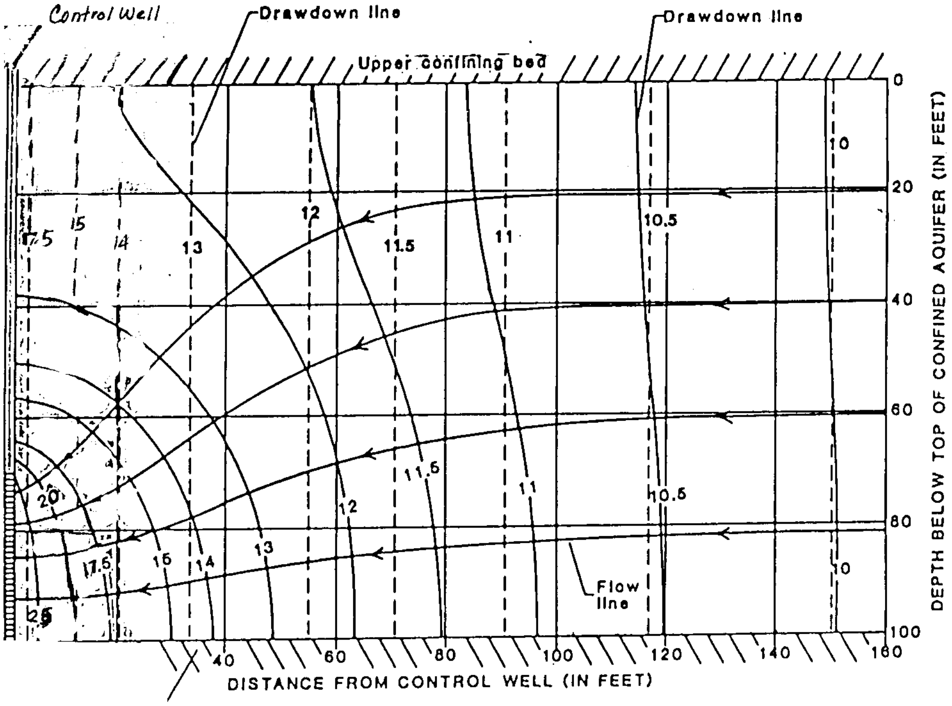
4.2 *Solutions*—Solutions are given by Hantush **(2)** for the drawdown near a partially penetrating control well being pumped at a constant rate and tapping a homogeneous, isotropic artesian aquifer:

$$s = \frac{Q}{4\pi T}\left[W(u) + f_s\right] \tag{1}$$

where:

$$W(u) = \int_u^\infty \frac{e^{-y}}{y}\,dy \tag{2}$$

and f_s is the dimensionless drawdown correction factor. The function [$W(u) + f_s$] in Eq 1 can be referred to as the partial penetration well function.



NOTE 1—Solid lines are for a well screened in the bottom three tenths of the aquifer; dashed lines are for a well screened the full thickness.

FIG. 1 Vertical Section Showing Drawdown Lines and Approximate Flow Paths Near a Pumped Well in an Ideal Artesian Aquifer

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

4.2.1 The dimensionless drawdown correction factor for a piezometer is given by:

$$f_s = f\left(u, \frac{ar}{b}, \frac{l}{b}, \frac{d}{b}, \frac{z}{b}\right) \qquad (3)$$

$$= \frac{2b}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{1}{n}\left(\sin\frac{n\pi l}{b} - \sin\frac{n\pi d}{b}\right) \cos\frac{n\pi z}{b}\, W\left(u, \frac{n\pi ar}{b}\right)$$

and the solution for the dimensionless drawdown correction factor for an observation well is given by:

$$f_s = f\left(u, \frac{ar}{b}, \frac{l}{b}, \frac{d}{b}, \frac{l'}{b}, \frac{d'}{b}\right) \qquad (4)$$

$$= \frac{2b^2}{\pi^2(l-d)}(l'-d') \sum_{n=1}^{\infty} \frac{1}{n^2}\left(\sin\frac{n\pi l}{b} - \sin\frac{n\pi d}{b}\right)$$

$$\left(\sin\frac{n\pi l'}{b} - \sin\frac{n\pi d'}{b}\right) W\left(u, \frac{n\pi ar}{b}\right)$$

where:

$$W(m, x) = \int_u^{\infty} \frac{\exp\left(-y - \frac{x^2}{4y}\right)}{y}\, dy \qquad (5)$$

The hydrogeologic conditions and symbols used in connection with piezometer and well geometries are shown in Fig. 2.

4.2.2 For large values of time, that is, for $t > b^2S/(2a^2T)$ or $t > bS/(2K_z)$, the effects of partial penetration are constant in time, and $W(u, (n\pi ar)/b))$ can be approximated by $2K_0((n\pi ar)/b)$ **(2)**. K_0 is the modified Bessel function of the second kind of order zero.

4.2.3 Eq 1 can be written

$$s = \frac{Q}{4\pi T} W(u) + \frac{Q}{4\pi T} f_s \qquad (6)$$

The first term in Eq 6 is the drawdown in an isotropic homogeneous confined aquifer under radial flow, as given by Theis **(3)**. The second term is deviation from the Theis drawdown caused by partial penetration of the control well. This term is designated as the drawdown deviation by Weeks **(1)** and is given by:

$$\delta s = \frac{Q}{4\pi T} f_s \qquad (7)$$

4.2.4 The effects of partial penetration need to be considered for $ar/b < 1.5$. There is a response curve for each value of ar/b, d/b, l/b, and either z/b for piezometers, or l'/b and d'/b for observation wells. A table of dimensionless drawdown factors for piezometers from Weeks **(1)** is given in Table 1 covering 56 different partial-penetration situations. A graph of one of the many families of curves showing the dimensionless drawdown factor f_s versus ar/b for a control well screened, or open, from $z = 0.6b$ to $z = 0.9b$ for various values of piezometer penetration, z/b, is shown in Fig. 3. Because of the even greater number of possible drawdown factors for observation wells, drawdown correction factors for wells are not tabulated.

5. Significance and Use

5.1 *Assumptions*:

5.1.1 Control well discharges at a constant rate, Q.

5.1.2 Control well is of infinitesimal diameter and partially penetrates the aquifer.

5.1.3 The nonleaky artesian aquifer is homogeneous, and aerially extensive. The aquifer may also be anisotropic and, if so, the directions of maximum and minimum hydraulic conductivity are horizontal and vertical, respectively. The methods may be used to analyze tests on unconfined aquifers under conditions described in a following section.

5.1.4 Discharge from the well is derived exclusively from storage in the aquifer.

5.1.5 The geometry of the assumed aquifer and well conditions are shown in Fig. 2.

5.2 *Implications of Assumptions*—The vertical flow components in the aquifer are induced by a control well that partially penetrates the aquifer, that is, a well that is not open to the aquifer through its full thickness. The effects of vertical flow components are measured in piezometers near the control well, that is, within a distance, r, in which vertical flow components are significant, that is:

$$r < 1.5b\sqrt{Kr/Kz} \qquad (8)$$

5.3 *Application of Method to Unconfined Aquifers*:

5.3.1 Although the assumptions are applicable to artesian or confined conditions, Weeks **(1)** has pointed out that the solution may be applied to unconfined aquifers if drawdown is small compared with the saturated thickness of the aquifer or if the

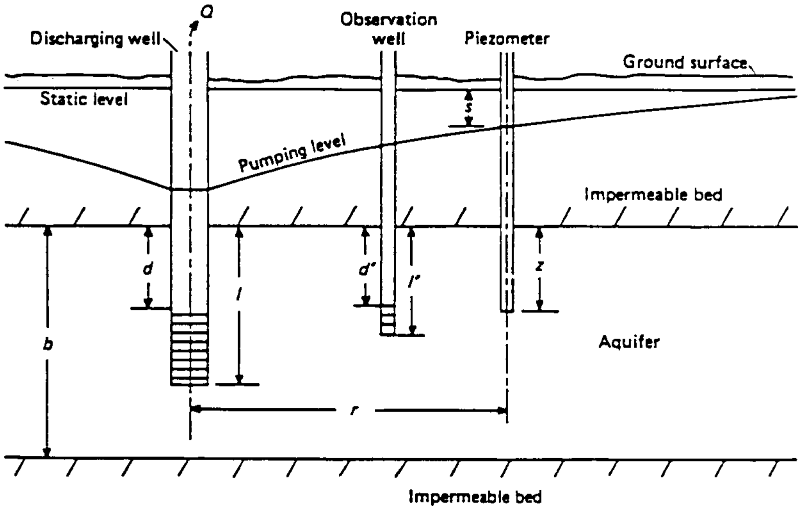

FIG. 2 Cross Section Through a Discharging Well That is Screened in a Part of a Nonleaky Aquifer

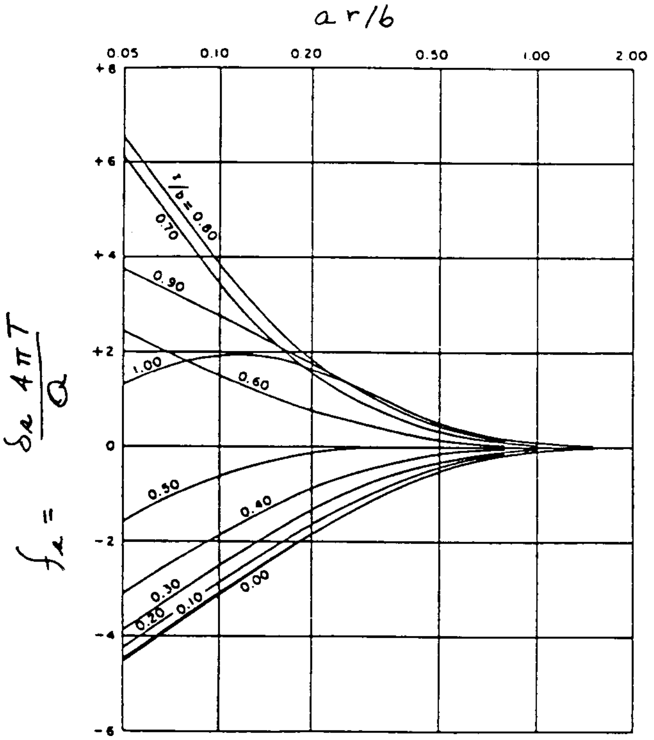

FIG. 3 Graph of Dimension Less Drawdown Factor, f_s, versus *ar/b* for a Pumped Well Screened from $z = 0.66$ to $z = 0.96$ for Values of Piezometer Penetration, *z/b*

drawdown is corrected for reduction in thickness of the aquifer, and the effects of delayed gravity response are small. The effects of gravity response become negligible after a time as given, for piezometers near the water table, by the equation:

$$t = \frac{bS_y}{K_z} \tag{9}$$

for values of *ar/b* < 0.4 and by the equation:

$$t = \frac{bS_y}{K_z}\left(0.5 + 1.25\frac{r}{b}\sqrt{\frac{K_z}{K_r}}\right) \tag{10}$$

for greater values of *ar/b*.

5.3.2 Drawdown in an unconfined aquifer is also affected by curvature of the water table or free surface near the control well, and by the decrease in saturated thickness, that causes the transmissivity to decline toward the control well. This test method should be applicable to analysis of tests on water-table aquifers for which the control well is cased to a depth below the pumping level and the drawdown in the control well is less than $0.2b$. Moreover, little error would be introduced by effects of water-table curvature, even for a greater drawdown in the control well, if the term $(s^2/2\,b)$ for a given piezometer is small compared to the $\delta\ s$ term.

5.3.3 The transmissivity decreases as a result of decreasing thickness of the unconfined aquifer near the control well. Jacob **(4)** has shown that the effect of decreasing transmissivity on the drawdown may be corrected by the equation:

$$s' = s - (s^2/2b) \tag{11}$$

where s is the observed drawdown and s' is the drawdown in an equivalent confined aquifer.

6. Apparatus

6.1 Apparatus for withdrawal tests is given in Test Method D 4050. The apparatus described as follows are those components of the apparatus that require special attributes for this specific test method.

6.2 *Construction of Control Well*—Screen the control well through only part of the vertical extent of the aquifer to be tested. The screened interval of the control well must be known as a function of aquifer thickness.

6.3 *Construction and Placement of Piezometers and Observation Wells*—The requirements for observation wells and piezometers are related to the method of analysis to be used. Two methods of analysis are prescribed in Section 8; the observation well and piezometer requirements for each method are given as follows. The piezometers and observation wells may be on the same or various radial lines from the control well.

6.3.1 The type curve fitting methods require one or more piezometers near the control well within the radial distance affected by vertical flow components. This distance is given by $r < 1.5b/(K_z/K_r)^{1/2}$. The depth of the piezometer opening must be known as a function of the aquifer thickness. Construction of piezometers or wells for a specific test shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells.

6.3.2 Method 1 of the drawdown deviation methods requires one or more piezometers or wells near the control well within the radial distance affected by vertical flow components. The depth of these piezometers and the screened interval of wells must be known as a function of aquifer thickness. Construction of piezometers or wells for a specific test within the distance affected by vertical flow components shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells. In addition, the method requires two or more observation wells or piezometers at a distance from the control well beyond the effect of vertical flow components.

6.3.3 Method 2 of the drawdown deviation methods requires two or more piezometers within the radial distance affected by vertical flow components. Construction of piezometers or wells for a specific test within the distance affected by vertical flow components shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells.

NOTE 1—The drawdown deviation methods were originated by Weeks **(1)** who published tables of the drawdown correction factors for piezometers. Partially penetrating observation wells may be used in place of or in addition to the piezometers. Weeks **(1)** has found that data from observation wells screened for less than 20 % of the aquifer thickness, using the center of the screen as the piezometer depth, can be used in place of piezometers if the position of the screen in the observation well is above or below that of the screen in the pumped well. However, if the observation well is screened at the same level or overlaps that in the pumped well, Eq 1, or the values in Table 1 derived from Eq 1, should be used only when the screen length of the observation well is less than about 5 % of the aquifer thickness. Data obtained from observation wells open or screened in a larger part of the aquifer thickness could be analyzed by values of the drawdown correction factor derived from Eq 4. Drawdown correction factors can be derived from values of [$W(u) + f_s$], computed from the Fortran code of Reed **(5)** or the basic code of Dawson and Istok **(6)**.

7. Procedure

7.1 *Pretest Preparations*—Pretest preparations are given in more detail in Test Method D 4050.

7.1.1 *Testing Response of Piezometers and Observation Wells*—The piezometers and observation wells are tested by pumping or injecting water to assure hydraulic connection between the well and the aquifer.

7.1.2 Measure water levels to determine the trend of water levels before the commencement of the test.

7.1.3 *Step Test*—Pump the control well at steady, progressively greater rates to estimate the transmissivity and select a steady rate of pumping for the aquifer test.

7.2 *Aquifer Testing*—The field procedure summarized below for pumping the control well and measurement of water levels is given in detail in Test Method D 4050.

7.2.1 *Pump Control Well*—Pump the control well at a constant rate. Measure well discharge periodically.

7.2.2 *Measure Water Level in Piezometers and Observation Wells*—Measure water levels frequently during the early phase of pumping; increase the interval between measurements logarithmically as pumping continues.

7.3 *Analysis of the Test Data*—The field test data are analyzed by methods described in Section 8.

8. Calculation and Interpretation of Results

8.1 *Type Curve Methods*—Two type curve methods are presented. The first method is employed by plotting drawdown versus time for each observation well and matching the data plot with prepared-type curves of $[W(u) + f_s]$ versus $1/u$. The second method is employed by plotting drawdown versus r^2/t for one or more wells on the same graph and matching with prepared families of type curves of $[W(u) + f_s]$ versus $1/u$.

8.1.1 *Type Curve Method 1*—This test method is applicable where one or more piezometers or wells are within the distance from the control well affected by vertical flow components.

8.1.2 Select a range of values of $a = (K_z/K_r)^{1/2}$ and prepare a set of type curves for each observation well. For each type curve having values of a and ar/b, plot $[W(u) + f_s]$ versus $1/u$ on logarithmic paper (see Fig. 4).

NOTE 2—The type curves can be plotted from values of $[W(u) + f_s]$ calculated from the Fortran program in Table 2.1 of Reed **(5)** or the Basic program, TYPE6, of Dawson and Istok **(6)**.

8.1.3 For each observation well, prepare plots of data by plotting s versus t using the same logarithmic scales used to plot the type curves (Fig. 4).

8.1.4 Overlay the data plot on the family of type curves developed for that observation well. Shift the plots relative to each other, keeping the axes parallel, until a position of best fit is found between the data plot and one of the type curves.

8.1.5 Select a common match point on the data plot and the type curve. Record the value of a for the type curve and values of $[W(u) + f_s]$, s, u, and t for the data and type curve match point.

8.1.6 Calculate transmissivity, T, from Eq 1.

8.1.7 Calculate $K_r = T/b$.

8.1.8 From the value of $a = (K_z/K_r)^{1/2}$ for the type curve, calculate $K_z = K_r * a^2$.

8.1.9 Substitute values of T, u, t, and r in the equation $u = (r^2 S/4Tt)$ and solve for storage coefficient, S.

NOTE 3—From the match point in Fig. 4, transmissivity is calculated:

$$T = Q/4\pi s\,(W(u) + f_s) \tag{12}$$

$$T = (19\,250 * 10)/(4 * \pi * 3.22) = 4800\ \text{ft}^2\ \text{day}^{-1}\ \text{(rounded)}$$

The hydraulic conductivity radially from the well is calculated:

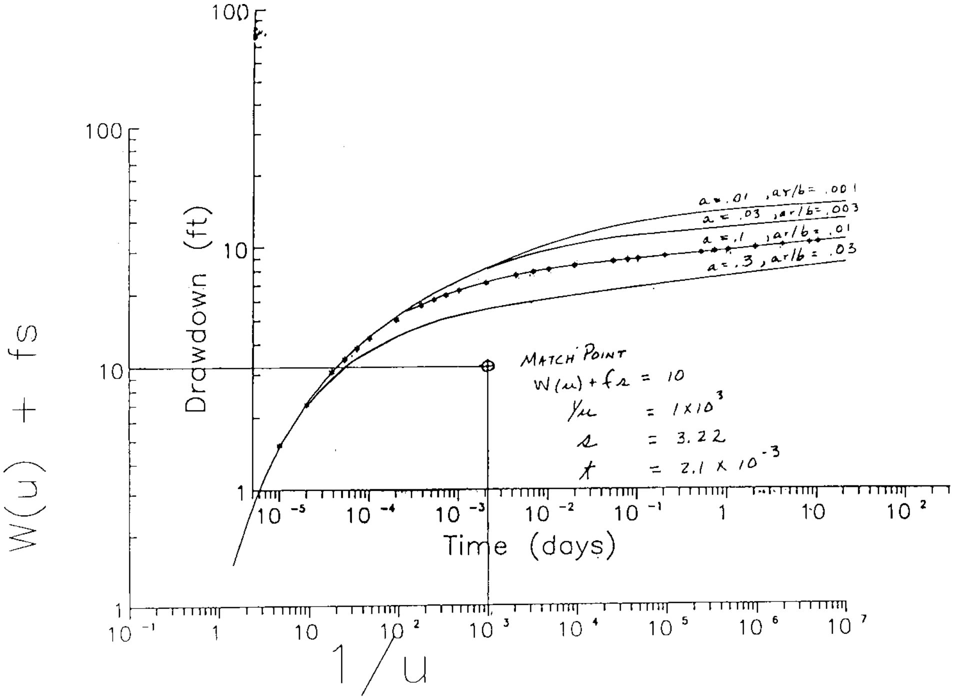

FIG. 4 Data and Type Curves

$$K_r = T/b = 4800/100 = 480 \text{ ft day}^{-1} \quad (13)$$

The hydraulic conductivity normal to the plane of the aquifer is calculated:

$$K_z = 480 * 0.01 = 4.8 \text{ ft day}^{-1} \quad (14)$$

The storage coefficient is calculated:

$$S = 4Tu(t/r^2) \quad (15)$$

$$S = (4 * 4800 * 2.1 * 10^{-3})/(100 * 1000) = 4 * 10^{-5}$$

Note that the curves are similar for both early and late times. In calculating the values for a single well, both early and late water-level measurements are needed to select the proper curve. Without early and late data to select the proper curve, values of transmissivity, and radial and vertical hydraulic conductivity are affected less than the value of storage coefficient.

8.1.10 *Type Curve Method 2*—This test method is applicable where two or more observation wells are within the distance from the control well affected by vertical flow components.

8.1.11 Prepare a set of family-type curves, each family of several curves for selected values of a. For each family of type curves, with equal a, plot $[W(u) + f_s]$ versus $1/u$ on logarithmic paper (see Fig. 5). The type curves can be plotted from values of $[W(u) + f_s]$ calculated from the Fortran program in Table 2.1 of Reed **(5)** or the basic program, TYPE6, of Dawson and Istok **(6)**.

8.1.12 Prepare a data plot of all observation wells on the same graph. Plot data for each well as s versus r^2/t using the same sized logarithmic scales used to plot the type curves (see Fig. 5).

8.1.13 Overlay the data plots on each family of type curves. Shift the plots relative to each other, keeping the axes parallel, until a position of best fit is found between the data plots and one family of type curves.

8.1.14 Select a common match point on the data plot and the type curve plot. Record values of $[W(u) + f_s]$, s, u, and t for the match point and the value of a for the family of type curves.

8.1.15 Calculate transmissivity, T, from Eq 1.

8.1.16 Calculate the value of $K_r = T/b$.

8.1.17 From the value of $a = (K_z/K_r)^{1/2}$ for the match point, the transmissivity, and the thickness of the aquifer, b, calculate K_z from Eq 12.

8.1.18 Substitute values of T, u, t, and r in the equation $u = (r^2 S/4Tt)$ and solve for storage coefficient, S.

NOTE 4—From the match point in Fig. 5, the transmissivity is calculated:

$$T = Q/4\pi s\,(W(u) + f_s) \quad (16)$$

$$T = (204\,050 * 1.0)/(4 * \pi * 1.0) = 16\,000 \text{ (rounded)}$$

The hydraulic conductivity radially from the control well is calculated:

$$K_r = T/b = 16\,000/80 = 200 \text{ ft day}^{-1} \quad (17)$$

The hydraulic conductivity normal to the plane of the aquifer is calculated:

$$K_z = 200 * 0.04 = 8 \text{ ft day}^{-1} \quad (18)$$

The storage coefficient is calculated:

$$S = 4Tu(t/r^2) \quad (19)$$

$$S = (4 * 16\,000 * 0.001)(1/300) = 0.21$$

It is noted in Fig. 5 that the early time data for each well lies above the type curve. This is typical of the water level-data from unconfined aquifers to plot above the type curves for confined aquifers. This response has been attributed to delayed gravity release of water from the aquifer under water table conditions. Applying Eq 9, $t = bS_y/K_z$, the effect of delayed gravity response is negligible after the time, $t = (80 * 0.21)/8 = 2.1$ days or for values of $r^2/t < (50)^2/2.1 = 1190$ for well 1E and $r^2/t < (116)^2/2.1 = 6408$ for well 2E. Applying Eq 10, $t = (bS_y/K_z)(0.5 + 1.25)(r/b)(K_z/K_r)^{1/2}$ the

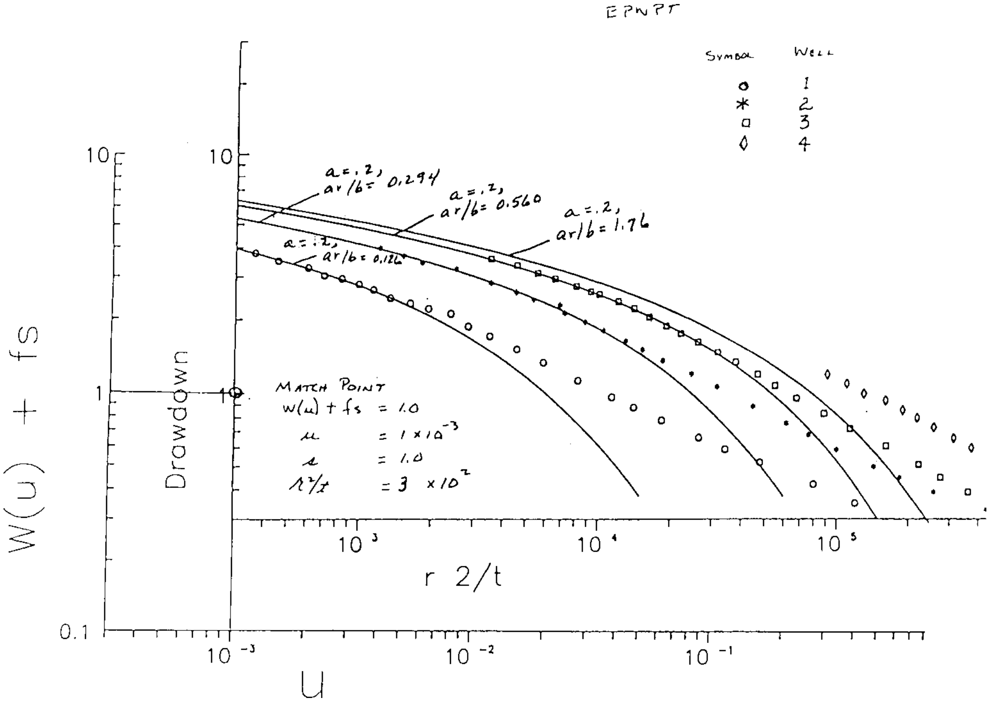

FIG. 5 Data and Type Curves for Multiple Observation Points and Match Point Located

effect of delayed gravity response is negligible at well 3*E* for $t > ((80 * 0.21)/8)\ (0.5 + 1.25)\ (221/80) * 0.2 = 24.0 * (0.5 + 0.69) = 18$, or for values of $r^2/t < 2713$.

8.2 *Drawdown Deviation Methods*—Drawdown near a partially penetrating control well deviates from drawdown that would occur near a control well fully penetrating the aquifer. These deviations occur when a well partially penetrating the aquifer is pumped because water levels are drawn down more in piezometers open near the level of the screen, and less in piezometers open at an interval somewhat above or below the screened interval, than they would be if the pumped well fully penetrated the aquifer. Drawdown deviations due to partial penetration are amplified when the vertical hydraulic conductivity is less than the horizontal hydraulic conductivity. The drawdown deviation methods **(1)** employ the relationship between the drawdown deviation in an anisotropic aquifer and the drawdown deviation in an equivalent isotropic aquifer. The drawdown deviation at a given distance, *r*, due to pumping a partially penetrating well in an anisotropic aquifer is the same as that at the distance $r\ (K_r/K_z)^{1/2}$ in an equivalent isotropic aquifer. The drawdown deviation due to partial penetration of the control well is determined from the field data by graphical analysis. The theoretical drawdown that would occur for the same pumped well in an equivalent isotropic aquifer is determined using Eq 1. From the computed curve, the distances from the pumped well at which the observed drawdown deviations would occur in the equivalent isotropic aquifer are found, and the ratio of horizontal to vertical hydraulic conductivity is computed by equating the ratio to the square of the ratio of the actual distance to the distance in an equivalent isotropic aquifer.

8.2.1 *Drawdown Deviation Method 1*—This method is applicable for aquifer tests for which piezometers are available to define the potentiometric profile of the cone of depression to distances both within and beyond the effects of partial penetration.

8.2.1.1 Prepare a plot of drawdown, *s*, versus log *r* for a time, *t*, at or near the end of the test (see Fig. 6).

8.2.1.2 Compute the transmissivity and storage coefficient from the straight line part of the curve defined by the most distant wells or piezometers using the modified Theis nonequilibrium method. This procedure is given in Test Method D 4105.

8.2.1.3 Evaluate the values of *T* and *S* by calculating the value of $u = r^2S/4\ Tt$ for the data used to calculate *T* and *S*. The value of *u* shall be equal or less than 0.01 for the most distant piezometer or well used in the determination of transmissivity and storage coefficient.

NOTE 5—The limiting value for *u* of less than 0.01 may be excessively restrictive in some applications. The errors for small values of *u*, from Kruseman and De Ridder **(7)** are:

Error less than:	1 %	2 %	5 %	10 %
For *u* smaller than:	0.03	0.05	0.1	0.15

NOTE 6—If the values of *u* are not less than the limiting value for the piezometers used to calculate *T* and *S*, calculate *T* and *S* from time-drawdown plots at later times as prescribed in Test Method D 4105. Draw line of slope $\Delta s = -2.3Q/2\pi T$ beneath the data points. Continue with 8.2.1.4 through 8.2.1.11. Recalculate the position of the straight line in Fig. 6 and repeat 8.2.1.4 through 8.2.1.11 until the recomputed value of *S* changes by less than 10 %.

NOTE 7—Wells used to calculate *T* and *S* (see 8.1) shall be at a distance beyond the effects of partial penetration, that is, beyond a distance such that $(K_z/K_r)^{1/2}r/b > 1.5$. Because K_r and K_z will not be known, this evaluation cannot be made prior to the completion of the final step of the procedure. Proceed through the following steps and recompute the radial distance from the control well affected by vertical flow components. If the

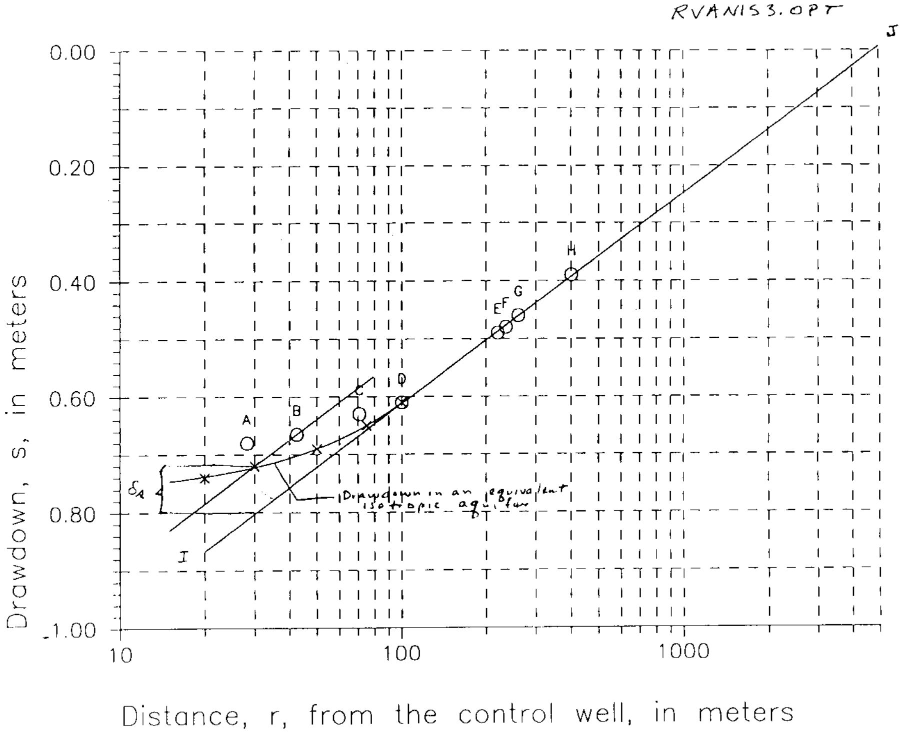

FIG. 6 Drawdown Plot in an Anisotropic Aquifer With Computed Drawdown in an Equivalent Isotropic Aquifer

piezometers are not beyond the affected distance, it may be possible to evaluate the data by the second drawdown deviation method.

8.2.1.4 Extend the straight line down to an r value somewhat smaller than that for the closest piezometer, I–J in Fig. 6.

8.2.1.5 Compute values of drawdown deviation, $\delta s = (Q/4\pi T)f_s$ for assumed values of r within the distance from the control well where the measured drawdown departs from the straight line. This line is shown by deviation from the straight line drawdown in piezometers *A*, *B*, and *C*, in Fig. 6. Values of f_s are calculated from Eq 3 or interpolated from Table 1.

8.2.1.6 Construct the curve representing the drawdown profile that would occur in an equivalent isotropic aquifer by adding, algebraically, the δs term for each of the r values, to the drawdown of the straight line plot, I–J. Connect the resulting points by a smooth curve (see Fig. 6).

8.2.1.7 Draw a line parallel to the line I–J through a point of measured drawdown (such as Piezometer *B* in Fig. 6) and the computed drawdown profile for the equivalent isotropic aquifer.

8.2.1.8 Determine the r_c value for the intercept of this parallel line with the computed drawdown profile for equivalent isotropic conditions. The distance $r_c = 20$ m for the intercept of the parallel line through *B* with the drawdown in an equivalent isotropic aquifer.

8.2.1.9 Compute the ratio of horizontal to vertical hydraulic conductivity from the formula:

$$\frac{K_r}{K_z} = \left(\frac{r}{r_c}\right)^2 \quad (20)$$

where r is the distance from pumped well to piezometer through which the line drawn in 8.1.2 was constructed. In Fig. 6, for Piezometer B:

$$r = 42.4, \quad r_c = 30, \quad K_r/K_z = 2 \quad (21)$$

8.2.1.10 Repeat 8.2.1.7 through 8.2.1.9 for each piezometer in which the drawdown deviates from the drawdown in an equivalent isotropic aquifer.

8.2.1.11 Find the storage coefficient from data obtained in piezometers located beyond the effects of partial penetration using the following equation from Test Method D 4105:

$$S = \frac{2.25Tt}{r^2} \quad (22)$$

where r is the value at the zero drawdown intercept.

8.2.2 *Method 2*—This method is applicable where two or more piezometers are within the radial distant affected by partial penetration but where piezometers are not available or the period of pumping is too short to determine the position of the distance-drawdown curve for the region unaffected by partial penetration.

8.2.2.1 Determine values of transmissivity from each piezometer by the modified Theis nonequilibrium method, as described in Test Method D 4105, using the data obtained during the later part of the test.

8.2.2.2 Prepare a semilogarithmic plot, plotting drawdown, s, values for the piezometers for a selected time on the arithmetic scale and distance, r, on the logarithmic scale. Draw any line of slope $\Delta s = -2.3Q/2\pi T$ beneath the plotted drawdown values if δs is indicated to be negative (drawdown less than for an equivalent isotropic aquifer) or above the drawdown value if δs appears to be positive. An example of such a plot is shown in Fig. 7, showing drawdown in piezometers and the straight line plot E–F.

8.2.2.3 Determine values of the drawdown deviation, δs, for each piezometer by subtracting the drawdown value for the straight-line plot, E–F, from the observed drawdown.

8.2.2.4 Use the δs values to compute values of f_s from the formula: $f_s = 4\pi T\delta s/Q$, and prepare a semilogarithmic graph plotting f_s on the arithmetic axis and (r/b) on the logarithmic axis. An example of such a plot is shown in Fig. 8.

8.2.2.5 Prepare a semilogarithmic-type curve by plotting values of f_s from Eq 3 or Eq 4 or Table 1 on the arithmetic axis for various values of r_c/b plotted on the logarithmic axis. An

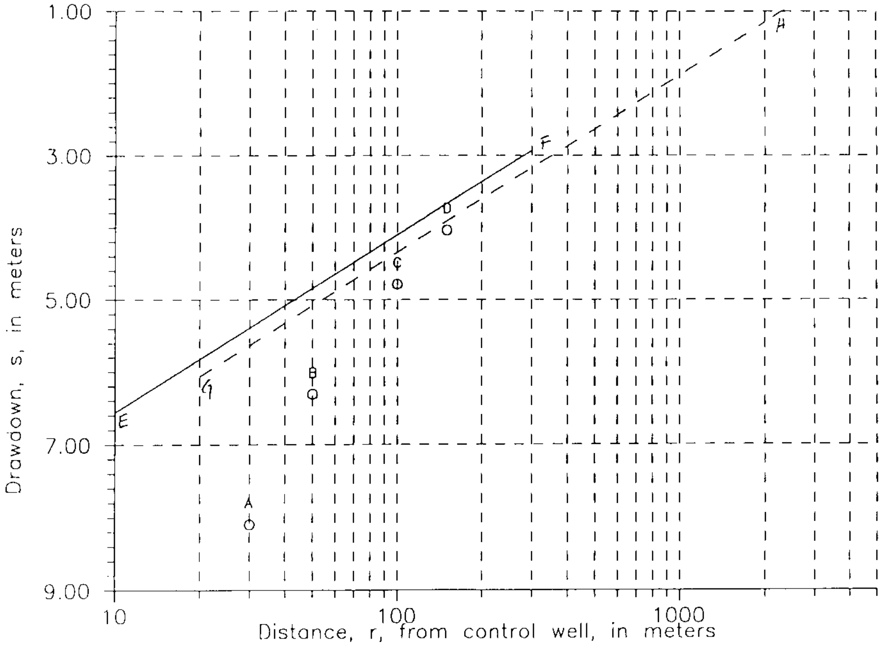

FIG. 7 Data Plots of Drawdown in Piezometer Near a Control Well and Straight-line Plots

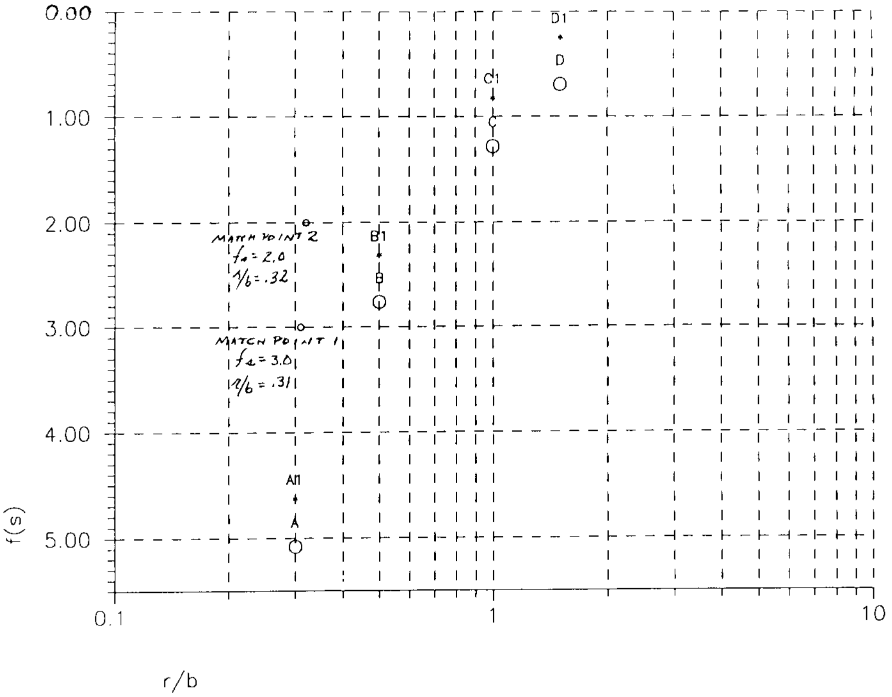

FIG. 8 Data Plot of *fs* , Dimensionless Drawdown Correction Factor, Versus *r/b* for Drawdown in Piezometers

example of such a plot is shown in Fig. 9.

8.2.2.6 Match the data plot to the type curve, keeping the coordinate axes of the two plots parallel, and select any convenient point common to both plots (see Fig. 8 and Fig. 9).

8.2.2.7 Determine for the selected match point, the coordinate value of *r/b* from the data plot and the value of r_c/b from the type-curve plot. Solve for K_r/K_z from the formula:

$$\frac{K_r}{K_z} = \left(\frac{r/b}{r_c/b}\right)^2 \tag{23}$$

8.2.2.8 For the selected match point, subtract the data-plot value of f_s (see Fig. 8) from the type-curve value of f_s (Fig. 9) and correct the data-plot values of f_s (see 8.2.2.4) by adding, algebraically, the amount to each f_s.

8.2.2.9 Replot data using corrected values of f_s and repeat 8.2.2.6 (Points, B1, C1, and D1 in Fig. 8); recalculate K_r/K_z.

8.2.2.10 If the calculated values of K_r/K_z differ by more than 10 %, repeat 8.2.2.8 and 8.2.2.9.

8.2.2.11 Correct straight-line plot in 8.2.2.2 (E–F, in Fig. 7)

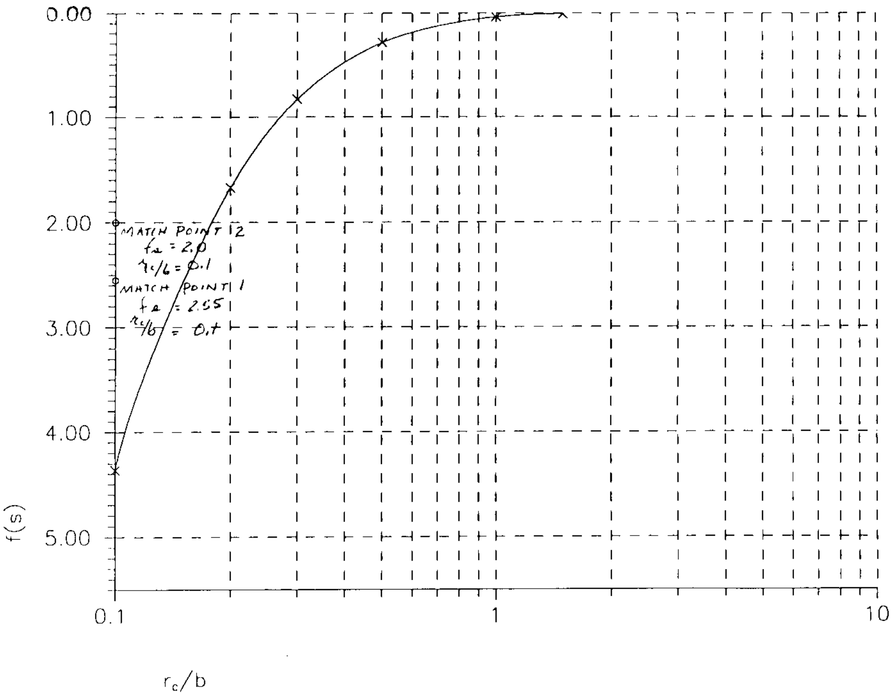

FIG. 9 Type Curve of *fs* , Dimensionless Drawdown Factor, Versus *rc/b*

by adding, algebraically, $Q/4\pi T$ * (f_s(type-curve) − f_s(data-curve). Corrected line is G–H in Fig. 7.

8.2.2.12 Using the zero drawdown intercept of the redrawn straight-line plot, determine the coefficient of storage from Eq 22.

NOTE 8—The following is provided to complement the procedures for calculation of hydraulic properties using Deviation Method 2. Plot of drawdown in Fig. 7 is indicated to be greater than for an equivalent isotropic aquifer. Straight line E–F of slope $\Delta s = -2.3Q/2\pi T = (-2.3 * 10\,000\ m^3 d^{-1})/(2 * \pi * 1500\ m^2 d^{-1}) = -2.44$ m/log cycle is drawn above drawdown values in Fig. 7.

Drawdown deviation, δs, for each piezometer is the observed drawdown minus the drawdown value for the straight-line plot, E–F, as shown in the accompanying table. The corresponding values of $f_s = 4\pi T\delta s/Q$ are calculated and a semilogarithmic graph of f_s on the arithmetic scale versus r/b (r of $A = 30$ m, $B = 50$ m, $C = 100$ m, and $D = 150$ m; $b = 100$ m) on the logarithmic scale as shown in Fig. 8.

	A	B	C	D
δs	2.70	1.47	0.68	0.37
f_s	5.08	2.76	1.28	0.70
r/b	0.3	0.5	1.0	1.50

A type curve is prepared plotting values of f_s versus r_c/b, shown in Fig. 9.

The plot of Points A, B, C, and D (see Fig. 8) are matched with the type curve (see Fig. 9). Match point 1, Fig. 8 and Fig. 9, are selected, and values of f_s and r/b from the data plot (see Fig. 8) are recorded and values of f_s and r_c/b from the type curve (see Fig. 9) are recorded. From the match point, determine:

$$K_r/K_z = [(r/b)/(r_c/b)]^2 = [0.31/0.1]^2 = 9.6 \qquad (24)$$

For the selected match point, subtract data point f_s from the type-curve f_s:

$$f_s\ (\text{type curve}) - f_s\ (\text{data plot}) = 2.55 - 3 = -0.45 \qquad (25)$$

Correct the data plot by adding, algebraically, this amount to the f_s (data plot) values, as shown below:

	A1	B1	C1	D1
f_s	4.63	2.31	0.83	0.35

Replot data in Fig 8 using corrected values of f_s, match the type curve to the replotted data (March Point 2), and recalculate k_r/K_z:

$$K_r/K_z = [(r/b)/(r_c/b)]^2 = [0.32/0.1]^2 = 10.2 \qquad (26)$$

Recalculate the drawdown deviation, $\delta s = f_s * (Q/4\pi T)$

	A	B	C	D
δ_s	2.45	1.22	0.44	0.13

Redraw straight-line plot using these values of drawdown deviation, as shown by Line G–H in Fig. 7.

8.2.2.13 Using the zero drawdown intercept, r, of the redrawn straight-line plot, determine the storage coefficient,

$$S = (2.25Tt)/r^2 = (2.25 * 1500\ m^2 * d^{-1} * 1d)/(5400\ m)^2 = 1 * 10^{-4} \qquad (27)$$

9. Report

9.1 Prepare a report including the following:

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of this test method. Briefly summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells or piezometers, or both, the method of measurement of discharge and water levels, and the duration of the test and pumping rate.

9.1.2 *Conceptual Model*—Review the information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the selection of this method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened and gravel packed intervals, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of piezometers and observation wells.

9.1.4 *Instrumentation*—Describe the field instrumentation for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturer's name, model number, and basic specifications for each major item, and the name and date and method of the last calibration, if applicable.

9.1.5 *Testing Procedures*—State the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in piezometers and observation wells, and other environmental data recorded during the testing procedure.

9.1.6 *Presentation and Interpretation of Test Results*:

9.1.6.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for background water-level and barometric changes and calculation of drawdown and residual drawdown.

9.1.6.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.1.7 Evaluate qualitatively the overall accuracy of the test, the corrections and adjustments made to the original water-level measurements, the adequacy and accuracy of instrumentation, accuracy of observations of stress and response, and the conformance of the hydrogeologic conditions and the performance of the test to the model assumptions.

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 anistroph; aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient; transmissivity

TABLE 1 Tabulated Values of the Dimensionless Drawdown Correction Factor

All values, including those for piezometer depth, are listed for percentages of the aquifer thickness, as measured from the top of the aquifer or from the pumped well.

The *f(s)* values listed are for an isotropic aquifer. For an anisotropic aquifer the value of *f(s)* would be read as the value of *r/b*[*Kz/Kr)*$^{1/2}$], expressed as a percentage, equivalent to the *r* value listed.

Each of the tables listed below may also be used for the situation where values for the bottom and the top of the screen are reversed by reading the *z* value in the table equivalent to (100 *z*) for the field situation. For example, the first table listed could also be used to determine values of *fs* for a well screened from the top of the aquifer down to a depth equal to 90 % of the adapter thickness. If the piezometers penetrated 20 % of the aquifer thickness, the correction value for a given *r/b* value would be found from the *z* = 80 listing.

Frequently it would be necessary to make a double or triple interpolation to use the data from these tables. Such interpolation probably would be best accomplished from a plot of *f(s)* versus log *r/b* for each of the *d/b*, *zw/b*, and *z/b* values bounding the actual values of these parameters.

Bottom of Screen in Pumped Well is 100. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.828	−3.457	−2.674	−2.134	−1.732	−1.421	−0.972	−0.673	−0.468	−0.229	−0.113	−0.056	−0.020
10.	−4.785	−3.415	−2.633	−2.095	−1.696	−1.387	−0.944	−0.650	−0.451	−0.219	−0.219	−0.053	−0.019
20.	−4.651	−3.284	−2.506	−1.976	−1.585	−1.284	−0.860	−0.584	−0.400	−0.191	−0.093	−0.046	−0.016
30.	−4.408	−3.048	−2.280	−1.763	−1.388	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.012
40.	−4.020	−2.674	−1.925	−1.434	−1.086	−0.833	−0.503	−0.312	−0.198	−0.085	−0.039	−0.018	−0.006
50.	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	0.000
60.	−2.444	−1.185	−0.566	−0.225	−0.035	0.067	0.138	0.135	0.111	0.063	0.033	0.017	0.006
70.	−0.736	0.341	0.725	0.829	0.808	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.012
80.	2.897	3.170	2.791	2.312	1.875	1.511	0.983	0.648	0.432	0.199	0.095	0.046	0.016
90.	13.344	8.218	5.575	3.974	2.926	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.019
100.	21.264	11.404	7.087	4.778	3.395	2.499	1.454	0.899	0.578	0.256	0.120	0.058	0.020

Top of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.785	−3.415	−2.633	−2.095	−1.696	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.019
10.	−4.739	−3.371	−2.590	−2.055	−1.658	−1.352	−0.916	−0.628	−0.434	−0.210	−0.103	−0.051	−0.018
20.	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
30.	−4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011
40.	−3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006
50.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000
60.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006
70.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.032	0.011
80.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015
90.	12.080	7.287	4.939	3.545	2.635	2.005	1.219	0.773	0.505	0.228	0.107	0.052	0.018
100.	13.344	8.218	5.575	3.973	2.926	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.019

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.710	−3.342	−2.562	−2.029	−1.634	−1.330	−0.897	−0.613	−0.423	−0.204	−0.100	−0.049	−0.017
10.	−4.659	−3.293	−2.515	−1.985	−1.593	−1.293	−0.868	−0.591	−0.406	−0.195	−0.095	−0.047	−0.017
20.	−4.500	−3.138	−2.368	−1.848	−1.468	−1.179	−0.778	−0.523	−0.355	−0.168	−0.082	−0.040	−0.014
30.	−4.203	−2.853	−2.100	−1.601	−1.245	−0.981	−0.626	−0.410	−0.273	−0.126	−0.600	−0.029	−0.010
40.	−3.705	−2.381	−1.666	−1.212	−0.902	−0.683	−0.408	−0.254	−0.162	−0.071	−0.033	−0.016	−0.005
50.	−2.853	−1.601	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000
60.	−1.189	−0.230	0.100	0.218	0.251	0.248	0.206	0.157	0.115	0.059	0.030	0.015	0.005
70.	3.064	2.155	1.638	1.286	1.028	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.010
80.	7.239	4.463	3.104	2.289	1.745	1.359	0.859	0.561	0.374	0.173	0.083	0.040	0.014
90.	8.651	5.592	3.958	2.925	2.220	1.716	1.067	0.687	0.453	0.206	0.098	0.048	0.017
100.	9.019	5.915	4.223	3.134	2.382	1.840	1.140	0.731	0.481	0.218	0.103	0.050	0.017

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
10.	−4.538	−3.175	−2.403	−1.880	−1.497	−1.206	−0.799	−0.538	−0.367	−0.174	−0.084	−0.041	−0.015
20.	−4.348	−2.994	−2.233	−1.725	−1.358	−1.082	−0.705	−0.470	−0.318	−0.149	−0.072	−0.035	−0.012
30.	−3.986	−2.650	−1.918	−1.442	−1.110	−0.868	−0.549	−0.358	−0.239	−0.110	−0.053	−0.026	−0.009
40.	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
50.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000
60.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005
70.	4.424	2.679	1.847	1.358	1.037	0.811	0.518	0.342	0.231	0.108	0.052	0.026	0.009
80.	5.634	3.670	2.622	1.958	1.502	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.012
90.	6.154	4.140	3.026	2.295	1.777	1.397	0.890	0.582	0.388	0.179	0.086	0.042	0.015
100.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.434	−3.075	−2.307	−1.791	−1.415	−1.131	−0.739	−0.493	−0.333	−0.156	−0.075	−0.037	−0.013
10.	−4.360	−3.005	−2.243	−1.732	−1.364	−1.087	−0.707	−0.470	−0.317	−0.149	−0.072	−0.035	−0.012

TABLE 1 *Continued*

20.	−4.119	−2.777	−2.036	−1.549	−1.205	−0.951	−0.611	−0.403	−0.271	−0.127	−0.061	−0.030	−0.010
30.	−3.626	−2.327	−1.642	−1.214	−0.924	−0.719	−0.453	−0.296	−0.198	−0.092	−0.044	−0.022	−0.008
40.	−2.609	−1.486	−0.976	−0.691	−0.513	−0.392	−0.243	−0.157	−0.105	−0.048	−0.023	−0.011	−0.004
50.	−0.000	−0.000	−0.000	−0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60.	2.609	1.486	0.976	0.691	0.513	0.392	0.243	0.157	0.105	0.048	0.023	0.011	0.004
70.	3.626	2.327	1.642	1.214	0.924	0.719	0.453	0.296	0.198	0.092	0.044	0.022	0.008
80.	4.119	2.777	2.036	1.549	1.205	0.951	0.611	0.403	0.271	0.127	0.061	0.030	0.010
90.	4.360	3.005	2.243	1.732	1.364	1.087	0.707	0.470	0.317	0.149	0.072	0.035	0.012
100.	4.434	3.075	2.307	1.791	1.415	1.131	0.739	0.493	0.333	0.156	0.075	0.037	0.013

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.203	−2.853	−2.100	−1.601	−1.245	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.010	
10.	−4.102	−2.760	−2.017	−1.530	−1.185	−0.931	−0.593	−0.388	−0.259	−0.120	−0.057	−0.028	−0.010
20.	−3.756	−2.447	−1.748	−1.305	−1.002	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.008
30.	−2.949	−1.786	−1.231	−0.905	−0.691	−0.541	−0.345	−0.228	−0.154	−0.072	−0.035	−0.017	−0.006
40.	−0.798	−0.569	−0.439	−0.349	−0.282	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.003
50.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	0.000
60.	2.224	1.370	0.929	0.662	0.488	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.003
70.	2.657	1.767	1.279	0.961	0.740	0.578	0.366	0.239	0.159	0.074	0.035	0.017	0.006
80.	2.899	1.996	1.489	1.150	0.905	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.008
90.	3.025	2.117	1.602	1.253	0.998	0.804	0.532	0.359	0.244	0.116	0.056	0.028	0.010
100.	3.064	2.155	1.638	1.286	1.028	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.010

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
10.	−3.020	−1.822	−1.235	−0.886	−0.659	−0.501	−0.305	−0.193	−0.126	−0.057	−0.027	−0.013	−0.005
20.	−1.576	−1.070	−0.788	−0.600	−0.467	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.004
30.	−0.057	−0.248	−0.278	−0.261	−0.230	−0.197	−0.140	−0.098	−0.068	−0.033	−0.016	−0.008	−0.003
40.	0.519	0.219	0.083	0.014	−0.020	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001
50.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	0.000
60.	0.978	0.643	0.458	0.338	0.255	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001
70.	1.084	0.745	0.554	0.426	0.334	0.265	0.170	0.112	0.075	0.034	0.016	0.008	0.003
80.	1.149	0.808	0.614	0.482	0.385	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.004
90.	1.185	0.843	0.647	0.514	0.415	0.338	0.229	0.157	0.109	0.053	0.026	0.013	0.005
100.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005

Bottom of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.743	−3.373	−2.592	−2.057	−1.660	−1.354	−0.916	−0.628	−0.434	−0.210	−0.103	−0.051	−0.018	
10.	−4.694	−3.326	−2.547	−2.015	−1.621	−1.318	−0.887	−0.606	−0.417	−0.201	−0.098	−0.048	−0.017
20.	−4.547	−3.179	−2.407	−1.883	−1.499	−1.207	−0.799	−0.538	−0.366	−0.174	−0.084	−0.041	−0.015
30.	−4.263	−2.910	−2.151	−1.666	−1.283	−1.013	−0.648	−0.425	−0.283	−0.131	−0.062	−0.030	−0.011
40.	−3.803	−2.470	−1.747	−1.274	−0.952	−0.722	−0.431	−0.267	−0.170	−0.074	−0.034	−0.016	−0.006
50.	−3.048	−1.763	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.008	−0.002	−0.001	0.000
60.	−1.708	−0.569	−0.096	0.111	0.193	0.218	0.198	0.156	0.116	0.061	0.031	0.015	0.006
70.	1.189	1.644	1.500	1.258	1.032	0.843	0.566	0.384	0.263	0.125	0.061	0.030	0.011
80.	9.712	5.389	3.509	2.491	1.859	1.431	0.895	0.582	0.387	0.179	0.086	0.042	0.015
90.	10.816	6.356	4.303	3.117	2.344	1.803	1.115	0.716	0.471	0.214	0.101	0.049	0.017
100.	5.425	5.032	4.064	3.168	2.457	1.915	1.190	0.763	0.500	0.226	0.107	0.052	0.018

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.651	−3.284	−2.506	−1.976	−1.585	−1.284	−1.860	0.584	−0.400	−0.191	−0.093	−0.046	−0.016
10.	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
20.	−4.424	−3.085	−2.299	−1.784	−1.409	−1.127	−0.737	−0.492	−0.333	−0.157	−0.076	−0.037	−0.013
30.	−4.100	−2.755	−2.010	−1.520	1.173	−0.919	−0.582	−0.379	−0.252	−0.116	−0.056	−0.027	−0.009
40.	−3.547	−2.235	−1.536	−1.101	−0.810	−0.069	−0.361	−0.224	−0.144	−0.064	−0.030	−0.014	−0.005
50.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	0.000
60.	−0.562	0.248	0.433	0.439	0.395	0.339	0.240	0.168	0.117	0.057	0.028	0.014	0.005
70.	4.965	3.061	2.094	1.515	1.138	0.878	0.551	0.362	0.243	0.114	0.055	0.027	0.009
80.	9.410	5.109	3.260	2.277	1.680	1.283	0.796	0.517	0.344	0.160	0.076	0.037	0.013
90.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015
100.	2.897	3.170	2.791	2.312	1.875	1.511	0.983	0.648	0.432	0.199	0.095	0.046	0.016

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.520	−3.157	−2.384	−1.861	−1.478	−1.187	−0.782	−0.524	−0.355	−0.167	−0.081	−0.039	−0.014	
10.	−4.455	−3.095	−2.326	−1.808	−1.431	−1.145	−0.750	−0.501	−0.334	−0.159	−0.077	−0.037	−0.013
20.	−4.247	−2.897	−2.142	−1.641	−1.282	−1.015	−0.654	−0.432	−0.290	−0.136	−0.065	−0.032	−0.011
30.	−3.845	−2.517	−1.797	−1.335	−1.017	−0.789	−0.494	−0.321	−0.213	−0.009	−0.047	−0.023	−0.008
40.	−3.108	−1.848	−1.217	−0.847	−0.613	−0.458	−0.273	−0.173	−0.114	−0.052	−0.025	−0.012	−0.004
50.	−1.601	−0.626	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000	0.000	0.000	0.000
60.	2.410	1.533	1.066	0.774	0.577	0.440	0.269	0.172	0.113	0.052	0.025	0.012	0.004

TABLE 1 *Continued*

70.	6.144	3.458	2.220	1.534	1.113	0.836	0.506	0.374	0.214	0.099	0.047	0.023	0.008
80	6.547	3.837	2.566	1.840	1.378	1.062	0.666	0.435	0.291	0.136	0.065	0.032	0.011
90	3.757	2.780	2.176	1.735	1.395	1.127	0.746	0.500	0.338	0.159	0.077	0.037	0.013
100.	1.318	1.905	1.838	1.609	1.358	1.129	0.767	0.520	0.354	0.167	0.081	0.039	0.014

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011	
10.	−4.254	−2.902	−2.145	−1.642	−1.280	−1.012	−0.648	−0.425	−0.284	−0.131	−0.063	−0.030	−0.011
20.	−3.986	−2.650	−1.918	−1.442	−1.110	−0.868	−0.549	−0.358	−0.239	−0.110	−0.053	−0.026	−0.009
30.	−3.430	−2.146	−1.482	−1.076	−0.809	−0.672	−0.388	−0.253	−0.169	−0.079	−0.038	−0.019	−0.007
40.	−2.256	−1.189	−0.739	−0.506	−0.369	−0.282	−0.177	−0.118	−0.081	−0.039	−0.019	−0.010	−0.003
50.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
60.	3.872	2.154	1.362	0.920	0.650	0.473	0.269	0.163	0.103	0.045	0.021	0.010	0.003
70.	4.716	2.823	1.871	1.310	0.953	0.714	0.428	0.271	0.177	0.081	0.038	0.019	0.007
80.	4.424	2.679	1.847	1.358	1.037	0.811	0.518	0.342	0.231	0.108	0.052	0.026	0.009
90.	2.114	1.701	1.410	1.172	0.973	0.807	0.554	0.380	0.262	0.125	0.061	0.030	0.011
100.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.032	0.011

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.078	−2.732	−1.985	−1.494	−1.147	−0.893	−0.557	−0.357	−0.234	−0.105	−0.050	−0.024	−0.008	
10.	−3.966	−2.629	−1.894	−1.417	−1.083	−0.840	−0.523	−0.336	−0.220	−0.100	−0.047	−0.023	0.008
20.	−3.577	−2.279	−1.596	−1.171	−0.885	−0.683	−0.424	−0.274	−0.181	−0.083	−0.040	−0.019	−0.007
30.	−2.658	−1.533	−1.021	−0.734	−0.552	−0.428	−0.272	−0.180	−0.122	−0.058	−0.028	−0.014	−0.005
40.	−0.153	−0.148	−0.141	−0.132	−0.122	−0.111	−0.088	−0.068	−0.051	−0.027	−0.014	−0.007	−0.003
50.	2.327	1.214	0.719	0.453	0.296	0.198	0.092	0.044	0.022	0.005	0.001	0.000	0.000
60.	3.158	1.881	1.228	0.840	0.592	0.428	0.237	0.139	0.086	0.036	0.016	0.008	0.003
70.	3.336	2.052	1.389	0.988	0.726	0.547	0.328	0.207	0.135	0.061	0.029	0.014	0.005
80.	2.899	1.761	1.228	0.917	0.711	0.564	0.368	0.247	0.168	0.080	0.039	0.019	0.007
90.	0.961	0.896	0.807	0.709	0.612	0.523	0.374	0.264	0.185	0.091	0.045	0.022	0.008
100.	−0.575	0.305	0.548	0.588	0.555	0.497	0.373	0.269	0.191	0.095	0.047	0.023	0.008

Top of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −3.705	−2.381	−1.666	−1.212	−0.902	−0.683	−0.408	−0.254	−0.162	−0.071	−0.033	−0.016	−0.005	
10.	−3.528	−2.227	−1.540	−1.113	−0.827	−0.627	−0.376	−0.235	−0.151	−0.067	−0.031	−0.015	−0.005
20.	−2.844	−1.684	−1.134	−0.815	−0.608	−0.465	−0.286	−0.183	−0.120	−0.055	−0.026	−0.013	−0.004
30.	−0.798	−0.569	−0.439	−0.349	−0.283	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.003
40.	1.264	0.560	0.271	0.130	0.055	0.015	−0.019	−0.026	−0.024	−0.015	−0.008	−0.004	−0.002
50.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	0.000
60.	2.260	1.388	0.927	0.643	0.457	0.331	0.181	0.104	0.063	0.025	0.011	0.005	0.002
70.	2.224	1.370	0.929	0.662	0.488	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.003
80.	1.767	1.041	0.719	0.539	0.421	0.338	0.225	0.154	0.106	0.051	0.025	0.012	0.004
90.	0.106	0.277	0.328	0.330	0.309	0.279	0.213	0.157	0.113	0.057	0.029	0.014	0.005
100.	−1.189	−0.230	0.100	0.218	0.251	0.248	0.206	0.157	0.115	0.059	0.030	0.015	0.005

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −3.123	−1.854	−1.211	−0.830	−0.588	−0.428	−0.239	−0.141	−0.087	−0.036	−0.016	−0.008	−0.003	
10.	−2.768	−1.594	−1.035	−0.714	−0.511	−0.375	−0.213	−0.128	−0.080	−0.034	−0.015	−0.007	−0.002
20.	−1.137	−0.754	−0.542	−0.404	−0.307	−0.237	−0.145	−0.092	−0.060	−0.027	−0.013	−0.006	−0.002
30.	0.565	0.152	0.008	−0.046	−0.065	−0.068	−0.058	−0.044	−0.033	−0.017	−0.008	−0.004	−0.002
40.	1.167	0.603	0.370	0.221	0.133	0.078	0.024	0.003	−0.004	−0.006	−0.004	−0.002	−0.001
50.	1.411	0.851	0.554	0.372	0.253	0.174	0.083	0.041	0.020	0.005	0.001	0.000	0.000
60.	1.467	0.904	0.605	0.419	0.296	0.114	0.114	0.063	0.037	0.014	0.006	0.003	0.000
70.	1.344	0.802	0.530	0.369	0.266	0.197	0.115	0.071	0.045	0.020	0.009	0.004	0.002
80.	0.899	0.471	0.303	0.221	0.173	0.140	0.096	0.068	0.048	0.024	0.012	0.006	0.002
90.	−0.552	−0.211	−0.056	0.020	0.056	0.071	0.073	0.061	0.047	0.026	0.013	0.007	0.002
100.	−1.670	−0.653	−0.260	−0.084	−0.000	0.039	0.062	0.057	0.046	0.026	0.014	0.007	0.003

Top of Screen in Pumped Well is 10. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	−0.000	
10.	−1.070	−0.600	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.003	−0.001	−0.000	−0.000
20.	0.219	−0.014	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001	−0.000	−0.000	−0.000
30.	0.643	0.338	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001	0.000	0.000	−0.000
40.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	−0.000
50.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
60.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	0.000
70.	0.643	0.338	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001	0.000	0.000	0.000
80.	0.219	0.014	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001	−0.000	−0.000	0.000
90.	−1.070	−0.600	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.003	−0.001	−0.000	0.000
100.	−2.054	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000

Bottom of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

TABLE 1 *Continued*

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.560	−3.196	−2.421	−1.895	−1.509	−1.215	−0.803	−0.539	−0.366	−0.172	−0.083	−0.041	−0.014	
10.	−4.500	−3.137	−2.366	−1.844	−1.463	−1.174	−0.771	−0.516	−0.349	−0.164	−0.079	−0.039	−0.014
20.	−4.306	−2.952	−2.192	−1.685	−1.320	−1.047	−0.676	−0.447	−0.300	−0.140	−0.067	−0.033	−0.012
30.	−3.937	−2.601	−1.868	−1.393	−1.063	−0.825	−0.515	−0.334	−0.221	−0.102	−0.049	−0.024	−0.008
40.	−3.292	−1.999	−1.330	−0.927	−0.668	−0.495	−0.240	−0.182	−0.119	−0.054	−0.026	−0.013	−0.004
50.	−2.095	−0.944	−0.451	−0.219	−0.108	−0.053	−0.003	−0.003	−0.000	0.000	0.000	0.000	0.000
60.	0.584	1.065	0.962	0.768	0.596	0.460	0.282	0.180	0.118	0.054	0.026	0.013	0.004
70.	8.740	4.479	2.688	1.772	1.244	0.913	0.537	0.339	0.223	0.102	0.049	0.024	0.008
80.	9.109	4.830	3.012	2.063	1.500	1.135	0.698	0.452	0.302	0.140	0.067	0.033	0.012
90.	1.792	2.203	1.997	1.686	1.390	1.139	0.763	0.514	0.349	0.164	0.079	0.039	0.014
100.	0.369	1.308	1.519	1.456	1.294	1.108	0.776	0.532	0.364	0.172	0.083	0.041	0.014

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.408	−3.048	−2.280	−1.763	−1.388	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.012	
10.	−4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011
20.	−4.100	−2.755	−2.010	−1.520	−1.173	−0.919	−0.582	−0.379	−0.252	−0.116	−0.056	−0.027	−0.009
30.	−3.636	−2.321	−1.620	−1.180	−0.884	−0.677	−0.417	−0.269	−0.178	−0.083	−0.040	−0.020	−0.007
40.	−2.761	−1.537	−0.954	−0.633	−0.444	−0.326	−0.194	−0.126	−0.085	−0.041	−0.020	−0.010	−0.004
50.	−0.877	−0.057	0.147	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	0.000
60.	4.468	2.585	1.647	1.105	0.769	0.551	0.304	0.180	0.112	0.048	0.022	0.011	0.004
70.	8.622	4.365	2.581	1.672	1.154	0.833	0.475	0.293	0.140	0.086	0.040	0.020	0.007
80.	4.965	3.061	2.094	1.515	1.138	0.878	0.551	0.362	0.243	0.114	0.055	0.027	0.009
90.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.037	0.011
100.	−0.736	0.341	0.725	0.829	0.808	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.012

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −4.200	−2.848	−2.090	−1.587	−1.227	−0.961	−0.603	−0.388	−0.254	−0.114	−0.054	−0.026	−0.009	
10.	−4.108	−2.760	−2.011	−1.517	−1.167	−0.910	−0.568	−0.365	−0.239	−0.108	−0.051	−0.024	−0.008
20.	−3.800	−2.474	−1.755	−1.295	−0.980	−0.755	−0.466	−0.298	−0.196	−0.089	−0.042	−0.021	−0.007
30.	−3.153	−1.892	−1.259	−0.886	−0.650	−0.492	−0.301	−0.195	−0.131	−0.062	−0.030	−0.015	−0.005
40.	−1.741	−0.762	−0.404	−0.250	−0.175	−0.135	−0.093	−0.069	−0.051	−0.028	−0.014	−0.007	−0.003
50.	2.155	1.286	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.007	0.002	0.000	0.000
60.	5.732	3.062	1.847	1.190	0.802	0.558	0.292	0.165	0.099	0.040	0.017	0.008	0.003
70.	5.892	3.216	1.994	1.327	0.927	0.672	0.382	0.233	0.149	0.066	0.031	0.015	0.005
80.	2.662	1.775	1.292	0.981	0.763	0.604	0.393	0.263	0.179	0.085	0.041	0.020	0.007
90.	−0.786	0.150	0.445	0.524	0.516	0.475	0.366	0.268	0.192	0.096	0.048	0.024	0.008
100.	−1.506	−0.354	0.129	0.335	0.408	0.414	0.351	0.268	0.195	0.100	0.050	0.025	0.009

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006	
10.	−3.784	−2.454	−1.731	−1.267	−0.948	−0.721	−0.432	−0.268	−0.171	−0.074	−0.034	−0.016	−0.006
20.	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
30.	−2.256	−1.189	−0.739	−0.506	−0.369	−0.282	−0.177	−0.118	−0.081	−0.039	−0.019	−0.010	−0.003
40.	0.759	0.432	0.259	0.153	0.085	0.042	−0.002	−0.018	−0.021	−0.015	−0.009	−0.005	−0.002
50.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	0.000
60.	4.374	2.493	1.559	1.022	0.692	0.480	0.246	0.135	0.078	0.029	0.012	0.006	0.002
70.	3.872	2.154	1.362	0.920	0.650	0.473	0.269	0.163	0.103	0.045	0.021	0.010	0.003
80.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005
90.	−1.503	−0.469	−0.067	0.107	0.180	0.203	0.189	0.151	0.114	0.060	0.031	0.015	0.006
100.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006

Top of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.497	−2.183	−1.481	−1.042	−0.751	−0.549	−0.307	−0.179	−0.108	−0.043	−0.019	−0.009	−0.003
10.	−3.295	−2.007	−1.339	−0.933	−0.669	−0.489	−0.274	−0.161	−0.098	−0.040	−0.018	−0.008	−0.003
20.	−2.506	−1.385	−0.880	−0.601	−0.430	−0.317	−0.183	−0.112	−0.071	−0.031	−0.014	−0.007	−0.002
30.	−0.104	−0.101	−0.096	−0.090	−0.083	−0.075	−0.059	−0.045	−0.034	−0.018	−0.009	−0.005	−0.002
40.	2.278	1.167	0.674	0.411	0.257	0.162	0.063	0.022	0.005	−0.004	−0.003	−0.002	−0.001
50.	3.005	1.732	1.087	0.707	0.470	0.317	0.149	0.072	0.035	0.009	0.002	0.001	0.000
60.	3.053	1.780	1.132	0.750	0.510	0.353	0.178	0.094	0.052	0.018	0.007	0.003	0.001
70.	2.431	1.315	0.815	0.543	0.379	0.273	0.151	0.089	0.055	0.023	0.010	0.005	0.002
80.	0.178	0.171	0.161	0.148	0.134	0.119	0.091	0.068	0.049	0.025	0.013	0.006	0.002
90.	−2.036	−0.939	−0.466	−0.227	−0.098	−0.026	0.033	0.045	0.041	0.026	0.014	0.007	0.003
100.	−2.512	−1.282	−0.693	−0.372	−0.190	−0.085	0.009	0.036	0.038	0.026	0.014	0.008	0.003

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0 −2.853	−1.601	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	−0.000	
10.	−2.447	−1.305	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.006	−0.001	−0.000	−0.000
20.	−0.569	−0.349	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.002	−0.001	−0.000	−0.000
30.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	−0.000

TABLE 1 *Continued*

40.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	−0.000
50.	2.155	1.286	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.007	0.002	0.000	0.000
60.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	0.000
70.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	0.000
80.	−0.569	−0.349	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.002	−0.001	−0.000	0.000
90.	−2.447	−1.305	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.006	−0.001	−0.000	0.000
100.	−2.853	−1.601	−0.981	−0.626	−0.410	0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000

Bottom of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.256	−2.901	−2.140	−1.632	−1.266	−0.994	−0.626	−0.404	−0.264	−0.118	−0.056	−0.027	−0.009
10.	−4.172	−2.821	−2.066	−1.565	−1.208	−0.944	−0.592	−0.380	−0.249	−0.112	−0.053	−0.025	−0.009
20.	−3.895	−2.559	−1.828	−1.355	−1.027	−0.791	−0.488	−0.311	−0.204	−0.093	−0.044	−0.021	−0.007
30.	−3.334	−2.041	−1.371	−0.966	−0.705	−0.529	−0.318	−0.204	−0.136	−0.064	−0.031	−0.015	−0.005
40.	−2.229	−1.075	−0.577	−0.339	−0.219	−0.156	−0.098	−0.070	−0.052	−0.028	−0.015	−0.008	−0.003
50.	0.341	0.829	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.008	0.002	0.001	0.000
60.	8.352	4.104	2.333	1.442	0.943	0.642	0.326	0.180	0.106	0.042	0.018	0.009	0.003
70.	8.504	4.251	2.473	1.573	1.064	0.752	0.414	0.248	0.157	0.069	0.032	0.016	0.005
80.	0.820	1.293	1.176	0.967	0.775	0.621	0.405	0.271	0.184	0.088	0.043	0.021	0.007
90.	−1.339	−0.219	0.228	0.402	0.450	0.440	0.359	0.269	0.195	0.098	0.049	0.024	0.009
100.	−1.841	−0.626	−0.069	0.203	0.323	0.363	0.335	0.265	0.197	0.102	0.051	0.026	0.009

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.020	−2.674	−1.925	−1.434	−1.086	−0.833	−0.503	−0.312	−0.198	−0.085	−0.039	−0.018	−0.006
10.	−3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006
20.	−3.547	−2.235	−1.536	−1.101	−0.810	−0.609	−0.361	−0.224	−0.144	−0.064	−0.030	−0.014	−0.005
30.	−2.761	−1.537	−0.954	−0.633	−0.444	−0.326	−0.194	−0.126	−0.085	−0.041	−0.020	−0.010	−0.004
40.	−0.965	−0.144	0.059	0.089	0.072	0.045	0.006	−0.013	−0.018	−0.015	−0.009	−0.005	−0.002
50.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
60.	8.306	4.060	2.290	1.401	0.905	0.607	0.297	0.158	0.089	0.032	0.013	0.006	0.002
70.	4.468	2.585	1.647	1.105	0.769	0.551	0.304	0.180	0.112	0.048	0.022	0.011	0.004
80.	−0.562	0.248	0.433	0.439	0.395	0.339	0.240	0.168	0.177	0.057	0.028	0.014	0.005
90.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006
100.	−2.444	−1.185	−0.566	−0.225	−0.035	0.067	0.138	0.135	0.111	0.063	0.033	0.017	0.006

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.695	−2.364	−1.638	−1.173	−0.856	−0.632	−0.355	−0.206	−0.124	−0.048	−0.021	−0.010	−0.003
10.	−3.545	−2.227	−1.519	−1.075	−0.777	−0.570	−0.319	−0.186	−0.112	−0.045	−0.019	−0.009	−0.003
20.	−3.013	−1.756	−1.128	−0.763	−0.535	−0.387	−0.215	−0.128	−0.080	−0.034	−0.015	−0.007	−0.002
30.	−1.696	−0.719	−0.362	−0.210	−0.138	−0.100	−0.065	−0.047	−0.034	−0.018	−0.010	−0.005	−0.002
40.	2.110	1.243	0.788	0.513	0.337	0.221	0.093	0.037	0.012	−0.002	−0.003	−0.002	−0.001
50.	5.592	2.925	1.716	1.067	0.687	0.453	0.206	0.098	0.048	0.012	0.003	0.001	0.000
60.	5.637	2.969	1.758	1.107	0.724	0.487	0.235	0.120	0.065	0.021	0.008	0.003	0.001
70.	2.250	1.379	0.919	0.537	0.458	0.327	0.179	0.104	0.063	0.026	0.011	0.005	0.002
80.	−1.441	−0.471	0.126	0.011	0.065	0.084	0.082	0.065	0.050	0.026	0.013	0.007	0.002
90.	−2.601	−1.359	−0.755	−0.419	−0.224	−0.109	−0.002	0.031	0.036	0.026	0.015	0.008	0.003
100.	−2.890	−1.605	−0.948	−0.562	−0.326	−0.180	−0.034	0.016	0.030	0.025	0.015	0.008	0.003

Bottom of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00	
0.0	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	−0.000
10.	−2.994	−1.725	−1.082	−0.706	−0.470	−0.318	−0.149	−0.072	−0.035	−0.009	−0.002	−0.001	−0.000
20.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	−0.000
30.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	−0.000
40.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	−0.000
50.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
60.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	0.000
70.	0.864	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
80.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000
90.	−2.994	−1.725	−1.082	−0.705	−0.470	−0.318	−0.149	−0.072	−0.035	−0.009	−0.002	−0.001	0.000
100.	−3.232	−1.979	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000

Bottom of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.784	−2.446	−1.711	−1.235	−0.907	−0.673	−0.380	−0.221	−0.132	−0.051	−0.022	−0.010	−0.003
10.	−3.651	−2.323	−1.607	−1.142	−0.830	−0.611	−0.343	−0.199	−0.120	−0.047	−0.020	−0.009	−0.003
20.	−3.200	−1.911	−1.245	−0.846	−0.593	−0.426	−0.234	−0.137	−0.085	−0.035	−0.016	−0.008	−0.003
30.	−2.187	−1.033	−0.537	−0.300	−0.183	−0.123	−0.070	−0.048	−0.035	−0.019	−0.010	−0.005	−0.002
40.	0.298	0.788	0.695	0.517	0.362	0.247	0.109	0.045	0.016	−0.001	−0.003	−0.002	−0.001
50.	8.218	3.973	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.013	0.003	0.001	0.000
60.	8.261	4.015	2.247	1.361	0.867	0.573	0.269	0.136	0.072	0.023	0.008	0.004	0.001

TABLE 1 *Continued*

70.	0.432	0.918	0.821	0.637	0.474	0.350	0.194	0.112	0.067	0.027	0.012	0.006	0.002
80.	−1.944	−0.797	−0.311	−0.088	0.014	0.057	0.075	0.064	0.050	0.027	0.014	0.007	0.003
90.	−2.812	−1.536	−0.890	−0.516	−0.292	−0.155	−0.022	0.022	0.032	0.025	0.015	0.008	0.003
100.	−3.047	−1.745	−1.063	−0.653	−0.394	−0.229	−0.059	0.005	0.025	0.024	0.015	0.008	0.003
Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer													
Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	−0.000
10.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	−0.000
20.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	−0.000
30.	−0.877	−0.057	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	−0.000
40.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	−0.000
50.	8.218	3.973	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.013	0.003	0.001	0.000
60.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
70.	−0.877	−0.057	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	0.000
80.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	0.000
90.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000
100.	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	0.000

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(**1**) Weeks, E. P., "Determining the Ratio of Horizontal to Vertical Permeability by Aquifer-Test Analysis," *Water Resources Research*, Vol 5, No. 1, 1969, pp. 196–214.

(**2**) Hantush, M. S., "Drawdown Around a Partially Penetrating Well," American Society of Civil Engineers, *Proceedings*, Vol 87, No. HY4, 1961, pp. 83–98.

(**3**) Theis, C. V., *The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage: American Geophysical Union Transactions*, Vol 16, Part 2, 1935, pp. 519–524.

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(**5**) Reed, J. E., "Type Curves for Selected Problems of Flow to Wells in Confined Aquifers," *U.S. Geological Survey Techniques of Water-Resources Investigations*, Book 3, Ch. B3, 1980.

(**6**) Dawson, K. J., and Istok, J. D., *Aquifer Testing—Design and Analysis of Pumping and Slug Tests*, Lewis Publishers, Chelsea, Michigan, 1991.

(**7**) Kruseman, G. P., and DeRidder, N. S., *Analysis and Evaluation of Pumping Test Data*, International Institute for Land and Reclamation and Improvement, Bulletin 11, Wageningen, The Netherlands, 1979.

Designation: D 5716 – 95 (Reapproved 2000)

Standard Test Method for Measuring the Rate of Well Discharge by Circular Orifice Weir[1]

This standard is issued under the fixed designation D 5716; 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 construction and operation of a circular orifice weir for measuring the discharge from a well. This test method is a part of a series of standards prepared on the in situ determination of hydraulic properties of aquifer systems by single- or multiple-well tests. Selection of a well discharge measurement test method is described in Guide D 5737.

1.2 This test method is common to a number of aquifer test methods and to evaluation of well and pump performance.

1.3 *Limitations*—This test method is limited to the description of a method common to hydraulic engineering for the purpose of ground water discharge measurement in temporary or test conditions.

1.4 Much of the information presented in this test method is based on work performed by the Civil Engineering Department of Purdue University during the late 1940s. The essentials of that work have been presented in a pamphlet prepared by Layne-Bowler, Inc.[2] and updated by Layne Western Company, Inc.[3]

1.5 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

1.6 *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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[4]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[4]

D 5737 Guide for Methods for Measuring Well Discharge

3. Terminology

3.1 *Definitions:*

3.1.1 *circular orifice weir*—a circular restriction in a pipe that causes back pressure that can be measured in a piezometer tube. Also called *orifice tube* and *orifice meter*.

3.1.2 *control well*—a well by which the head and flow in the aquifer is changed, by pumping, injection, or imposing a change of head.

3.1.3 *discharge*—or rate of flow, is the volume of water that passes a particular reference section in a unit of time.

3.2 For definitions of other terms used in this guide, see Terminology D 653.

3.3 *Symbols:Symbols and Dimensions:*

3.3.1 A—orifice plate open area [L^2].

3.3.2 C—coefficient of discharge for the orifice [*nd*].

3.3.3 g—acceleration due to gravity [LT^{-2}].

3.3.4 h—head in manometer [L].

3.3.5 Q—control well discharge [L^3T^{-1}].

3.3.6 o—orifice diameter [L].

3.3.7 d—pipe inside diameter [L].

4. Summary of Test Method

4.1 This test method involves pumping a control well at a constant or variable rate for a given period of time. Discharge is through an orifice weir that allows determination of the discharge rate.

4.2 This test method provides design information for construction of an orifice weir. It also describes setup, operation, inspection, calculation of discharge, and reporting.

5. Significance and Use

5.1 Many mathematical equations for determining aquifer properties based on controlled field tests utilizing a single or multiple-pumping wells include a dependent variable, termed discharge, and generally designated as Q. Equations have been developed for constant and variable discharge. Those for variable discharge may specify regularly increasing, or regularly decreasing, or randomly varying discharge rate.

5.2 Aquifer testing has been conducted for the purposes of production and pressure relief well design and water resource assessment. Production wells are used for public and industrial

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

Current edition approved April 15, 1995. Published August 1995.

[2] *Measurement of Water Flow Through Pipe Orifice With Free Discharge*, Bulletin 501, Layne-Bowler, Inc., Mission, KS, 1958.

[3] *Measurement of Water Flow Through Pipe Orifice With Free Discharge*, Layne-Western Company, Inc., Mission, KS, 1988.

[4] *Annual Book of ASTM Standards*, Vol 04.08.

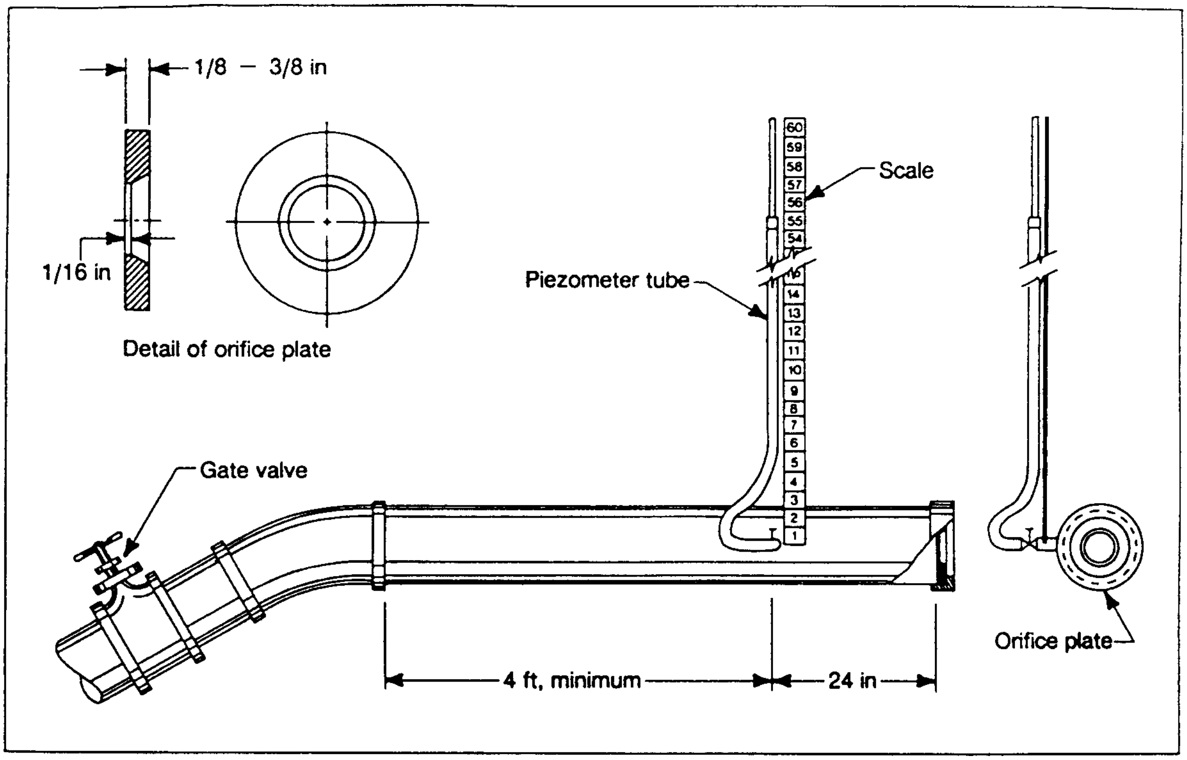

FIG. 1 Construction of a Circular Orifice Weir[5]

water supplies, hydraulic controls, and ground water capture. Pressure relief wells are for hydraulic controls. Test wells are for the purpose of water resource assessment.

5.3 Discharge must also be known for certain methods to evaluate well and pump performance.

6. Apparatus

6.1 *Construction of a Circular Orifice Weir*—A construction diagram of a circular orifice weir is presented in Fig. 1.[5] The circular orifice is a hole located in the center of a plate attached to a straight horizontal length of discharge pipe. The pipe is at least 6 ft (1.8 m) in length. Twenty-four inches (609 mm) from the end plate and at least 4 ft (1.2 m) from the other end of the discharge pipe, a manometer is attached to the discharge pipe so that the head in the discharge pipe can be measured.

6.1.1 *Orifice Plate*—The orifice is a round hole with clean, square edges in the center of a circular steel plate. The plate must be a minimum of 1⁄16 in. (1.59 mm) thick around the circumference of the hole. The remaining thickness of the orifice should be chamfered to 45° and with the chamfered edge down stream.

6.1.2 *Discharge Pipe*—The discharge pipe must be straight and level for a distance of at least 6 ft (1.8 m) before the water reaches the orifice plate. This approach channel should be longer if possible. The end of the pipe must be cut squarely so the plate will be vertical. The bore of the pipe should be smooth and free of any obstruction that might cause abnormal turbulence.

6.1.3 *Manometer*—The discharge pipe wall is tapped midway between the top and bottom with a 1⁄8-in. (3.17 mm) or 1⁄4-in. (6.35 mm) hole exactly 24 in. (609 mm) from the orifice plate. The manometer should be a distance of at least ten discharge pipe diameters from the gate valve used to control pipe flow. Any burrs inside the pipe resulting from the drilling or tapping of the hole should be filed off. A nipple is screwed into the tapped hole. The nipple must not protrude inside the discharge pipe. A clear plastic tube 4 or 5 ft (1.2 or 1.5 mm) long is connected at one end to the nipple. A scale is fastened to a support so that the vertical distance from the center of the discharge pipe up to the water level in the manometer can be measured. Alternately, a u-tube manometer or pressure transducer may be used. During a test the manometer must be free of air bubbles.

6.2 The water level in the manometer indicates the pressure head in the approach pipe when water is being pumped through the orifice. For any given size of orifice discharge pipe, the rate of flow through the orifice varies with the pressure head as measured in this manner. Table 1 presents the flow in gallons per minute (gpm) for various combinations of orifice and pipe diameters.

6.3 The diameter of the orifice should be less than 80 % of the inside diameter of the approach channel pipe.

7. Procedure

7.1 Set up the apparatus as shown in Fig. 1 and Fig. 2. The apparatus should be set up so that the orifice pipe is horizontal and the discharge is unimpeded. Use a combination of pipe and orifice diameter so that the anticipated head will be at least three times the diameter of the orifice. The orifice plate must be vertical and centered in the discharge pipe.

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[5] Driscoll, F. G., *Ground Water and Wells,* Johnson Division, St. Paul, MN, 1986, pp. 537–541.

TABLE 1 Flow Rates Through Circular Orifice Weirs[5,A]

NOTE 1—Flow rates indicated below the line are more exact than those above the line because the head developed in the piezometer tube for particular pipe and orifice diameters is large enough to ensure the accuracy of results obtained from Eq 5.

Head of Water in.	4-in. Pipe		6-in. Pipe		8-in. Pipe			10-in. Pipe			12-in. Pipe		16-in. Pipe		
	2½-in. Orifice gpm	3-in. Orifice gpm	3-in. Orifice gpm	4-in. Orifice gpm	4-in. Orifice gpm	5-in. Orifice gpm	6-in. Orifice gpm	6-in. Orifice gpm	7-in. Orifice gpm	8-in. Orifice gpm	6-in. Orifice gpm	8-in. Orifice gpm	8-in. Orifice gpm	10-in. Orifice gpm	12-in. Orifice gpm
5	55	89	76	145	131	220	355	310	460	680	300	580	530	880	1420
6	60	97	82	158	144	240	390	340	500	740	325	640	580	960	1560
7	65	105	88	171	156	260	420	370	540	830	350	690	620	1040	1680
8	69	112	94	182	166	275	450	395	580	880	375	730	670	1110	1800
9	73	119	100	193	176	295	475	420	610	940	400	780	710	1180	1910
10	77	126	106	204	186	310	500	440	640	990	420	820	750	1240	2010
12	85	138	115	223	205	340	550	480	700	1080	460	900	820	1360	2200
14	92	149	125	241	220	365	595	520	760	1170	500	970	880	1470	2380
16	98	159	132	258	235	390	635	555	810	1250	530	1040	940	1570	2540
18	104	168	140	273	250	415	675	590	860	1330	560	1100	1000	1670	2690
20	110	178	150	288	265	440	710	620	910	1400	590	1160	1050	1760	2840
22	115	186	158	302	275	460	745	650	950	1470	620	1220	1110	1840	2980
25	122	198	168	322	295	490	795	690	1020	1560	660	1300	1180	1960	3180
30	134	217	182	353	325	540	870	760	1120	1710	730	1420	1290	2150	3480
35	145	235	198	380	355	580	940	820	1210	1850	790	1530	1400	2320	3760
40	155	251	210	405	370	620	1000	880	1290	1980	840	1640	1490	2480	4020
45	164	267	223	430	395	660	1060	930	1370	2030	890	1740	1580	2630	4260
50	173	280	235	455	415	690	1120	980	1440	2140	940	1830	1670	2780	4490
60	190	310	260	500	455	760	1230	1080	1580	2340	1030	2010	1830	3040	4920
70	205	350	280	525	490	810	1280	1140	1710	2530	1110	2170	1970	3280	5310

[A] Values in mm are obtained by multiplying 25.38 mm/in. Values in Lpm are obtained by multiplying 3.785 L/gal.

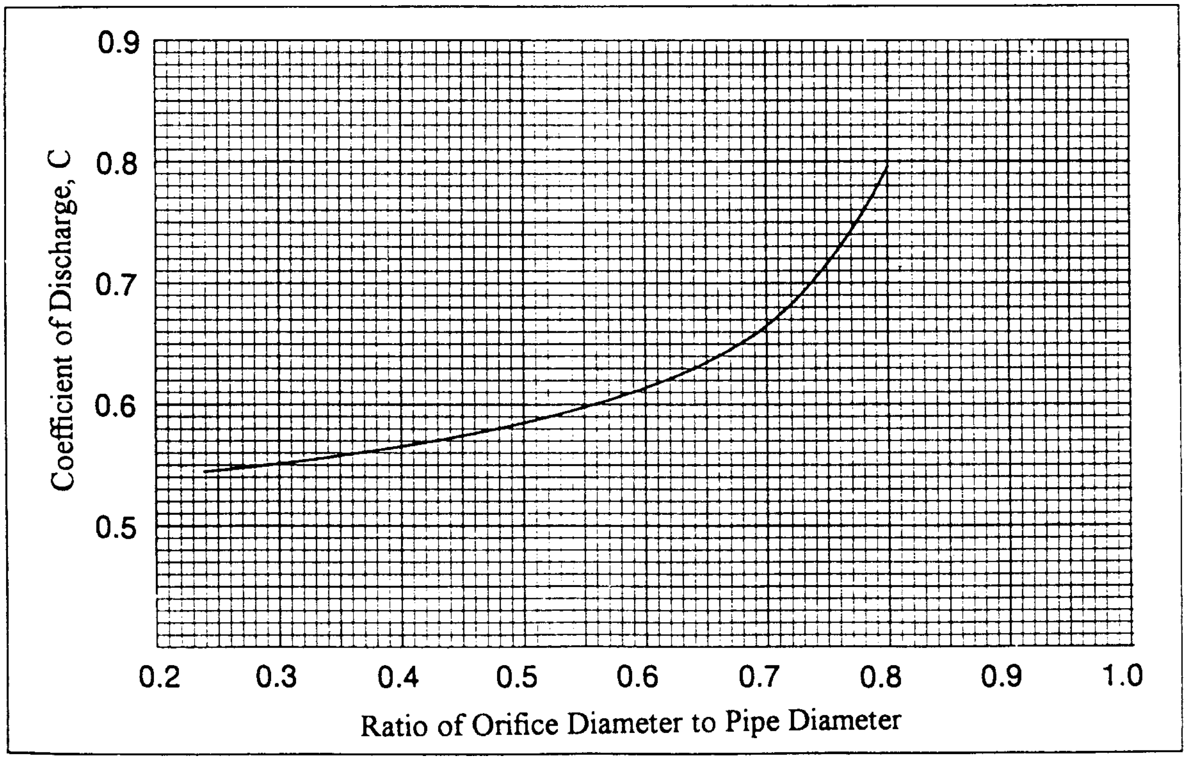

FIG. 2 The Coefficient of Discharge, *C*, in the Orifice-Weir Equation[5]

7.2 Equipment should be inspected to minimize the potential of wear, damage or misuse causing increased head loss that will bias results.

7.3 Initiate flow through the discharge pipe. Check that the manometer is free of air bubbles. Record the manometer level. Using Table 1 for the appropriate pipe and orifice size, read the discharge.

8. Calculation

8.1 Calculate the flow through the orifice using the basic equation:

$$Q = AVC \quad (1)$$

where:

Q = the flow per unit time,
A = the area of the orifice,
V = the velocity of flow through the orifice, and
C = the coefficient of discharge for the orifice.

The velocity of the water at the orifice consists of its velocity in the approach channel plus the additional velocity head created by the pressure drop that occurs between the connection for the manometer and the orifice. Because the water discharges at atmospheric pressure, the pressure head indicated by the manometer can be converted to the velocity if friction in the pipe is neglected.

8.2 Relate the velocity to the head in the manometer by the equation:

$$V = \sqrt{2gh} \tag{2}$$

where:
V = velocity,
g = acceleration due to gravity, and
h = the height of water in the manometer.

To compute the actual velocity through the orifice, the value of V from Eq 2 must be added to the velocity in the discharge pipe approach, and the sum of these must be corrected by two factors. One correction is for the contraction of the jet stream just outside of the orifice, and the other is for the sudden change in cross-sectional area of flow which is controlled by the size of the orifice relative to the size of the approach channel. The approach velocity and the two correction factors are combined into a single factor, C, whose value varies with the ratio of the orifice inside diameter to the approach-pipe inside diameter as presented in Fig. 2.

8.3 The equation for flow through the orifice is:

$$Q = CA\sqrt{2gh} = 8.025CA\sqrt{h} \tag{3}$$

Values of C may be obtained from Fig. 2, and Eq 3 may be used to calculate the pumping rate for any combination of orifice diameter, approach-pipe diameter, and water height in the piezometer tube. The pumping rate, Q, will be in the units of gallons (litres) per minute when the orifice area, A, is in square inches (millimetres) and the water level in the manometer, h, is in inches (millimetres). The value of C from Fig. 2 is only valid for use with this combination of units.

8.4 A discharge of 55 gpm (208 Lpm) will cause 5 in. (127 mm) of head due to a 2½-in. (63.5 mm) orifice and a 4-in. (102 mm) approach pipe. Similarly, a discharge of 5 310 gal (20.100 L) per minute will cause 70 in. (1.780 mm) of head due to a 12-in. (305 mm) orifice and a 16-in. (406 mm) approach pipe.

8.5 Extensive calibrations of circular orifice weirs indicated that they will measure the flow through the orifice within 3 % of the true value when properly constructed and used.[2 ,3]

9. Report

9.1 Record pertinent information, including orifice and pipe sizes and manometer reading, time of reading, and well discharge rate.

9.2 Describe the physical features of the apparatus and any unusual aspect of the measurements.

10. Precision and Bias

10.1 *Precision*—Due to the nature of this test method it is either not feasible or too costly at this time to develop a valid precision statement. Subcommittee D18.21 welcomes proposals that would allow for development of a valid precision statement.

10.2 *Bias*—There is no accepted reference value for this test method, therefore, bias cannot be determined.

11. Keywords

11.1 aquifers; aquifer test methods; discharge rate; ground water; orifice weir

Designation: D 5785 – 95 (Reapproved 2000)

Standard Test Method for (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Underdamped Well Response to Instantaneous Change in Head (Slug Test)[1]

This standard is issued under the fixed designation D 5785; 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 determination of transmissivity from the measurement of the damped oscillation about the equilibrium water level of a well-aquifer system to a sudden change of water level in a well. Underdamped response of water level in a well to a sudden change in water level is characterized by oscillatory fluctuation about the static water level with a decrease in the magnitude of fluctuation and recovery to initial water level. Underdamped response may occur in wells tapping highly transmissive confined aquifers and in deep wells having long water columns.

1.2 This analytical procedure is used in conjunction with the field procedure Test Method D 4044 for collection of test data.

1.3 *Limitations*—Slug tests are considered to provide an estimate of transmissivity of a confined aquifer. This test method requires that the storage coefficient be known. Assumptions of this test method prescribe a fully penetrating well (a well open through the full thickness of the aquifer), but the slug test method is commonly conducted using a partially penetrating well. Such a practice may be acceptable for application under conditions in which the aquifer is stratified and horizontal hydraulic conductivity is much greater than vertical hydraulic conductivity. In such a case the test would be considered to be representative of the average hydraulic conductivity of the portion of the aquifer adjacent to the open interval of the well. The method assumes laminar flow and is applicable for a slug test in which the initial water-level displacement is less than 0.1 or 0.2 of the length of the static water column.

1.4 This test method of analysis presented here is derived by van der Kamp **(1)**[2] based on an approximation of the underdamped response to that of an exponentially damped sinusoid. A more rigorous analysis of the response of wells to a sudden change in water level by Kipp **(2)** indicates that the method presented by van der Kamp **(1)** matches the solution of Kipp **(2)** when the damping parameter values are less than about 0.2 and time greater than that of the first peak of the oscillation **(2)**.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 4043 Guide for Selection of Aquifer-Test Method in Determining of Hydraulic Properties by Well-Techniques[3]

D 4044 Test Method for (Field Procedure for) Instantaneous Change in Head (Slug Test) for Determining Hydraulic Properties of Aquifers[3]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the aquifer is stressed, for example, by pumping, injection, or change in head.

3.1.4 *head, static*—the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

3.1.5 *observation well*—a well open to all or part of an aquifer.

3.1.6 *overdamped well response*—characterized by the water level returning to the static level in an approximately exponential manner following a sudden change in water level. (See for comparison *underdamped well response*.)

3.1.7 *slug*—a volume of water or solid object used to induce a sudden change of head in a well.

3.1.8 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the

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

Current edition approved Sept. 10, 1995. Published November 1995.

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

[3] *Annual Book of ASTM Standards*, Vol 04.08.

aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of specific storage and aquifer thickness. For an unconfined aquifer, the storage coefficient is approximately equal to the specific yield.

3.1.9 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.10 *underdamped well response*—response characterized by the water level oscillating about the static water level following a sudden change in water level (See for comparison *overdamped well response*.)

3.1.11 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 T—transmissivity [$L^{2}T^{-1}$].

3.2.2 S—storage coefficient [*nd*].

3.2.3 L—effective length of water column, equal to L_c + (r_c^2/r_s^2) (m/2).

3.2.3.1 *Discussion*—This expression for the effective length is given by Kipp **(2)**. The expression for the effective length of the water column from Cooper et al **(3)** is given as $L_c + 3/8L_s$ and assumes that the well screen and well casing have the same diameter.

3.2.4 L_{c}—length of water column within casing [L].

3.2.5 L_{s}—length of water column within well screen [L].

3.2.6 g—acceleration of gravity [LT^{-2}].

3.2.7 h—hydraulic head in the aquifer [L].

3.2.8 h_{o}—initial hydraulic head in the aquifer [L].

3.2.9 h_{s}—hydraulic head in the well screen [L].

3.2.10 r_{c}—radius of well casing [L].

3.2.11 r_{s}—radius of well screen [L].

3.2.12 t—time [T].

3.2.13 w—water level displacement from the initial static level [L].

3.2.14 w_{o}—initial water level displacement [L].

3.2.15 γ—damping constant [T^{-1}].

3.2.16 τ—wavelength [T].

3.2.17 ω—angular frequency [T^{-1}].

3.2.18 m—aquifer thickness, [L].

4. Summary of Test Method

4.1 This test method describes the analytical procedure for analyzing data collected during an instantaneous head (slug) test using a well in which the response is underdamped. The field procedures in conducting a slug test are given in Test Method D 4044. The analytical procedure consists of analyzing the response of water level in the well following the change in water level induced in the well.

4.2 *Theory*—The equations that govern the response of well to an instantaneous change in head are treated at length by Kipp **(2)**. The flow in the aquifer is governed by the following equation for cylindrical flow:

$$\frac{S}{T}\frac{dh}{dt} = \frac{1}{r}\frac{d}{dr}\left(r\frac{dh}{dr}\right) \tag{1}$$

where:

h = hydraulic head,
T = aquifer transmissivity, and
S = storage coefficient.

4.2.1 The initial condition is at $t = 0$ and $h = h_o$and the outer boundary condition is as $r \rightarrow \infty$ and $h \rightarrow h_o$.

4.3 The flow rate balance on the well bore relates the displacement of the water level in the well-riser to the flow into the well:

$$\pi r_c^2 \frac{dw}{dt} = 2\pi r_s T \left.\frac{\partial h}{\partial r}\right|_{r=r_s} \tag{2}$$

where:

r_c = radius of the well casing, and
w = displacement of the water level in the well from its initial position.

4.3.1 The third equation describing the system, relating $h_s$and w, comes from a momentum balance of Bird et al **(4)** as referenced in Kipp **(2)**.

$$\frac{d}{dt}\int_{-m}^{0} \pi r_s^2\, pv_d z = [-pv_2^2 + p_1 - p_2 - pgm]\pi r_s^2 \tag{3}$$

where:

v = velocity in the well screen interval,
m = aquifer thickness,
p = pressure,
ρ = fluid density,
g = gravitational acceleration, and
r_s = well screen radius. Well and aquifer geometry are shown in Fig. 1.

Atmospheric pressure is taken as zero.

5. Solution

5.1 The method of van der Kamp **(1)** assumes the water level response to a sudden change for the underdamped case, except near critical damping conditions, can be approximately described as an exponentially damped cyclic fluctuation that decays exponentially. The water-level fluctuation would then be given by:

$$w(t) = w_o e^{-\gamma t} \cos\ wt \tag{4}$$

5.1.1 The following solution is given by van der Kamp **(1)**.

$$d = \frac{-r_c^2\,(g/L)^{1/2}\ 1n[0.79 r_s^2 (S/T)(g/L)^{1/2}}{8T} \tag{5}$$

that may be written as:

$$T = b + a\ 1nT \tag{6}$$

where:

$$b = a\ 1n[0.79\ r_s^2 S(g/L)^{1/2} \tag{7}$$

$$a = \frac{r_c^2\ (g/L)^{1/2}}{8d} \tag{8}$$

$$d = \gamma/(g/L)^{1/2} \tag{9}$$

and

$$L = g/(\omega^2 + \gamma^2) \tag{10}$$

NOTE 1—Other analytical solutions are proposed by Kipp **(2)**, Krauss **(5)**, Uffink **(6)** and Kabala, Pinder, and Milly **(7)**.

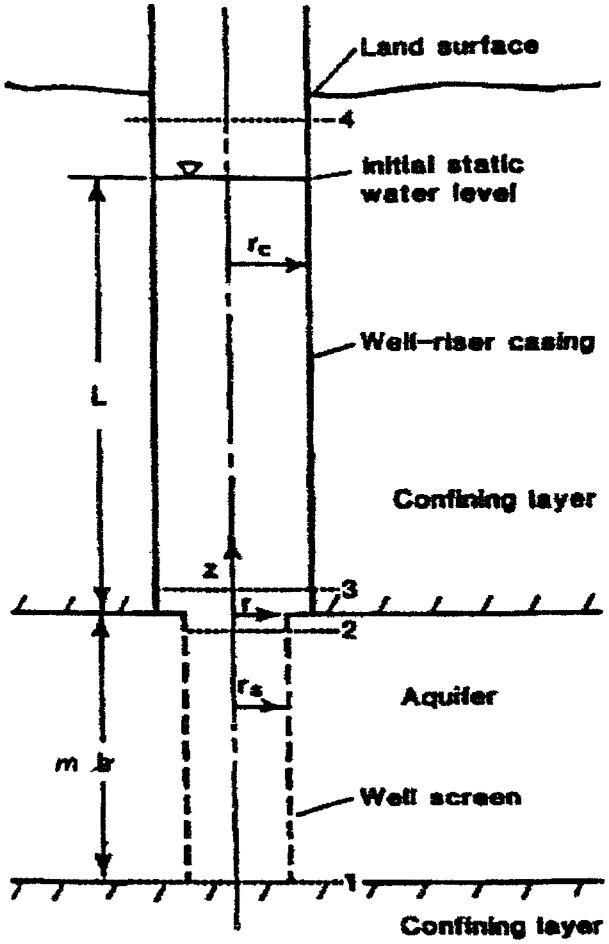

FIG. 1 Well and Aquifer Geometry

6. Significance and Use

6.1 The assumptions of the physical system are given as follows:

6.1.1 The aquifer is of uniform thickness and confined by impermeable beds above and below.

6.1.2 The aquifer is of constant homogeneous porosity and matrix compressibility and of homogeneous and isotropic hydraulic conductivity.

6.1.3 The origin of the cylindrical coordinate system is taken to be on the well-bore axis at the top of the aquifer.

6.1.4 The aquifer is fully screened.

6.2 The assumptions made in defining the momentum balance are as follows:

6.2.1 The average water velocity in the well is approximately constant over the well-bore section.

6.2.2 Flow is laminar and frictional head losses from flow across the well screen are negligible.

6.2.3 Flow through the well screen is uniformly distributed over the entire aquifer thickness.

6.2.4 Change in momentum from the water velocity changing from radial flow through the screen to vertical flow in the well are negligible.

6.2.5 The system response is an exponentially decaying sinusoidal function.

7. Procedure

7.1 The overall procedure consists of:

7.1.1 Conducting the slug test field procedure (see Test Method D 4044), and

7.1.2 Analyzing the field data, that is addressed in this test method.

NOTE 2—The initial displacement of water level should not exceed 0.1 or 0.2 of the length of the static water column in the well, because of considerations for calculating L_c. Practically, the displacement should be small, a few times larger than the well radius, to minimize frictional losses. The measurement of displacement should be within 1 % of the initial water-level displacement. The water-level displacement needs to be calculated independently for comparison to the observed initial displacement.

8. Calculation and Interpretation of Test Data

8.1 Plot the water-level response in the well to the sudden change in head, as in Fig. 2.

8.2 Calculate the angular frequency, ω:

$$\omega = 2\pi/\tau \tag{11}$$

where:

$\tau = t_1 - t_2$, and t_1 and t_2 are times of successive maxima or minima of the oscillatory wave.

8.3 Calculate the damping factor, γ:

$$\gamma = 1n[w(t_1)/w(t_2)]/t_2 - t_1 \tag{12}$$

where:

$w(t_1)$ and $w(t_2)$ are the water-level displacements at times t_1 and t_2, respectively.

8.4 Determine transmissivity, T,

$$T = b + a\ 1nT \tag{13}$$

where:

$$a = [r_c^2\ (g/L)^{1/2}]/8d \tag{14}$$

$$d = \gamma/(g/L)^{1/2} \tag{15}$$

$$L = g/(\omega^2 + \gamma^2) \tag{16}$$

and:

$$b = -a\ 1n[0] \tag{17}$$

8.4.1 Solve for transmissivity iteratively using an initial estimate value for transmissivity, T, and a known or estimated value of storage coefficient, S.

8.5 Check the results.

8.5.1 Compare the effective length of the water column, L, calculated by the following two relationships:

$$L = g/(\omega^2 + \gamma^2) \tag{18}$$

and:

$$L = L_c + (r_c^2/r_s^2)m/2 \tag{19}$$

The values of L should agree within 20 %.

8.5.2 Check to see that the value of $\alpha << 0.1$, where:

$$\alpha = 0.89(S/T)^{1/2}\ (\omega^2 + \gamma^2)^{1/4}\ r_s < 0.1 \tag{20}$$

8.5.3 Check to see that the value of $d << 0.7$, where:

$$d = \gamma/(g/L)^{1/2} \tag{21}$$

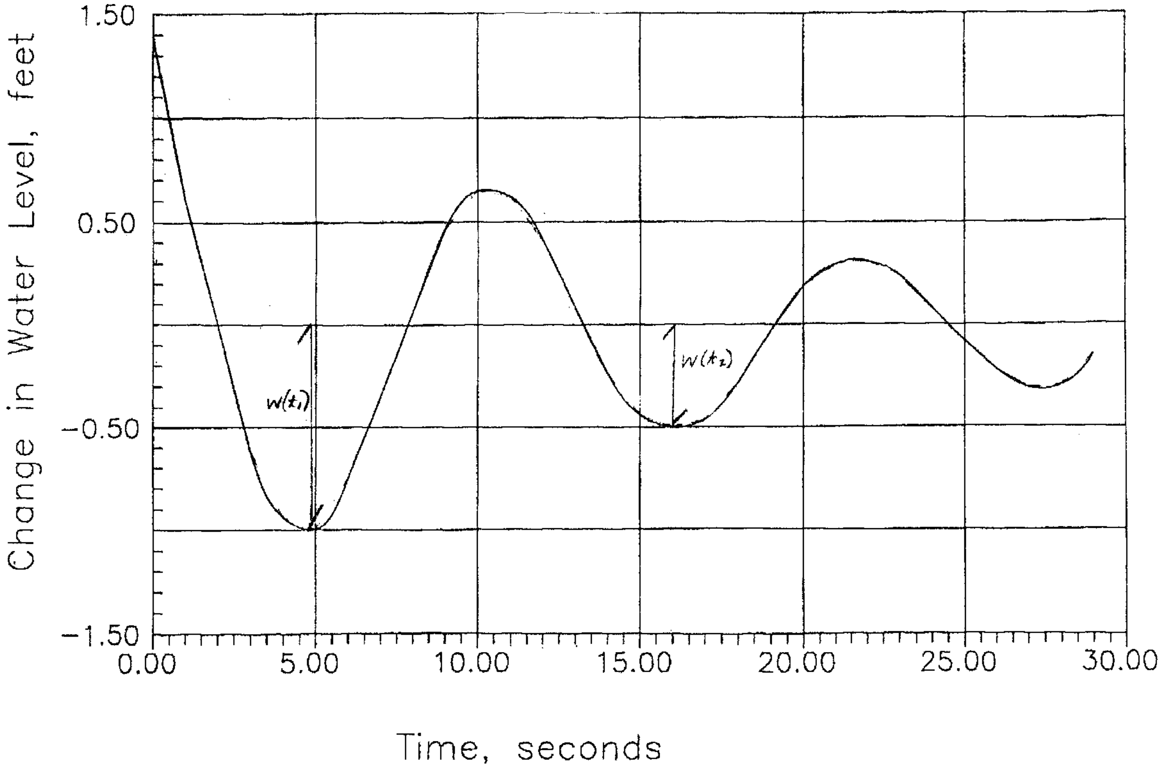

FIG. 2 Underdamped Response of Water Level to a Sudden Change in Head

8.5.4 *Example*—The following data are taken from the underdamped response to a slug test shown in Fig. 2:

$w(t_1)$ = -1.0 ft
$w(t_2)$ = -0.5 ft
t_1 = 4.9 s
t_2 = 16.9 s
r_c = 0.25 ft
r_s = 0.25 ft
L_c = 95 ft
L_s = 55 ft
$\tau = t_2 - t_1 = 16.9 - 4.9 = 12\ s$
$\omega = 2\pi/\tau = 2 * 3.1416/12.0 = 0.5236\ s^{-1}$
$\gamma = 1n\ (w(t_1)/w\ (t_2))/\tau = 1n\ (-1.0/-0.5)/12 = 0.6931/12 = 0.05776\ s^{-1}$
$T = b + a\ 1nT$
$(g/L)^{1/2} = (\omega^2 + \gamma^2)^{1/2} = ((0.5236)^2 + (0.05776)^2)^{1/2} = ((0.2742) + (0.0033362))^{1/2} = (0.2775)^{1/2} = 0.5268$
$d = \gamma(g/L)^{1/2} = 0.05776/0.5268 = 0.1096$
$a = (r_c^2\ (g/L)^{1/2})/8d = (0.25)^2(0.5268)/8(0.1096) = 0.03755\ ft^2/s$

Assume $S = 1.5 \times 10^{-5}$

$b = a\ 1n\ (0.79\ r_s^2 S\ (g/L)^{1/2})$
$= (-0.03755)1n\ (0.79(0.25)^2\ (0.000015)(0.5268) = 0.5541\ ft^2/s$
$T_1 = b + a\ 1nT_0$

Assume $T_0 \cong b$,

$T_1 = 0.5541 + (0.03755)1n\ (0.5541) = 0.5319\ ft^2/s$
$T_2 = 0.5541 + (0.03755)1n\ (0.5319) = 0.5304\ ft^2/s$
$T = 0.5304\ ft^2/s * 86\ 400\ s/day = 45\ 826\ ft^2/day$

Check the results:

$L = g/(\omega^2 + \gamma^2) = 32/(0.2775) = 115.3$ ft
$L = L_c + (r_c^2/r_s^2)m/2 = 95 + 27.5 = 122.5$
$122.5 - 115.3 = 7.2,\ 7.2/115.3 = 6.2 < 20\ \%$
$\alpha = 0.89(S/T)^{1/2}\ (\omega^2 + \gamma^2)^{1/4}\ r_s < 0.1$
$= 0.89\ (0.005318)(0.7258)\ 0.25 = 0.000859 < 0.1$
$d = 0.1096 < 0.7$

9. Report

9.1 Report the following information described as follows. The final report of the analytical procedure will include information from the report on test method selection, Guide D 4043, and the field testing procedure, Test Method D 4044.

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the slug test method for determining transmissivity and storativity. Summarize the field hydrogeologic conditions, the field equipment and instrumentation including the construction of the control well, the method of measurement of head, and the method of effecting the change in head. Discuss the rationale for selecting this test method.

9.1.2 *Hydrogeologic Setting*—Review information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the method selected for conducting and analyzing an aquifer test. Compare hydrogeologic characteristics of the site as it conforms and differs from assumptions made in the solution to the aquifer test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test. Include in the report, well construction information, diameter, depth, and open interval to the aquifer, and location of control well and pumping equipment. The construction, diameter, depth, and open interval of observation wells should be recorded.

9.1.3.1 Report the techniques used for observing water levels, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test; the manufacturers name, model number, and basic specifications for each major item; and the name and date of the last calibration, if applicable.

9.1.4 *Testing Procedures*—Report the steps taken in conducting the pretest and test phases. Include the frequency of head measurements made in the control well, and other environmental data recorded before and during the testing procedure.

9.1.5 *Presentation and Interpretation of Test Results*:

9.1.5.1 *Data*—Present tables of data collected during the test.

9.1.5.2 *Data Plots*—Present data plots used in analysis of the data.

9.1.5.3 Show calculation of transmissivity and coefficient of storage.

9.1.5.4 Evaluate the overall quality of the test on the basis of the adequacy of instrumentation and observations of stress and response and the conformance of the hydrogeologic conditions and the performance of the test to the assumptions (see 5.1).

10. Precision and Bias

10.1 It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; slug test; storage coefficient; transmissivity

REFERENCES

(**1**) van der Kamp, Garth, "Determining Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case," *Water Resources Research*, Vol 12, No. 1, 1976, pp. 71–77.

(**2**) Kipp, K. L., Jr., "Type Curve Analysis of Inertial Effects in the Response of a Well to a Slug Test," *Water Resources Research*, Vol 21, No. 9, 1985, pp. 1397–1408.

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(**6**) Kruseman and de Ridder, "Analysis and Evaluation of Pumping Test Data," *Publication 47, International Institute for Land and Reclamation and Improvement*, Wageningen, The Netherlands, 1991.

(**7**) Kabala, Z. J., Pinder, G. F., and Milly, P. C. D., "Analysis of Well-Aquifer Response to a Slug Test," *Water Resources Research*, Vol 21, No. 9, 1985, pp. 1433–1436.

Designation: D 5786 – 95 (Reapproved 2000)

Standard Practice for (Field Procedure) for Constant Drawdown Tests in Flowing Wells for Determining Hydraulic Properties of Aquifer Systems[1]

This standard is issued under the fixed designation D 5786; 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 practice covers the methods for controlling drawdown and measuring discharge rates and head to analyze the hydraulic properties of an aquifer or aquifers.

1.2 This practice is used in conjunction with analytical procedures such as those of Jacob and Lohman **(1)/(2)**, and Hantush **(3)/(4)**.

1.3 The appropriate field and analytical procedures for determining hydraulic properties of aquifer systems are selected as described in Guide D 4043.

1.4 *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.*

1.5 *This practice offers a set of instructions for performing one or more specific operations. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this practice may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining of Hydraulic Properties by Well Techniques[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this practice, see Terminology D 653.

4. Summary of Practice

4.1 This practice describes the field procedures for conducting an aquifer test on a well that is flowing, that is, the head in the well remains above the top of the well casing. This method involves inducing a constant drawdown and measuring the varying discharge rate from the control well.

5. Significance and Use

5.1 Constant drawdown test procedures are used with appropriate analytical procedures to determine transmissivity, hydraulic conductivity, and storage coefficient of aquifers.

6. Apparatus

6.1 Various types of equipment can be used to measure the flow rate of the well. The equipment shall be sized so that it does not constrict the flow rate from the well.

6.2 An apparatus shall be placed on the control well discharge line such that the well can be shut in to prevent flow prior to conducting this field procedure and so that the apparatus will not constrict flow from the well when it is allowed to flow.

6.3 Head measurements can be made using one of the following apparatuses:

6.3.1 *Standpipe*—A pipe or piece of well casing may be installed to extend above the elevation of the discharge. This standpipe will also extend above the elevation of the head in the control well. This standpipe will allow for direct measurement of the water level following methods described in Test Method D 4750.

6.3.2 *Pressure Measurement*—A pressure gage (mechanical gage, manometer, or pressure transducer) may be installed below the shut-in mechanism in the control well. Determine the head elevation by adding the pressure reading (expressed in the height of the water) to the elevation of the sensor of the pressure gage.

6.4 *Control Well*—This practice requires that water flow from a single well. This well, known as the control well, shall

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

Current edition approved Sept 10, 1995. Published October 1995.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

be drilled and completed such that it transmits water from the aquifer (usually the entire thickness of the aquifer) as efficiently as possible to reduce head loss between the aquifer and the well. Well development should be as complete as possible to eliminate additional production of sediments (aquifer particles or drill cuttings) and consequent changes in well efficiency during the test.

7. Procedure

7.1 *Pretest Procedures*:

7.1.1 *Select Aquifer Test Method*—Develop a conceptual model of the site hydrogeology and select the appropriate aquifer test method according to Guide D 4043. Observe the requirements of the selected test method with regard to specifications for the control well and observation wells.

7.1.2 *Field Reconnaissance*—Make a field reconnaissance of the site before conducting the test to collect as much detail as possible on the depth, continuity, extent, and preliminary estimates of the hydrologic properties of the aquifers and confining beds. Note the location of existing wells and water-holding or conveying structures that might interfere with the test. Turn off nearby wells well before the test, and disable automatic pump controls throughout the anticipated test period. Alternately, it may be necessary to pump some nearby wells or allow them to flow throughout the test. If so, the discharge shall be at a constant rate, and shall not be started or stopped during the test and prior to the test for a duration at least equal to that of the test. The control well should be equipped with a pipeline or conveyance structure adequate to transmit water away from the test site, such that the structure does not impede the flow of water from the control well.

7.1.3 *Construction of Control Well*—Screen the control well throughout the full extent of the aquifer to be tested.

7.1.4 *Test of Control Well*—Test the control well by allowing the well to flow and then stopping the flow. Based on the recovery response, make a preliminary estimate of the hydraulic properties of the aquifer and estimate the initial flow rate from the control well expected during the aquifer test.

7.1.5 *Testing Observation Wells*—Test observation wells or piezometers prior to the aquifer test to ensure that they are hydraulically connected to the aquifer. Accomplish this by adding or withdrawing a known volume of water (slug) and measure the water-level response in the well. The resultant response should be rapid enough to ensure that the water level in the observation well or piezometer will reflect the water level in the aquifer during the test. Alternatively, if observation wells are flowing, measure their response in a manner similar to that described for the control well. Redevelop wells or piezometers with unusually sluggish response.

7.1.6 Measure the pressure head in the shut-in control well and observation wells (if any) to determine the trend of water levels before the commencement of the test. This period should be at least equal to the length of the flowing portion of the test.

7.2 *Test Procedure*:

7.2.1 Based on pretesting results and the conceptual model of the site (see Guide D 4043), select the duration of the test.

7.2.2 *Shut in the Control Well*—Completely stop flow from the control well prior to conducting the test for a period at least as long as the anticipated duration of the flowing portion of the test.

7.2.3 *Discharge from Control Well*—Allow the control well to flow at a variable rate. The flow rate will vary naturally to maintain a constant drawdown at the control well.

7.2.4 *Measure Discharge Rate*—Measure and record the discharge rate frequently during the early phase of discharge; increase the interval between measurements in a logarithmic manner as pumping continues.

NOTE 1—Table 1 presents a suggested frequency of discharge measurements.

7.2.5 *Measure Water Level*—Measure and record the water levels in nearby wells at a frequency similar as presented in Table 1.

7.3 *Post-Testing Procedures*:

7.3.1 Tabulate water levels, including pre-flowing (shut-in), flowing, and post-flowing levels. For each well or piezometer record the date, clock time, time since flowing started or stopped, and the measurement point.

7.3.2 Tabulate the rate of discharge of the control well, the date, clock time, time since flowing started or stopped, and the method of measurement.

7.3.3 Prepare a written description of each well, describing the measuring point, giving its elevation and the method of obtaining the elevation, and the distance of the measuring point above the mean land surface.

7.3.4 *Plot the Rate of Discharge Versus Time*—Prepare a plot of the rate of discharge versus the time since discharge began.

8. Report

8.1 Prepare a report containing field data including a description of the field site, plots of water level and discharge with time, and preliminary analysis of data:

8.1.1 An introduction stating the purpose of the test, dates and times water-level measurements commenced, dates and times the control well was shut in, dates and times the control well began to flow, and the stabilized head in the control well prior to the test.

8.1.2 The "as built" description and diagrams of all control wells, observation wells, and piezometers.

8.1.3 A map of the site showing all well locations, the distances between wells, and locations of all geologic boundaries or surface-water bodies which might affect the test.

8.1.3.1 The locations of wells and boundaries that affect the aquifer tests need to be known with sufficient accuracy to provide a valid analysis. For most analyses, this means the locations must provide data points within the plotting accuracy

TABLE 1 Example of Measurement Frequency

Frequency	Elapsed Time
1 measurement every:	
30 s	3 min
1 min	3 to 15 min
5 min	15 to 60 min
10 min	60 to 120 min
20 min	2 to 3 h
1 h	3 to 15 h
5 h	15 to 60 h

on the semilog or log-log graph paper used in the analysis. Radial distances from the control well to the observation wells usually need to be known with ±0.5 %. For prolonged large-scale testing, it may be sufficient to locate wells from maps or aerial photographs. However, for small-scale tests, well locations should be surveyed using land surveying methods. When test wells are deep relative to their spacing it may be necessary to conduct well-deviation surveys to determine the true horizontal distance between well screens in the aquifer.

8.1.4 Include tabulated field data collected during the test.

9. Keywords

9.1 aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient; transmissivity

REFERENCES

(**1**) Jacob, C. E., and Lohman, S. W., "Nonsteady Flow to a Well of Constant Drawdown in an Extensive Aquifer," *American Geophysical Union Transactions*, Vol 33, No. 4, 1952, pp. 552–569.

(**2**) Lohman, S. W., "Ground-Water Hydraulics," *Professional Paper 708*, U.S. Geological Survey, 1972.

(**3**) Hantush, M. S., "Nonsteady Flow to Flowing Wells in Leaky Aquifer," *Journal of Geophysical Research*, Vol 64, No. 8, 1959, pp. 1043–1052.

(**4**) This document is presently under development in D18.21.04 and may be obtained by contacting the Committee D-18 Staff Manager.

Designation: D 5850 – 95 (Reapproved 2000)

Standard Test Method for (Analytical Procedure) Determining Transmissivity, Storage Coefficient, and Anisotropy Ratio from a Network of Partially Penetrating Wells[1]

This standard is issued under the fixed designation D 5850; 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, and ratio of vertical to horizontal hydraulic conductivity of a confined aquifer using observation well drawdown measurements from a constant-rate pumping test. This test method uses data from a minimum of four partially penetrating, properly positioned observation wells around a partially penetrating control well.

1.2 The analytical procedure is used in conjunction with the field procedure in Test Method D 4050.

1.3 *Limitations*—The limitations of the technique for determination of the horizontal and vertical hydraulic conductivity of aquifers are primarily related to the correspondence between the field situation and the simplifying assumption of this test method.

1.4 The values stated in inch-pound units are to be regarded as the standard. The SI units given in parentheses are for information only.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method for (Field Procedure for) Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method for (Analytical Procedure for) Determining Transmissivity and Storativity of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method for (Analytical Procedure for) Determining Transmissivity and Storativity of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

D 5473 Test Method (Analytical Procedure) for Analyzing the Effects of Partial Penetration of Control Well and Determining the Horizontal and Vertical Hydraulic Conductivity in a Nonleaky Confined Aquifer[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—well by which the head and flow in the aquifer is changed, for example, by pumping, injection, or imposing a constant change of head.

3.1.4 *drawdown*—vertical distance the static head is lowered due to the removal of water.

3.1.5 *hydraulic conductivity*—(field aquifer test) the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.6 *observation well*—a well open to all or part of an aquifer.

3.1.7 *piezometer*—a device so constructed and sealed as to measure hydraulic head at a point in the subsurface.

3.1.8 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.1.9 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.10 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 A—K_z/K_r, anisotropy ratio [*nd*].

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

3.2.2 b—thickness of aquifer [L].

3.2.3 C_f—drawdown correction factor, equal to the ratio of the drawdown for a fully penetrating well network to the drawdown for a partially penetrating well network ($W(u)/(W(u) + f_s)$).

3.2.4 d—distance from top of aquifer to top of screened interval of control well [L].

3.2.5 d'—distance from top of aquifer to top of screened interval of observation well [L].

3.2.6 f_s—incremental dimensionless drawdown component resulting from partial penetration [*nd*].

3.2.7 K—hydraulic conductivity [LT^{-1}].

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

3.2.8 K_o—modified Bessel function of the second kind and zero order.

3.2.9 K_r—hydraulic conductivity in the plane of the aquifer, radially from the control well (horizontal hydraulic conductivity) [LT^{-1}].

3.2.10 K_z—hydraulic conductivity normal to the plane of the aquifer (vertical hydraulic conductivity) [LT^{-1}].

3.2.11 l—distance from top of aquifer to bottom of screened interval of control well [L].

3.2.12 l'—distance from top of aquifer to bottom of screened interval of observation well [L].

3.2.13 Q—discharge [L^3T^{-1}].

3.2.14 r—radial distance from control well [L].

3.2.15 S—storage coefficient [*nd*].

3.2.16 s—drawdown observed in partially penetrating well network [L].

3.2.17 s_f—drawdown observed in fully penetrating well network [L].

3.2.18 T—transmissivity [L^2T^{-1}].

3.2.19 t—time since pumping began [T].

3.2.20 u—$(r^2S)/(4Tt)$ [*nd*].

3.2.21 $W(u)$—an exponential integral known in hydrology as the Theis well function of u[*nd*].

4. Summary of Test Method

4.1 This test method makes use of the deviations in drawdown near a partially penetrating control well from those that would occur near a control well fully penetrating the aquifer. In general, drawdown within the screened horizon of a partially penetrating control well tends to be greater than that which would have been observed near a fully penetrating well, whereas the drawdown above or below the screened horizon of the partially penetrating control well tends to be less than the corresponding fully penetrating case. Drawdown deviations due to partial penetration are amplified when the vertical hydraulic conductivity is less than the horizontal hydraulic conductivity. The effects of partial penetration diminish with increasing distance from the pumped well, becoming negligible at a distance of about $1.5b/(K_z/K_r)^{1/2}$. This test method relies on obtaining drawdown measurements at a minimum of two locations within this distance of the pumped well and at each location obtaining data from observation wells completed to two different depths. At each location, one observation well should be screened at about the same elevation as the screen in the pumped well, while the other observation well should be screened in sediments not screened by the pumped well.

4.2 According to Theis **(1)**,[4] the drawdown around a fully penetrating control well pumped at a constant rate and tapping a homogeneous, confined aquifer is as follows:

$$s_f = \frac{Q}{4\pi T} W(u) \tag{1}$$

where:

$$W(u) = \int_u^\infty \frac{e^{-x}}{x} dx \tag{2}$$

4.2.1 Drawdown near a partially penetrating control well pumped at a constant rate and tapping a homogeneous, anisotropic, confined aquifer is presented by Hantush **(2, 3, 4)**:

$$s = \frac{Q}{4\pi T}(W(u) + f_s) \tag{3}$$

According to Hantush **(2, 3, 4)**, at late pumping times, when $t > b^2S/(2TA)$, f_s can be expressed as follows:

$$f_s = \frac{4b^2}{\pi^2(l - d)(l' - d')}\sum_{n=1}^{\infty}\left(\frac{1}{n^2}\right) K_o\left(\frac{n\pi r\sqrt{K_z/K_r}}{b}\right) \tag{4}$$
$$\left[\sin\left(\frac{n\pi i}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right]\left[\sin\left(\frac{n\pi l'}{b}\right) - \sin\left(\frac{n\pi d'}{b}\right)\right]$$

4.2.2 For a given observed drawdown, it is possible to compute a correction factor, C_f, defined as the ratio of the drawdown for a fully penetrating well to the drawdown for a partially penetrating well:

$$C_f = \frac{W(u)}{W(u) + f_s} \tag{5}$$

The observed drawdown for each observation well may be corrected to the fully penetrating equivalent drawdown by multiplying by the correction factor:

$$s_f = C_f s \tag{6}$$

The drawdown values corresponding to the fully penetrating case may then be analyzed by conventional distance-drawdown methods to compute transmissivity and storage coefficient.

4.2.3 The correction factors are a function of both transmissivity and storage coefficient, that are the parameters being sought. Because of this, the test method relies on an iterative procedure in which an initial estimate of T and S are made from which initial correction factors are computed. Using these correction factors, fully penetrating drawdown values are computed and analyzed using distance-drawdown methods to determine revised values for T and S. The revised T and S values are used to compute revised correction factors, C_f. This process is repeated until the calculated T and S values change only slightly from those obtained in the previous iteration.

4.2.4 The correction factors are also a function of the anisotropy ratio, A. For this reason, all of the calculations described above must be performed for several different assumed anisotropy ratios. The assumed anisotropy value that

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

leads to the best solution, that is, best straight line fit or best curve match, is deemed to be the actual anisotropy ratio.

5. Significance and Use

5.1 This test method is one of several available for determining vertical anisotropy ratio. Among other available methods are Weeks (**(5)**; see Test Method D 5473), that relies on distance-drawdown data, and Way and McKee **(6)**, that utilizes time-drawdown data. An important restriction of the Weeks distance-drawdown method is that the observation wells must have identical construction (screened intervals) and two or more of the observation wells must be located at a distance from the pumped well beyond the effects of partial penetration. The procedure described in this test method general distance-drawdown method, in that it works in theory for any observation well configuration incorporating three or more wells, provided some of the wells are within the zone where flow is affected by partial penetration.

5.2 *Assumptions*:

5.2.1 Control well discharges at a constant rate, Q.

5.2.2 Control well is of infinitesimal diameter and partially penetrates the aquifer.

5.2.3 Data are obtained from a number of partially penetrating observation wells, some screened at elevations similar to that in the pumped well and some screened at different elevations.

5.2.4 The aquifer is confined, homogeneous and areally extensive. The aquifer may be anisotropic, and, if so, the directions of maximum and minimum hydraulic conductivity are horizontal and vertical, respectively.

5.2.5 Discharge from the well is derived exclusively from storage in the aquifer.

5.3 *Calculation Requirements*—Application of this method is computationally intensive. The function, f_s, shown in (Eq 4) must be evaluated numerous times using arbitrary input parameters. It is not practical to use existing, somewhat limited, tables of values for f_s and, because this equation is rather formidable, it is not readily tractable by hand. Because of this, it is assumed the practitioner using this test method will have available a computerized procedure for evaluating the function f_s. This can be accomplished using commercially available mathematical software including some spreadsheet applications, or by writing programs in languages such as Fortran or C.

6. Apparatus

6.1 Apparatus for withdrawal tests is given in Test Method D 4050. The apparatus described below are those components of the apparatus that require special attributes for this specific test.

6.2 *Construction of the Control Well*—Screen the control well through only part of the vertical extent of the aquifer to be tested. The exact distances from the top of the aquifer to the top and bottom of the pumped well screen interval must be known.

6.3 *Construction and Placement of Observation Wells*—The procedure will work for arbitrary positioning of observation wells and placement of their screens, as long as three or more observation wells are used and some of the observation wells fall inside the zone where flow is affected by partial penetration, that is, the area where significant vertical flow components exists. However, strategic selection of the number and location of observation wells will maximize the quality of the data set and improve the reliability of the interpretation.

6.3.1 Optimum results will be obtained by using a minimum of four observation wells incorporating two pairs of observation wells located at two different distances from the pumped well, both within the zone where flow is affected by partial penetration. Each well pair should consist of a shallow well and a deep well, that span vertically the area in which vertical anisotropy is sought. For each well pair, one observation well screen should be at the same elevation as the screen in the pumped well, whereas the other observation well screen should be at a different elevation than the screen in the pumped well.

6.3.2 This test method relies on choosing several arbitrary anisotropy ratios, correcting the observed drawdowns for partial penetration, and evaluating the results. If all observation wells are screened at the same elevation, the quality of the data trace produced by correcting the observed drawdown measurements is not sensitive to the choice of anisotropy, making it difficult to determine this parameter accurately. If, however, observation well screens are located both within the pumped zone (where drawdown is greater than the fully penetrating case) and the unpumped zone (where drawdown is less than the fully penetrating case), the quality of the corrected data is sensitive to the choice of anisotropy ratio, making it easier to quantify this parameter.

7. Procedure

7.1 Pre-test preparations, pumping test guidelines, and post-test procedures associated with the pumping test itself are described in Test Method D 4050.

7.2 Verify the quality of the data set. Review the record of measured flow rates to make sure the rate was held constant during the test. Check to see that hand measurements of drawdown agree well with electronically measured values. Finally, check the background water-level fluctuations observed prior to or following the pumping test to see if adjustments must be made to the observed drawdown values to account for background fluctuations. If appropriate, adjust the observed drawdown values accordingly.

7.3 Analysis of the field data is described in Section 8.

8. Calculation and Interpretation of Results

8.1 *Initial Estimates of Transmissivity and Storage Coefficient*—This test method requires that initial estimates of T and S be obtained. These estimates can be made using a wide variety of procedures, including time-drawdown analysis, recovery analysis, distance-drawdown analysis, estimation of T using specific capacity, grain-size analyses of formation samples, or results of laboratory permeability tests, and estimation of storage coefficient based on geology, sediment type, and aquifer thickness.

8.2 *Select Data for Analysis*—This test method requires a single drawdown observation for each observation well used in the test. The drawdowns used should all correspond to the same time since pumping began, usually near or at the end of the test. Select a time, t, late enough in the test so that it satisfies the relationship $t > b^2S/(2TA)$.

8.3 *Distance-Drawdown Analysis Methods*—The selected drawdown values will be corrected for partial penetration and the corrected drawdown will be analyzed using distance-drawdown methods. Use either a semilog procedure or a log-log procedure. The semilog procedure requires that u be small. For distant observation wells, this condition may be violated and the semilog method may be invalid. If u is not sufficiently small, the logarithmic approximation of the Theis well function, $W(u)$, is not accurate. Examples of errors for some u values are as follows:

u	Error, %
0.01	0.25
0.03	1.01
0.05	2.00
0.10	5.35

The log-log method is more general, being valid for all values of u.

8.3.1 *Semilog Method*:

8.3.1.1 If this method is used, plot the corrected drawdown, s_f, on the linear scale versus distance, r, on the log scale. Construct a straight line of best fit through the data points and record the slope of the line, Δs, and the zero drawdown intercept, R,

where:
Δs = change in drawdown over one log cycle, and
R = distance where line of best fit crosses 0 drawdown.

8.3.1.2 Using these input parameters, calculate transmissivity and storage coefficient as follows:

$$T = \frac{2.3026Q}{2\pi\Delta s} \tag{7}$$

$$S = \frac{2.25\,Tt}{R^2} \tag{8}$$

8.3.2 *Log-Log Method*—If the log-log method is selected, plot corrected drawdown, s_f, on the vertical logarithmic axis versus the reciprocal of the distance squared, $1/r^2$, on the horizontal logarithmic axis. On a separate graph having the same scale as the data plot, prepare a standard Theis type curve by plotting $W(u)$ on the vertical axis versus $1/u$ on the horizontal axis (see Fig. 1). Overlay the data plot on the type curve and, while keeping the coordinate axes of the two plots parallel, shift the data plot to align with the type curve effecting a match position. Select and record the values of an arbitrary point, referred to as the match point, anywhere on the overlapping part of the plots. Record the match-point coordinates—$W(u)$, $1/u$, s_f, $1/r^2$. For convenience, the match point may be selected where $W(u)$ and $1/u$ are integer values. Using these match-point values, compute transmissivity and storage coefficient as follows:

$$T = \frac{Q}{4\pi s}W(u) \tag{9}$$

$$S = \frac{4Ttu}{r^2} \tag{10}$$

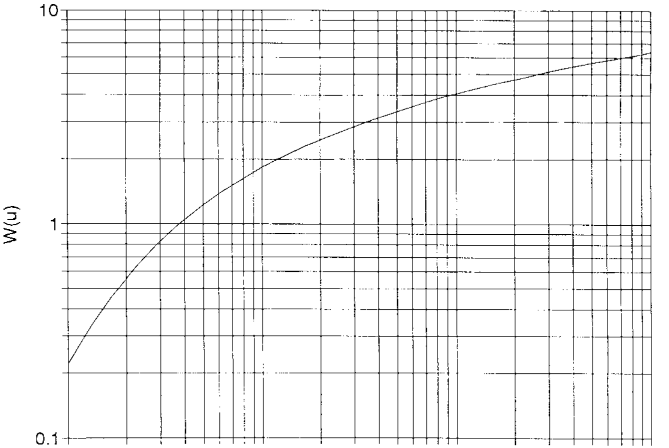


FIG. 1 Theis Type Curve

8.4 *Iterative Calculations*—Use the following steps to estimate vertical anisotropy ratio and refine the values for transmissivity and storage coefficient.

8.4.1 Select several arbitrary anisotropy ratios, spanning a range likely to include the actual anisotropy of the aquifer. Usually four or five values will suffice.

8.4.2 For each assumed anisotropy value, use the estimated T and S values to calculate correction factors, C_f, and corrected drawdowns, s_f, for each observation well. Use Eq 2, Eq 4, Eq 5, and Eq 6

8.4.3 Using the corrected drawdowns, prepare a distance-drawdown graph for each value of assumed anisotropy. Compare the graphs to determine which one provides the best data trace. For semilog graphs, this is the plot that best describes a straight line. For log-log graphs, it is the plot that best fits the Theis type curve. Record the corresponding anisotropy value as the best estimate for A.

8.4.4 Using the selected distance-drawdown graph, calculate T and S as described in 8.3. The values obtained are considered revised estimates of transmissivity and storage coefficient.

8.4.5 Select several new, arbitrary anisotropy values spanning a range that is narrower than the previous one and that includes the previous estimate for A. Go back to 8.4.2 to repeat the iteration process. Each iteration will generate new values for correction factors and corrected drawdowns, new distance-drawdown graphs and revised estimates for A, T, and S.

8.5 *Example Calculation*:

8.5.1 A test well screened in the bottom 10 ft (3.05 m) of a 50-ft (15.24 m) thick aquifer was pumped at a rate of 2 gpm (385 cubic feet per day [cfd]) for one day. The corresponding data parameters are as follows:

Q = 385 cfd (10.9 cmd)
b = 50 ft (15.24 m)
d = 40 ft (12.19 m)
l = 50 ft (15.24 m)
t = one day

8.5.2 Table 1 shows well geometry and drawdown data for four observation wells that were monitored during the pumping test. Observation Wells 1 and 2 comprise a shallow/deep pair near the pumped well, whereas Observation Wells 3 and 4 comprise and shallow/deep pair at a greater distance from the pumped well.

TABLE 1 Well Geometry and Drawdown Information

Observation Well	*r*, Distance from Pumped Well, in ft (m)	*d′*, Distance from Top of Aquifer to Top of Screen, in ft (m)	*l′*, Distance from Top of Aquifer to Bottom of Screen, in ft (m)	*s*, Drawdown after 1 Day, in ft (m)
1	10 (3.05)	0 (0)	10 (3.05)	3.11 (0.95)
2	11 (3.35)	30 (9.14)	40 (12.19)	7.49 (2.28)
3	50 (15.24)	40 (12.19)	50 (15.24)	4.56 (1.39)
4	60 (18.29)	0 (0)	10 (3.05)	2.65 (0.81)

8.5.3 Using other methods (omitted here), an initial transmissivity estimate of 400 gpd/ft (53.48 ft^2/day) was made. The storage coefficient was estimated at 0.0005. The vertical anisotropy ratio was estimated to range between 1 (isotropic) and 0.01 (severely anisotropic).

8.5.4 Use Eq 2, Eq 4, Eq 5, and Eq 6 to compute correction factors, C_f, and corrected drawdowns, s_f, for each observation well for several anisotropy ratio values. The results of these computer-generated calculations are shown in Table 2. Make a distance-drawdown graph for each anisotropy value as shown in Fig. 2.

8.5.5 Select the distance-drawdown graph that provides the best match with the Theis type curve and note the anisotropy ratio value. From Fig. 2, the best match is achieved with the graph corresponding to an anisotropy ratio value of 0.2.

8.5.6 Using this graph and Eq 9 and Eq 10, calculate revised estimates for *T* and *S* based upon matching the Theis type curve, as shown in Fig. 3.

$$T = \frac{385 \cdot 2}{4\pi 1.73} \tag{11}$$

$$= 35.42 \text{ ft}^2 \ (3.29 \text{ m}^2)\text{/day}$$

$$S = \frac{4 \cdot 35.42 \cdot 1 \cdot 0.000388}{100} \tag{12}$$

$$= 0.00055$$

8.5.7 Using the revised *T* and *S* values, repeat 8.5.4 through 8.5.6. The range of anisotropy ratios for which computations are made is narrowed based upon information gained from the previous step. This results in correction factors and corrected drawdowns as shown in Table 3 and the distance-drawdown graphs shown in Fig. 4. The distance-drawdown graph providing the best fit to the Theis type curve corresponds to an anisotropy ratio of 0.17 and is shown with the type curve in Fig. 5. Using the match-point values shown, *T* and *S* are calculated as follows:

$$T = \frac{385 \cdot 2}{4\pi 1.87} \tag{13}$$

$$= 32.77 \text{ ft}^2 \ (3.04 \text{ m}^2)\text{/day}$$

$$S = \frac{4 \cdot 32.77 \cdot 1 \cdot 0.000496}{100} \tag{14}$$

$$= 0.00065$$

TABLE 2 Correction Factors and Corrected Drawdown Calculated Assuming a *T* of 53.48 ft^2(4.97 m^2)/day and an *S* of 0.0005

Observation Well	C_f, Correction Factor	s_f, Corrected Drawdown, in ft (m)	*A*, Anisotropy Ratio
1	1.327	4.13 (1.26)	...
2	0.884	6.62 (2.02)	...
3	0.977	4.46 (1.36)	1
4	1.012	2.68 (0.82)	...
1	1.805	5.62 (1.71)	...
2	0.856	6.41 (1.95)	...
3	0.827	3.77 (1.15)	0.2
4	1.148	3.04 (0.93)	...
1	2.676	8.32 (2.54)	...
2	0.891	6.67 (2.03)	...
3	0.606	2.76 (0.84)	0.05
4	1.568	4.16 (1.27)	...
1	6.158	19.15 (5.84)	...
2	1.006	7.53 (2.30)	...
3	0.397	1.81 (0.55)	0.01
4	3.487	9.24 (2.82)	...

8.5.8 Using the revised *T* and *S* values, repeat 8.5.4-8.5.6 above. The range of anisotropy ratios for which computations are made is narrowed based upon information gained from the previous step. This results in correction factors and corrected drawdowns as shown in Table 4 and the distance-drawdown graphs shown in Fig. 6. The distance-drawdown graph providing the best fit to the Theis type curve corresponds to an anisotropy ratio of 0.18 and is shown with the type curve in Fig. 7. Using the match-point values shown, *T* and *S* are calculated as follows:

$$T = \frac{385 \cdot 2}{4\pi 1.91} \tag{15}$$

$$= 32.08 \text{ ft}^2 \ (2.98 \text{ m}^2)\text{/day}$$

$$S = \frac{4 \cdot 32.08 \cdot 1 \cdot 0.000545}{100} \tag{16}$$

$$= 0.0007$$

8.5.9 The iteration is complete because the change in transmissivity between the last two steps was negligible (about 2 %). Thus, the calculated aquifer coefficients are as follows: $T = 32.08$ ft^2 (2.98 m^2)/day, $S = 0.0007$, and $A = 0.18$.

9. Report

9.1 Report including the following information:

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the method for determining the transmissivity, storage coefficient, and ratio of horizontal to vertical hydraulic conductivity in a nonleaky confined aquifer. Briefly summarize the field hydrogeologic conditions and the field equipment and instrumentation, including the construction of the control well and observation wells, the method of measurement of discharge and water levels, and the duration of the test and pumping rate.

9.1.2 *Conceptual Model*—Review the information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the selection of this method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

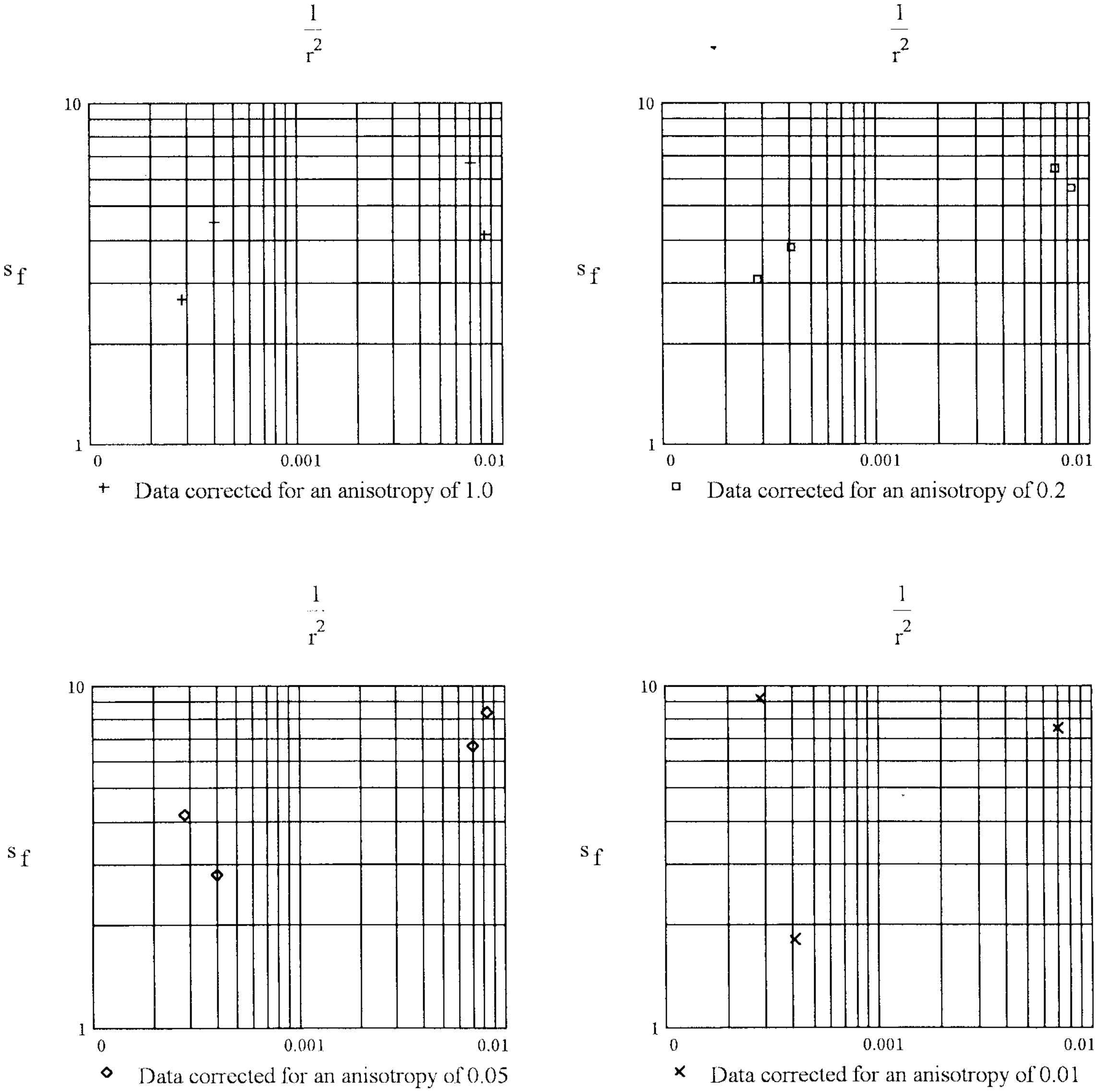


FIG. 2 Graphs of Corrected Drawdown in ft Versus Reciprocal of Distance Squared in ft^2(m^2) for Anisotropy Ratios of 1, 0.2, 0.05, and 0.01, a *T* of 53.48 ft^2(4.97 m^2)/day, and an *S* of 0.0005

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened and filter-packed intervals, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells.

9.1.4 *Instrumentation*—Describe the field instrumentation for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test, the manufacturer's name, model number, and basic specifications for each major item, and the name and date and method of the last calibration, if applicable.

9.1.5 *Testing Procedures*—List the steps taken in conducting pre-test, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.6 *Presentation and Interpretation of Test Results*:

9.1.6.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for background water-level and barometric changes and calculation of drawdown and residual drawdown.

9.1.6.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.1.7 Evaluate qualitatively the overall accuracy of the test, the corrections and adjustments made to the original water-level measurements, the adequacy and accuracy of instrumentation, accuracy of observations of stress and response, and the conformance of the hydrogeologic conditions and the performance of the test to the model assumptions.

10. Precision and Bias

10.1 It is not practicable to specify the precision of the procedure in this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses. No statement can be made about bias because no true

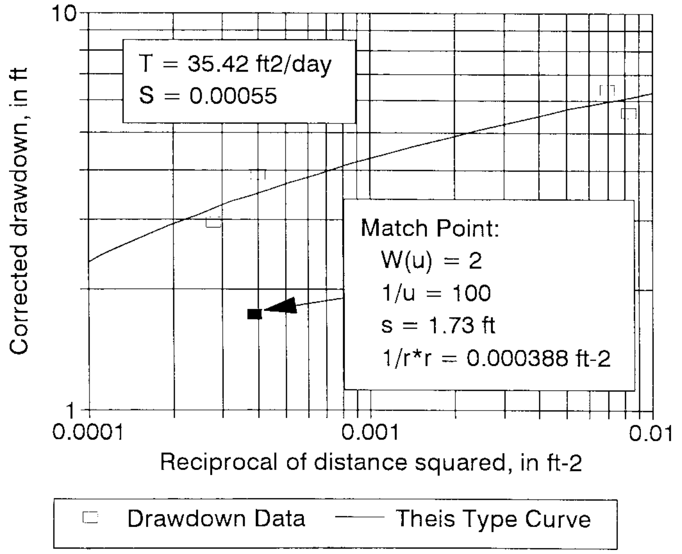


FIG. 3 Analysis of Drawdown Data Corrected for Partial Penetration Assuming an Anisotropy of 0.20, Estimated *T* of 53.48 ft^2(4.97 m^2)/day, and *S* of 0.0005 Yields a Revised *T* of 35.42 ft^2(3.29 m^2)/day and *S* of 0.00055

TABLE 3 Correction Factors and Corrected Drawdown Calculated Assuming a *T* of 35.42 ft^2(3.29 m^2)/day and an *S* of 0.00055

Observation Well	C_f, Correction Factor	s_f, Corrected Drawdown, in ft (m)	*A*, Anisotropy Ratio
1	1.745	5.43 (1.66)	...
2	0.847	6.34 (1.93)	...
3	0.864	3.94 (1.20)	0.29
4	1.108	2.94 (0.90)	...
1	1.848	5.75 (1.75)	...
2	0.846	6.34 (1.93)	...
3	0.831	3.79 (1.16)	0.23
4	1.145	3.03 (0.92)	...
1	2.002	6.23 (1.90)	...
2	0.848	6.35 (1.94)	...
3	0.784	3.57 (1.09)	0.17
4	1.206	3.20 (0.98)	...
1	2.277	7.08 (2.16)	...
2	0.855	6.41 (1.95)	...
3	0.711	3.24 (0.99)	0.11
4	1.327	3.52 (1.07)	...

reference values exist.

11. Keywords

11.1 anisotropy; aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation well; storage coefficient; transmissivity

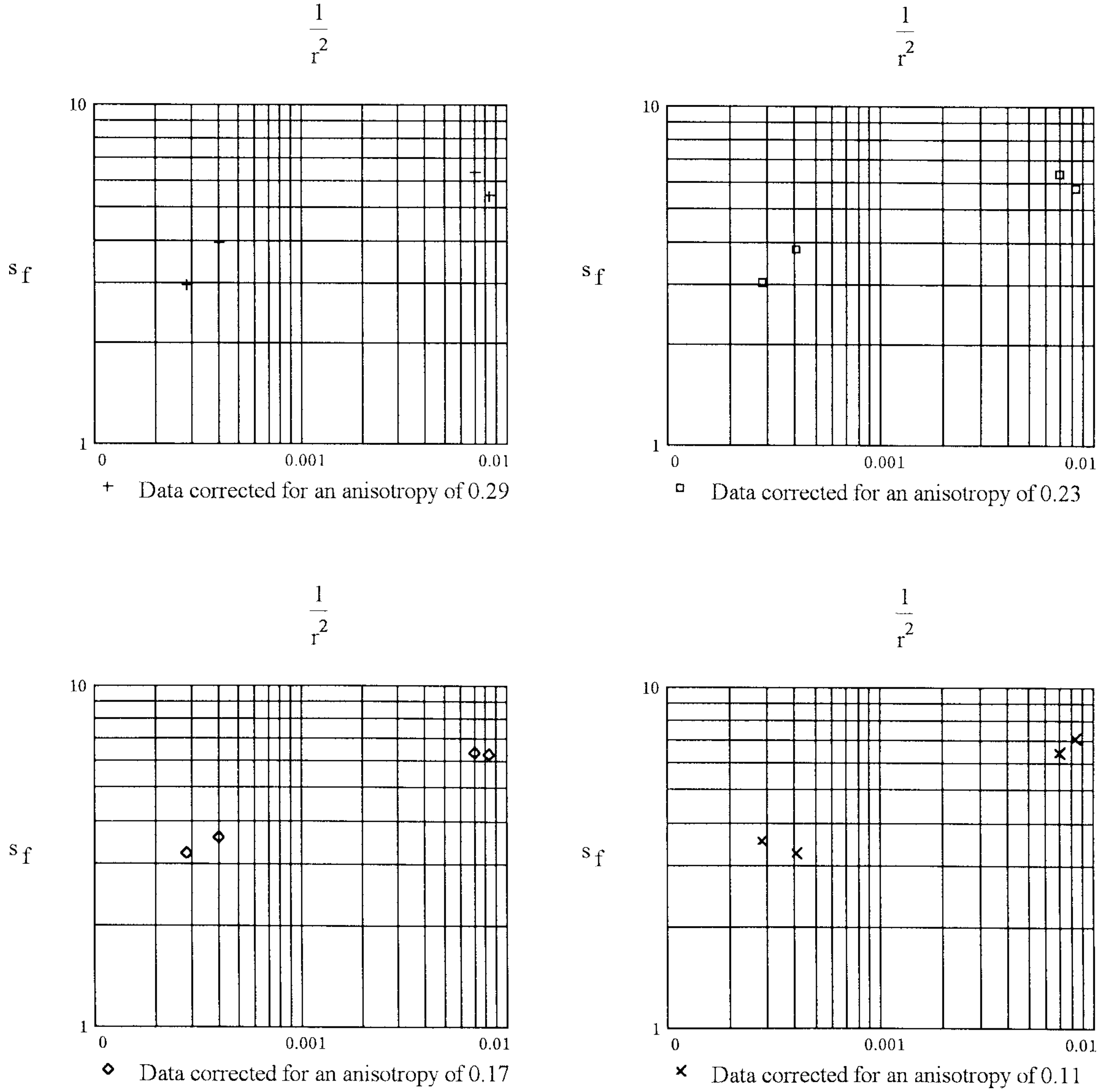


FIG. 4 Graphs of Corrected Drawdown in Feet Versus Reciprocal of Distance Squared in ft^2(m^2) for Anisotropy Ratios of 0.29, 0.23, 0.17, and 0.11, a *T* of 35.42 ft^2(3.29 m^2)/day, and an *S* of 0.00055

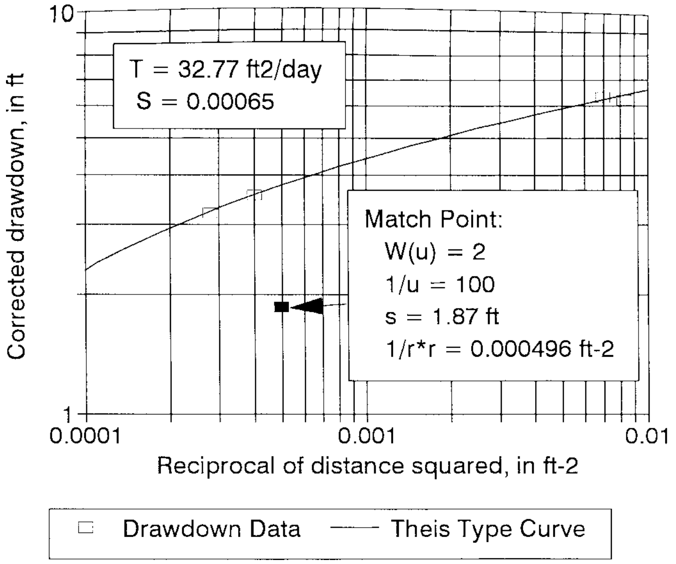
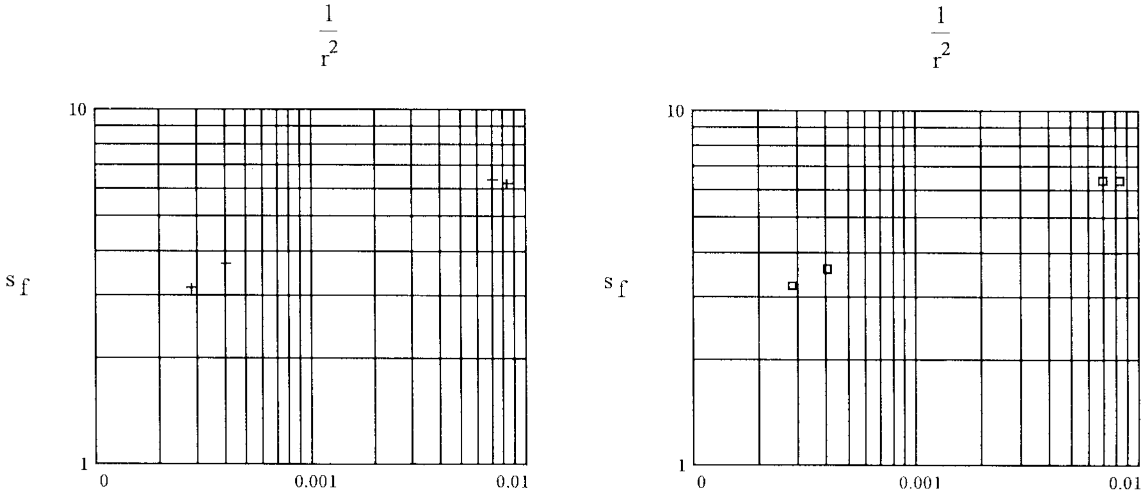


FIG. 5 Analysis of Drawdown Data Corrected for Partial Penetration Assuming an Anisotropy of 0.17, Estimated *T* of 35.42 ft^2(3.29 m^2)/day, and *S* of 0.00055 Yields a Revised *T* of 32.77 ft^2(3.04 m^2)/day and *S* of 0.00065

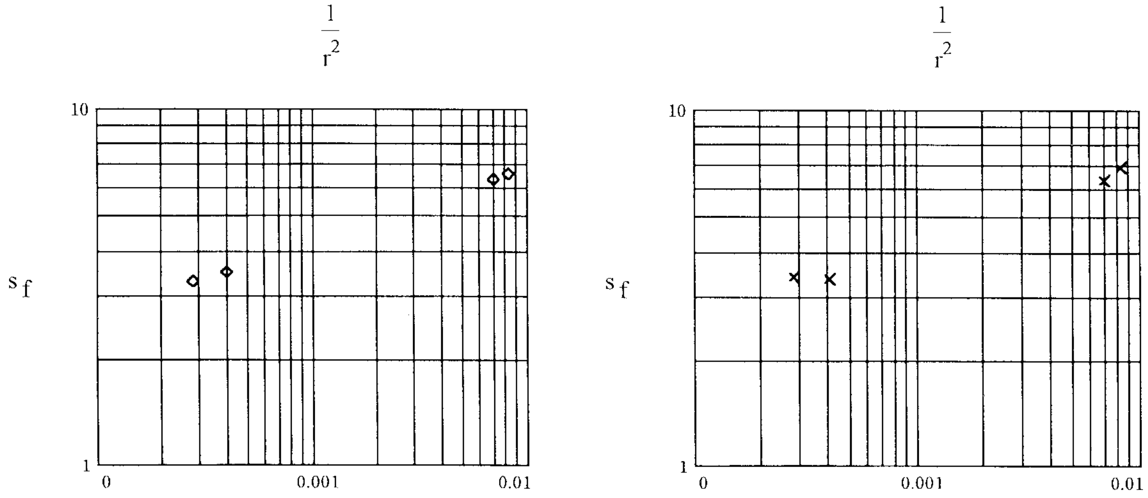
TABLE 4 Correction Factors and Corrected Drawdown Calculated Assuming a *T* of 32.77 ft^2(3.04 m^2)/day and an *S* of 0.00065

Observation Well	C_f, Correction Factor	s_f, Corrected Drawdown, in ft (m)	*A*, Anisotropy Ratio
1	1.981	6.16 (1.88)	...
2	0.842	6.31 (1.92)	...
3	0.800	3.65 (1.11)	0.2
4	1.185	3.14 (0.96)	...
1	2.042	6.35 (1.94)	...
2	0.843	6.31 (1.92)	...
3	0.783	3.57 (1.09)	0.18
4	1.209	3.20 (0.98)	...
1	2.114	6.58 (2.01)	...
2	0.844	6.32 (1.93)	...
3	0.763	3.48 (1.06)	0.16
4	1.239	3.28 (1.00)	...
1	2.204	6.85 (2.09)	...
2	0.846	6.34 (1.93)	...
3	0.740	3.37 (1.03)	0.14
4	1.277	3.38 (1.03)	...



+ Data corrected for an anisotropy of 0.2

□ Data corrected for an anisotropy of 0.18



◇ Data corrected for an anisotropy of 0.16

× Data corrected for an anisotropy of 0.14

FIG. 6 Graphs of Corrected Drawdown in Feet Versus Reciprocal of Distance Squared in $ft^2(m^2)$ for Anisotropy Ratios of 0.2, 0.18, 0.16, and 0.14, a *T* of 32.77 $ft^2(3.04\ m^2)$/day, and an *S* of 0.00065

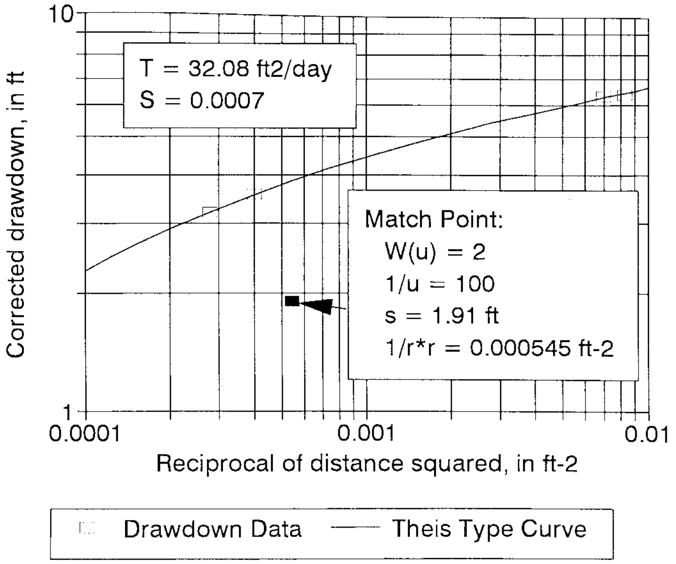


FIG. 7 Analysis of Drawdown Data Corrected for Partial Penetration Assuming an Anisotropy of 0.18, Estimated *T* of 32.77 ft^2(3.04 m^2)/day, and *S* of 0.00065 Yields a Revised *T* of 32.08 ft^2(2.98 m^2)/day and *S* of 0.0007

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Designation: D 5881 – 95 (Reapproved 2000)

Standard Test Method for (Analytical Procedure) Determining Transmissivity of Confined Nonleaky Aquifers by Critically Damped Well Response to Instantaneous Change in Head (Slug)[1]

1. Scope

1.1 This test method covers determination of transmissivity from the measurement of water-level response to a sudden change of water level in a well-aquifer system characterized as being critically damped or in the transition range from underdamped to overdamped. Underdamped response is characterized by oscillatory changes in water level; overdamped response is characterized by return of the water level to the initial static level in an approximately exponential manner. Overdamped response is covered in Guide D 4043; underdamped response is covered in D 5785.

1.2 The analytical procedure in this test method is used in conjunction with Guide D 4043 and the field procedure in Test Method D 4044 for collection of test data.

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

1.4 *Limitations*—Slug tests are considered to provide an estimate of the transmissivity of an aquifer near the well screen. The method is applicable for systems in which the damping parameter, ζ, is within the range from 0.2 through 5.0. The assumptions of the method prescribe a fully penetrating well (a well open through the full thickness of the aquifer) in a confined, nonleaky aquifer.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining of Hydraulic Properties by Well Techniques[2]

D 4044 Test Method (Field Procedure) for Instantaneous Change in Head (Slug Test) for Determining Hydraulic Properties of Aquifers[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

D 5785 Test Method (Analytical Procedure) for Determining Transmissivity of Confined Nonleaky Aquifers by Underdamped Well Response to Instantaneous Change in Head (Slug Test)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

3.1.3 *control well*—a well by which the head and flow in the aquifer is changed by pumping, injecting, or imposing a constant change of head.

3.1.4 *critically damped well response*—characterized by the water level responding in a transitional range between underdamped and overdamped following a sudden change in water level.

3.1.5 *head, static*—the height above a standard datum the surface of a column of water can be supported by the static pressure at a given point.

3.1.6 *observation well*—a well open to all or part of an aquifer.

3.1.7 *overdamped well response*—characterized by the water level returning to the static level in an approximately exponential manner following a sudden change in water level. (See for comparison *underdamped well response*.)

3.1.8 *slug*—a volume of water or solid object used to induce a sudden change of head in a well.

3.1.9 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness.

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

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[2] *Annual Book of ASTM Standards*, Vol 04.08.

[3] *Annual Book of ASTM Standards*, Vol 04.09.

3.1.10 *transmissivity*—the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 *underdamped well response*—response characterized by the water level oscillating about the static water level following a sudden change in water level (See for comparison *overdamped-well response*).

3.1.12 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 T—transmissivity [L^2T^{-1}].

3.2.2 S—storage coefficient [*nd*].

3.2.3 L—static water column length above top of aquifer [L].

3.2.4 L_e—effective length of water column in a well, equal to $L_c + (r_c^2/r_s^2)$ $(b/2)$ [L].

3.2.5 L_c—length of water column within casing [L].

3.2.6 L_s—length of water column within well screen [L].

3.2.7 g—acceleration of gravity [LT^{-2}].

3.2.8 h—hydraulic head in the aquifer [L].

3.2.9 h_o—initial hydraulic head in the aquifer [L].

3.2.10 h_s—hydraulic head in the well screen [L].

3.2.11 r_c—radius of well casing [L].

3.2.12 r_s—radius of well screen [L].

3.2.13 t—time [T].

3.2.14 t'—dimensionless time [*nd*].

3.2.15 t—dimensionless time [*nd*].

3.2.16 w—water level displacement from the initial static level [L].

3.2.17 w_o—initial water level displacement [L].

3.2.18 α—dimensionless storage parameter [*nd*].

3.2.19 β—dimensionless inertial parameter [*nd*].

3.2.20 γ—damping constant [T^{-1}].

3.2.21 τ—wavelength [T].

3.2.22 ω—angular frequency [T^{-1}].

3.2.23 ζ—dimensionless damping factor [*nd*].

4. Summary of Test Method

4.1 This test method describes the analytical procedure for analyzing data collected during an instantaneous head (slug) test for well and aquifer response at and near critical damping. Procedures in conducting a slug test are given in Test Method D 4044. The analytical procedure consists of analyzing the response of water level in the well following the change in water level induced in the well.

4.2 *Theory*—The equations that govern the response of well to an instantaneous change in head are treated at length by Kipp **(1)**.[4] The flow in the aquifer is governed by the following equation for cylindrical flow:

$$\frac{S}{T}\frac{dh}{dt} = \frac{1}{r}\frac{d}{dr}\left(r\frac{dh}{dr}\right) \tag{1}$$

where:

h = hydraulic head,

T = aquifer transmissivity, and

S = storage coefficient.

4.2.1 The initial condition is at $t = 0$ and $h = h_o$, and the outer boundary condition is as $r -$ and $h - h_o$.

4.2.1.1 An equation is given by Kipp **(1)** for the skin factor, that is, the effect of aquifer damage during drilling of the well. However, this factor is not treated by Kipp **(1)** and is not considered in this procedure.

4.2.2 The flow rate balance on the well bore relates the displacement of the water level in the well riser to the flow into the well:

$$\pi r_c^2 \frac{dw}{dt} = 2\pi r_s T \frac{dh}{dr}\Big|_{r = rs} \tag{2}$$

where:

r_c = radius of the well casing, and

w = displacement of the water level in the well from its initial position.

4.2.3 The fourth equation describing the system relating h_s and w, comes from a momentum balance equation of Bird et al **(2)** as referenced in Kipp **(1)**:

$$\frac{d}{dt}\int_{-b}^{0} \pi r_s^2\, pvdz = (-pv_2^2 + p_1 - p_2 - \rho gb)\, \pi r_s^2 \tag{3}$$

where:

v = velocity in the well screen interval,

b = aquifer thickness,

p = pressure,

ρ = fluid density,

g = gravitational acceleration, and

r_s = well screen radius.

The numerical subscripts refer to the planes described above and shown in Fig. 1. Atmospheric pressure is taken as zero.

5. Solution

5.1 Kipp **(1)** derives the following differential equation to represent for the response of the displacement of water level in the well:

$$\frac{d^2w}{dt^2} + \left(\frac{g}{L_e}\right) w = \frac{g}{(h_s - h_o)} / L_e \tag{4}$$

where:

L_e = effective water column length, defined as:

$$L_e = L + (r_c^2/r_s^2)(b/2) \tag{5}$$

where:

b = aquifer thickness with initial conditions:

$$at\ t = 0,\ w = w_o \tag{6}$$

$$dw/dt = w_o{*} \tag{7}$$

$$h_s = L = h_o \tag{8}$$

5.2 Kipp **(1)** introduces dimensionless variables and parameters in converting these equations to dimensionless form, solves the equations by Laplace transforms, and inverts the solution by a Laplace-transform-inversion algorithm.

5.2.1 The following dimensionless parameters are among those given by Kipp **(1)**:
dimensionless water-level displacement:

$$w' = -w/w_o \tag{9}$$

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

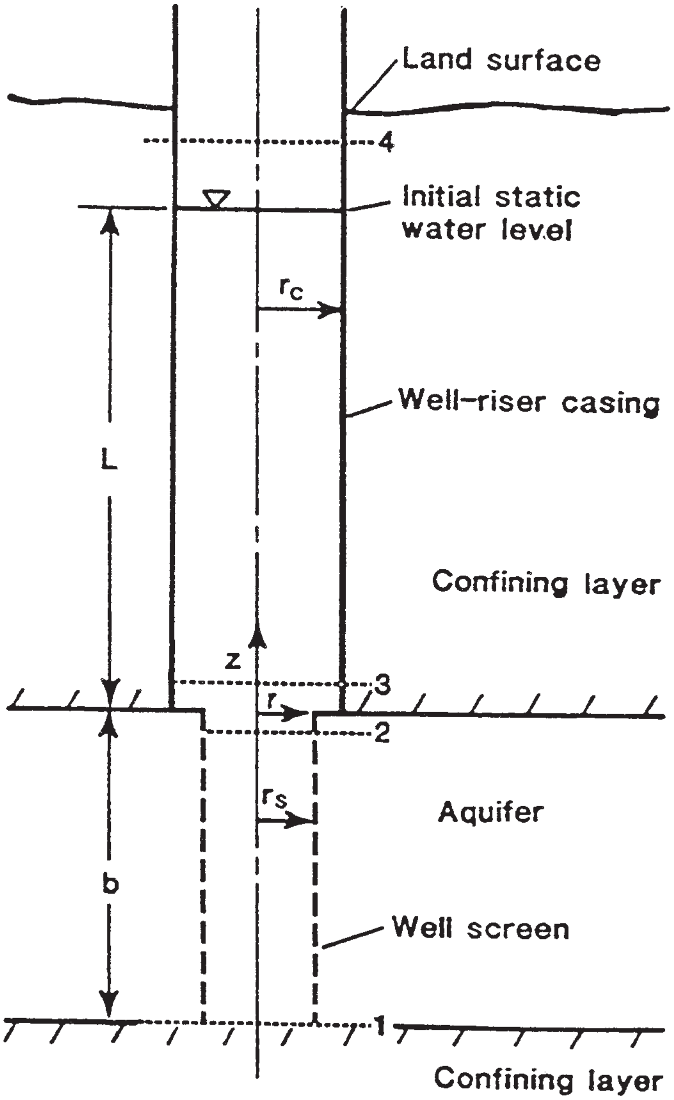

FIG. 1 Well and Aquifer Geometry from Kipp (1)

dimensionless time:

$$t' = (tT) / (r_s^2 S) \tag{10}$$

and:

$$\hat{t} = t'/\beta^{½} \tag{11}$$

dimensionless storage:

$$\alpha = (r_c^2)\ (2r_s^2 S) \tag{12}$$

dimensionless inertial parameter:

$$\beta = (Le / g)(T / (r_s^2 S))^2 \tag{13}$$

dimensionless skin factor:

$$\sigma = f/r_s \tag{14}$$

dimensionless frequency parameter:

$$\omega = \frac{[-d^2(\sigma + ¼\ 1n\beta) + 4\beta]^{½}}{2\beta} \tag{15}$$

dimensionless decay parameter:

$$\gamma = \frac{\alpha(\sigma + ¼\ 1n\beta)}{2\beta} \tag{16}$$

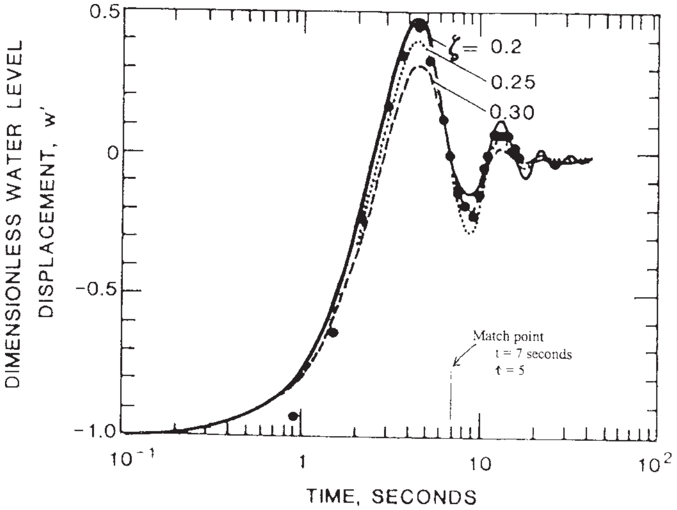

FIG. 2 Slug-Test Data Overlaid on Type Curves for Three Different Damping Factors, Modified from Kipp (1)

and dimensionless damping factor:

$$\zeta = \frac{\alpha(\sigma + ¼\ 1n\beta)}{2\beta^{½}} \tag{17}$$

5.3 For ζ less than one, the system is underdamped; for ζ greater than one, the system is overdamped. For ζ equal to one, the system is critically damped, yet the inertial effects are quite important **(1)**. For ζ greater than about five, the system responds as if the inertial effects can be neglected and the solution of Cooper et al **(3)** (given in Guide D 4043) is applicable. For ζ about 0.2 or less, the approximate solution of vander Kamp **(4)** is valid (given in Test Method D 5785). The solution of Kipp **(1)**, the subject of this test method, is applicable for the transition zone between systems that are underdamped and overdamped. Solutions are given here for ζ ranging from 0.2 to 5.0.

6. Significance and Use

6.1 The assumptions of the physical system are given as follows:

6.1.1 The aquifer is of uniform thickness, with impermeable upper and lower confining boundaries.

6.1.2 The aquifer is of constant homogeneous porosity and matrix compressibility and constant homogeneous and isotropic hydraulic conductivity.

6.1.3 The origin of the cylindrical coordinate system is taken to be on the well-bore axis at the top of the aquifer.

6.1.4 The aquifer is fully screened.

6.1.5 The well is 100 % efficient, that is, the skin factor, *f*, and dimensionless skin factor, σ, are zero.

6.2 The assumptions made in defining the momentum balance are as follows:

6.2.1 The average water velocity in the well is approximately constant over the well-bore section.

6.2.2 Frictional head losses from flow in the well are negligible.

6.2.3 Flow through the well screen is uniformly distributed over the entire aquifer thickness.

6.2.4 Change in momentum from the water velocity changing from radial flow through the screen to vertical flow in the well are negligible.

7. Procedure

7.1 The overall procedure consists of conducting the slug test field procedure (see Test Method D 4044) and analysis of the field data using this test method.

NOTE 1—The initial displacement of water level should not exceed 0.1 or 0.2 of the static water column in the well, the measurement of displacement should be within 1 % of the initial water-level displacement and the water-level displacement needs to be calculated independently.

8. Calculation and Interpretation of Results

8.1 Plot the normalized water-level displacement in the well versus the logarithm of time.

8.2 Prepare a set of type curves from Tables 1-10 by plotting dimensionless water level displacement, w', versus dimensionless time, $\hat{t}$, using the same scale as in plotting the observed water-level displacement.

8.3 Match the semilog plot of water-level displacement to the type curves by translation of the time axis.

TABLE 1 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 0.1 and α = 9988.1

t	*w′*	*t*	*w′*
3.162278E−02	−9.994887E−01	3.162278E + 00	7.100277E−01
3.636619E−02	−9.993281E−01	3.636619E + 00	6.204110E−01
3.952847E−02	−9.992086E−01	3.952847E + 00	4.871206E−01
4.269075E−02	−9.990793E−01	4.269075E + 00	3.138511E−01
4.743416E−02	−9.988666E−01	4.743416E + 00	2.218683E−02
5.375872E−02	−9.985483E−01	5.375872E + 00	−3.226809E−01
6.324555E−02	−9.979965E−01	6.324555E + 00	−5.191564E−01
7.115125E−02	−9.974688E−01	7.115125E + 00	−3.413663E−01
7.905694E−02	−9.968794E−01	7.905694E + 00	3.445623E−05
8.696264E−02	−9.962284E−01	8.696264E + 00	2.889492E−01
9.486833E−02	−9.955161E−01	9.486833E + 00	3.712172E−01
1.106797E−01	−9.939077E−01	1.106797E + 01	−1.758246E−02
1.264911E−01	−9.920552E−01	1.264911E + 01	−2.697976E−01
1.423025E−01	−9.899599E−01	1.423025E + 01	2.109260E−02
1.581139E−01	−9.876230E−01	1.581139E + 01	1.919487E−01
1.739253E−01	−9.850456E−01	1.739253E + 01	−2.455328E−02
1.897367E−01	−9.822293E−01	1.897367E + 00	−1.392019E−01
2.213594E−01	−9.758851E−01	2.213594E + 01	9.826209E−02
2.529822E−01	−9.686026E−01	2.529822E + 01	−7.129166E−02
2.846050E−01	−9.603946E−01	2.846050E + 01	4.976069E−02
3.162278E−01	−9.512748E−01	3.162278E + 01	−3.626029E−02
3.636619E−01	−9.359183E−01	3.636619E + 01	−9.997386E−03
3.952847E−01	−9.259452E−01	3.952847E + 01	7.200932E−03
4.269075E−01	−9.084819E−01	4.743416E + 01	5.892951E−03
4.743416E−01	−8.947298E−01	5.375872E + 01	2.737128E−03
5.375872E−01	−8.632514E−01	6.324555E + 01	−1.254582E−03
6.324555E−01	−8.135785E−01	7.115125E + 01	2.961127E−04
7.115125E−01	−7.673017E−01	7.905694E + 01	−5.757717E−05
7.905694E−01	−7.169702E−01	8.696264E + 01	−2.991356E−04
8.696264E−01	−6.629659E−01	9.486833E + 01	−1.835296E−04
9.486833E−01	−6.056883E−01	1.106797E + 02	−1.426791E−04
1.106797E + 00	−4.829810E−01	1.264911E + 02	−1.249977E−04
1.264911E + 00	−3.522848E−01	1.423025E + 02	−1.115579E−04
1.423025E + 00	−2.171309E−01	1.581139E + 02	−1.001696E−04
1.581139E + 00	−8.105198E−02	1.739253E + 02	−9.109389E−05
1.739253E + 00	5.974766E−02	1.897367E + 02	−8.347056E−05
1.897367E + 00	1.802728E−01	2.213594E + 02	−7.152232E−05
2.213594E + 00	4.066508E−01	2.529822E + 02	−6.256450E−05
2.529822E + 00	5.647406E−01	2.846050E + 02	−5.560200E−05
2.846050E + 00	6.811030E−01	...	...

TABLE 2 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 0.2 and α = 19976

t	*w′*	*t*	*w′*
3.162278E−02	−9.994902E−01	3.162278E + 00	4.939368E−•
3.636619E−02	−9.993263E−01	3.636619E + 00	4.349310E−•
3.952847E−02	−9.992107E−01	3.952847E + 00	3.465758E−•
4.269075E−02	−9.990815E−01	4.269075E + 00	2.343067E−•
4.743416E−02	−9.988695E−01	4.743416E + 00	5.160353E−•
5.375872E−02	−9.985520E−01	5.375872E + 00	−1.543438E−•
6.324555E−02	−9.980024E−01	6.324555E + 00	−2.671865E−•
7.115125E−02	−9.974810E−01	7.115125E + 00	−1.818502E−•
7.905694E−02	−9.968908E−01	7.905694E + 00	−2.600650E−•
8.696264E−02	−9.962437E−01	8.696264E + 00	9.764360E−•
9.486833E−02	−9.955360E−01	9.486833E + 00	1.324266E−•
1.106797E−01	−9.939399E−01	1.106797E + 01	3.871680E−•
1.264911E−01	−9.921040E−01	1.264911E + 01	−7.304361E−•
1.423025E−01	−9.900304E−01	1.423025E + 01	−3.623751E−•
1.581139E−01	−9.877207E−01	1.581139E + 01	3.430765E−•
1.739253E−01	−9.851770E−01	1.739253E + 01	−2.397516E−•
1.897367E−01	−9.824014E−01	1.897367E + 01	−2.051297E−•
2.213594E−01	−9.761622E−01	2.213594E + 01	8.187383E−•
2.529822E−01	−9.690205E−01	2.529822E + 01	−6.259136E−•
2.846050E−01	−9.609942E−01	2.846050E + 01	1.402892E−•
3.162278E−01	−9.521021E−01	3.162278E + 01	−2.331164E−•
3.636619E−01	−9.371834E−01	3.636619E + 01	−1.031248E−•
3.952847E−01	−9.262139E−01	3.952847E + 01	−7.347959E−•
4.269075E−01	−9.105352E−01	4.269075E + 01	−8.050596E−•
4.743416E−01	−8.975464E−01	4.743416E + 01	−6.352422E−•
5.375872E−01	−8.673412E−01	5.375872E + 01	−5.870822E−•
6.324555E−01	−8.201831E−01	6.324555E + 01	−5.087767E−•
7.115125E−01	−7.766091E−01	7.115125E + 01	−4.500425E−•
7.905694E−01	−7.295735E−01	7.905694E + 01	−4.046973E−•
8.696264E−01	−6.794859E−01	8.696264E + 01	−3.675505E−•
9.486833E−01	−6.267637E−01	9.486833E + 01	−3.366208E−•
1.106797E + 00	−5.151022E−01	1.106797E + 02	−2.881191E−•
1.264911E + 00	−3.979593E−01	1.264911E + 02	−2.518280E−•
1.423025E + 00	−2.786373E−01	1.423025E + 02	−2.236385E−•
1.581139E + 00	−1.602887E−01	1.581139E + 02	−2.011471E−•
1.739253E + 00	−3.860371E−02	1.739253E + 02	−1.827551E−•
1.897367E + 00	6.204784E−02	1.897367E + 02	−1.674534E−•
2.213594E + 00	2.492937E−01	2.213594E + 02	−1.434090E−•
2.529822E + 00	3.742380E−01	2.529822E + 02	−1.254123E−•
2.846050E + 00	4.694111E−01	2.846050E + 02	−1.113734E−•

8.4 From the type curve, record the value of ζ; from the match point, record the values of $\hat{t}$, and w' from the type curve. From the data plot, record the values of time, t, and water-level displacement, w.

8.5 Calculate the effective static water column length, L_e, from the following:

$$\hat{t} = \frac{t}{(L_e/g)^{1/2}} \tag{18}$$

$$L_e = (t/\hat{t})^2 g \tag{19}$$

The effective static water column length should agree, within 20 %, with the effective length calculated from the system geometry, (Eq 5).

8.6 Calculate the dimensionless inertial parameter, β, iteratively from the following expression:

$$\beta = [(\alpha \; 1n \; \beta)/8\zeta]^2 \tag{20}$$

where:

ζ = damping parameter,
α = dimensionless storage parameter as given in (Eq 12).

8.7 Calculate transmissivity from the following:

$$T = [(\beta g)/L_e]^{\frac{1}{2}} r_s^2 S \tag{21}$$

TABLE 3 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 0.5 and α = 49940

t	*w′*	*t*	*w′*
3.162278E−02	−9.994990E−01	3.162278E + 00	9.492086E−02
3.636619E−02	−9.993397E−01	3.636619E + 00	1.012577E−01
3.952847E−02	−9.992213E−01	3.952847E + 00	8.820339E−02
4.269075E−02	−9.990932E−01	4.269075E + 00	6.762111E−02
4.743416E−02	−9.988829E−01	4.743416E + 00	3.217532E−02
5.375872E−02	−9.985688E−01	5.375872E + 00	−8.337546E−03
6.324555E−02	−9.980257E−01	6.324555E + 00	−3.647544E−02
7.115125E−02	−9.975079E−01	7.115125E + 00	−3.476092E−02
7.905694E−02	−9.969310E−01	7.905694E + 00	−2.373581E−02
8.696264E−02	−9.962956E−01	8.696264E + 00	−1.338713E−02
9.486833E−02	−9.956020E−01	9.486833E + 00	−7.681039E−03
1.106797E−01	−9.940425E−01	1.106797E + 01	−6.737283E−03
1.264911E−01	−9.922559E−01	1.264911E + 01	−7.879678E−03
1.423025E−01	−9.902461E−01	1.423025E + 01	−6.928157E−03
1.581139E−01	−9.880166E−01	1.581139E + 01	−5.770595E−03
1.739253E−01	−9.855713E−01	1.739253E + 01	−5.154381E−03
1.897367E−01	−9.829139E−01	1.897367E + 01	−4.740291E−03
2.213594E−01	−9.769780E−01	2.213594E + 01	−3.991538E−03
2.529822E−01	−9.702398E−01	2.529822E + 01	−3.447316E−03
2.846050E−01	−9.627300E−01	2.846050E + 01	−3.033006E−03
3.162278E−01	−9.544800E−01	3.162278E + 01	−2.706963E−03
3.636619E−01	−9.407848E−01	3.636619E + 01	−2.330656E−03
3.952847E−01	−9.321798E−01	3.952847E + 01	−2.132780E−03
4.743416E−01	−9.053980E−01	4.269075E + 01	−1.966362E−03
5.375872E−01	−8.786102E−01	4.743416E + 01	−1.759041E−03
6.324555E−01	−8.380771E−01	5.375872E + 01	−1.542575E−03
7.115125E−01	−8.014756E−01	6.324555E + 01	−1.302071E−03
7.905694E−01	−7.627801E−01	7.115125E + 01	−1.152281E−03
8.696264E−01	−7.224138E−01	7.905694E + 01	−1.033361E−03
9.486833E−01	−6.807796E−01	8.696264E + 01	−9.366315E−04
1.106797E + 00	−5.952065E−01	9.486833E + 01	−8.565071E−04
1.264911E + 00	−5.088214E−01	1.106797E + 02	−7.312991E−04
1.423025E + 00	−4.239899E−01	1.264911E + 02	−6.380141E−04
1.581139E + 00	−3.426759E−01	1.423025E + 02	−5.658156E−04
1.739253E + 00	−2.592066E−01	1.581139E + 02	−5.082956E−04
1.897367E + 00	−1.964942E−01	1.739253E + 02	−4.613954E−04
2.213594E + 00	−7.843895E−02	1.897367E + 02	−4.198187E−04
2.529822E + 00	−4.874063E−03	2.213594E + 02	−3.613054E−04
2.846050E + 00	6.501678E−02	2.529822E + 02	−3.156807E−04
...	...	2.846050E + 02	−2.802644E−04

TABLE 4 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 0.7 and α = 69917

t	*w′*	*t*	*w′*
3.162278E−02	−9.995070E−01	3.162278E + 00	−6.213039E−02
3.636619E−02	−9.993420E−01	3.636619E + 00	−3.354664E−02
3.952847E−02	−9.992401E−01	3.952847E + 00	−2.515924E−02
4.269075E−02	−9.991031E−01	4.269075E + 00	−2.198880E−02
4.743416E−02	−9.988941E−01	4.743416E + 00	−2.246330E−02
5.375872E−02	−9.985822E−01	5.375872E + 00	−2.597889E−02
6.324555E−02	−9.980437E−01	6.324555E + 00	−2.841030E−02
7.115125E−02	−9.975307E−01	7.115125E + 00	−2.670372E−02
7.905694E−02	−9.969601E−01	7.905694E + 00	−2.343491E−02
8.696264E−02	−9.963325E−01	8.696264E + 00	−2.012564E−02
9.486833E−02	−9.956483E−01	9.486833E + 00	−1.743141E−02
1.106797E−01	−9.941127E−01	1.106797E + 01	−1.389694E−02
1.264911E−01	−9.923583E−01	1.264911E + 01	−1.171415E−02
1.423025E−01	−9.903899E−01	1.423025E + 01	−1.010995E−02
1.581139E−01	−9.882121E−01	1.581139E + 01	−8.865170E−03
1.739253E−01	−9.858299E−01	1.739253E + 01	−7.886036E−03
1.897367E−01	−9.832480E−01	1.897367E + 01	−7.099991E−03
2.213594E−01	−9.775043E−01	2.213594E + 01	−5.916365E−03
2.529822E−01	−9.710195E−01	2.529822E + 01	−5.068451E−03
2.846050E−01	−9.638311E−01	2.846050E + 01	−4.431953E−03
3.162278E−01	−9.559768E−01	3.162278E + 01	−3.936862E−03
3.636619E−01	−9.430270E−01	3.636619E + 01	−3.371269E−03
3.952847E−01	−9.350272E−01	3.952847E + 01	−3.076362E−03
5.375872E−01	−8.853626E−01	4.269075E + 01	−2.828780E−03
6.324555E−01	−8.485776E−01	4.743416E + 01	−2.523926E−03
7.115125E−01	−8.158209E−01	5.375872E + 01	−2.206660E−03
7.905694E−01	−7.816147E−01	6.324555E + 01	−1.856412E−03
8.696264E−01	−7.463554E−01	7.115125E + 01	−1.639455E−03
9.486833E−01	−7.104052E−01	7.905694E + 01	−1.467850E−03
1.106797E + 00	−6.377118E−01	8.696264E + 01	−1.328729E−03
1.264911E + 00	−5.657711E−01	9.486833E + 01	−1.213675E−03
1.423025E + 00	−4.963320E−01	1.106797E + 02	−1.034479E−03
1.581139E + 00	−4.307045E−01	1.264911E + 02	−9.013608E−04
1.739253E + 00	−3.625714E−01	1.423025E + 02	−7.985732E−04
1.897367E + 00	−3.142473E−01	1.581139E + 02	−7.168198E−04
2.213594E + 00	−2.201264E−01	1.739253E + 02	−6.502288E−04
2.529822E + 00	−1.617035E−01	1.897367E + 02	−5.949757E−04
2.846050E + 00	−9.684892E−02	2.213594E + 02	−5.085217E−04
...	...	2.529822E + 02	−4.439977E−04
...	...	2.846050E + 02	−3.939470E−04

8.7.1 Kipp **(1)** gives an example application of the method, using data from vander Kamp **(4)** for York Point well 6-2. This well has casing, screen, and well-bore radii of 0.051 m, a water column above the aquifer of 6.5 m, an aquifer thickness of 15 m, and an independently estimated storage coefficient of 8×10^{-5}.

8.7.2 A type curve of dimensionless water-level displacement, w', plotted against the log of dimensionless time, $\hat{t}$, for three values of the dimensionless damping factor, ζ, was prepared. Water-level displacement was calculated using an estimated initial displacement of 3.45 cm, and plotted against the log of elapsed time since maximum initial water-level displacement of paper of the same scale as the type curve.

8.7.3 The data curve was overlain on the type curve, and shifted horizontally, with the water-level displacement axes coincident, until the best match with the type curve was found. The best fit was for a dimensionless damping factor of 0.25. A match point of t = 7s for t = 5 was selected. The resulting graph is shown in Fig. 2.

8.7.4 The effective water column length can be calculated from Eq 19 as follows:

$$L_e = (t/\hat{t})^2 g = (7s/5)^2 (9.80 \text{ m/s}^2) = 19.2 \text{ m} \tag{22}$$

and from the system geometry (see 3.2.4) as:

$$L_e = L_c + (r_c^{\,2}/r_s^{\,2})(b/2) = 6.5 \text{ m} + (15 \text{ m}/2) = 14 \text{ m} \tag{23}$$

8.7.4.1 The lack of agreement between the estimated and measured effective water column length may be due to factors such as skin effect that may be significant, or assumptions such as "system linearity, high inertial parameter, negligible frictional flowing head loss, radial flow, uniform well-screen flux, and so forth are significantly violated" **(1)**.

8.7.5 Using the value of the dimensionless damping parameter, ζ, Eq 20 can be solved iteratively for β. An initial estimate of the value of α is first made using Eq 12:

$$\alpha = (r_c^{\,2})/(2r_s^{\,2}S) = (0.051 \text{ m})^2/[2(0.051 \text{ m})^2 (8 \times 10^{-5})] = 6250 \tag{24}$$

so that Eq 20 becomes:

$$\beta = [(\alpha\, ln\, \beta)/8\zeta]^2 = [(6250\ 1n\ \beta)/8(0.25)]^2 \tag{25}$$

Beginning with any estimate of β, such as the minimum value of 10^6, a few iterations will produce a value of $\beta = 4.9 \times 10^9$.

8.7.6 The transmissivity, T, is calculated from Eq 21 as follows:

TABLE 5 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 1.0 and α = 99881

t	*w′*	*t*	*w′*
3.162278E−02	−9.995190E−01	3.162278E + 00	−2.219805E−01
3.636619E−02	−9.993614E−01	3.636619E + 00	−1.781301E−01
3.952847E−02	−9.992445E−01	3.952847E + 00	−1.556584E−01
4.269075E−02	−9.991182E−01	4.269075E + 00	−1.371938E−01
4.743416E−02	−9.989111E−01	4.743416E + 00	−1.151268E−01
5.375872E−02	−9.986024E−01	5.375872E + 00	−9.311931E−02
6.324555E−02	−9.980706E−01	6.324555E + 00	−7.022901E−02
7.115125E−02	−9.975651E−01	7.115125E + 00	−5.700982E−02
7.905694E−02	−9.970039E−01	7.905694E + 00	−4.724055E−02
8.696264E−02	−9.963876E−01	8.696264E + 00	−3.986817E−02
9.486833E−02	−9.957171E−01	9.486833E + 00	−3.420016E−02
1.106797E−01	−9.942169E−01	1.106797E + 01	−2.623916E−02
1.264911E−01	−9.925094E−01	1.264911E + 01	−2.105718E−02
1.423025E−01	−9.906011E−01	1.423025E + 01	−1.749216E−02
1.581139E−01	−9.884982E−01	1.581139E + 01	−1.492222E−02
1.739253E−01	−9.862069E−01	1.739253E + 01	−1.299590E−02
1.897367E−01	−9.837333E−01	1.897367E + 01	−1.150439E−02
2.213594E−01	−9.782635E−01	2.213594E + 01	−9.352879E−03
2.529822E−01	−9.721364E−01	2.529822E + 01	−7.879054E−03
2.846050E−01	−9.653980E−01	2.846050E + 01	−6.807075E−03
3.162278E−01	−9.580927E−01	3.162278E + 01	−5.992307E−03
3.636619E−01	−9.461653E−01	3.636619E + 01	−5.080616E−03
3.952847E−01	−9.389866E−01	3.952847E + 01	−4.612882E−03
4.269075E−01	−9.247502E−01	4.269075E + 01	−4.224055E−03
5.375872E−01	−8.944811E−01	4.743416E + 01	−3.749946E−03
6.324555E−01	−8.624921E−01	5.375872E + 01	−3.261801E−03
7.115125E−01	−8.345350E−01	6.324555E + 01	−2.728883E−03
7.905694E−01	−8.058093E−01	7.115125E + 01	−2.401808E−03
8.696264E−01	−7.766480E−01	7.905694E + 01	−2.144707E−03
9.486833E−01	−7.473366E−01	8.696264E + 01	−1.937288E−03
1.106797E + 00	−6.891964E−01	9.486833E + 01	−1.767517E−03
1.264911E + 00	−6.328903E−01	1.106797E + 02	−1.501524E−03
1.423025E + 00	−5.794237E−01	1.264911E + 02	−1.305668E−03
1.581139E + 00	−5.294147E−01	1.423025E + 02	−1.152882E−03
1.739253E + 00	−4.759468E−01	1.581139E + 02	−1.035462E−03
1.897367E + 00	−4.408436E−01	1.739253E + 02	−9.383461E−04
2.213594E + 00	−3.675417E−01	1.897367E + 02	−8.578843E−04
2.529822E + 00	−3.213633E−01	2.213594E + 02	−7.322666E−04
2.846050E + 00	−2.602688E−01	2.529822E + 02	−6.387252E−04
...	...	2.846050E + 02	−5.663467E−04

TABLE 6 Values of the Dimensionless Water Level Displacement, *w′*, Versus Dimensionless Time, *t*, for Construction of Type Curves, ζ = 1.5 and α = 149821

t	*w′*	*t*	*w′*
3.162278E−02	−9.995363E−01	3.162278E + 00	−3.890578E−01
3.636619E−02	−9.993806E−01	3.636619E + 00	−3.398395E−01
3.952847E−02	−9.992652E−01	3.952847E + 00	−3.113242E−01
4.269075E−02	−9.991407E−01	4.269075E + 00	−2.857245E−01
4.743416E−02	−9.989368E−01	4.743416E + 00	−2.520498E−01
5.375872E−02	−9.986336E−01	5.375872E + 00	−2.144593E−01
6.324555E−02	−9.981127E−01	6.324555E + 00	−1.702739E−01
7.115125E−02	−9.976193E−01	7.115125E + 00	−1.419167E−01
7.905694E−02	−9.970732E−01	7.905694E + 00	−1.193325E−01
8.696264E−02	−9.964754E−01	8.696264E + 00	−1.012090E−01
9.486833E−02	−9.958272E−01	9.486833E + 00	−8.656077E−02
1.106797E−01	−9.943835E−01	1.106797E + 01	−6.487489E−02
1.264911E−01	−9.927509E−01	1.264911E + 01	−5.014254E−02
1.423025E−01	−9.909379E−01	1.423025E + 01	−3.9878338E−02
1.581139E−01	−9.889526E−01	1.581139E + 01	−3.254993E−02
1.739253E−01	−9.868033E−01	1.739253E + 01	−2.719151E−02
1.897367E−01	−9.844978E−01	1.897367E + 01	−2.318242E−02
2.213594E−01	−9.794484E−01	2.213594E + 01	−1.772176E−02
2.529822E−01	−9.738631E−01	2.529822E + 01	−1.426997E−02
2.846050E−01	−9.677964E−01	2.846050E + 01	−1.193176E−02
3.162278E−01	−9.612998E−01	3.162278E + 01	−1.025528E−02
3.636619E−01	−9.508522E−01	3.636619E + 01	−8.479138E−03
3.952847E−01	−9.448418E−01	3.952847E + 01	−7.606080E−03
4.269075E−01	−9.319204E−01	4.269075E + 01	−6.898443E−03
5.375872E−01	−9.073899E−01	4.743416E + 01	−6.056228E−03
6.324555E−01	−8.816423E−01	5.375872E + 01	−5.210778E−03
7.115125E−01	−8.597084E−01	6.324555E + 01	−4.310538E−03
7.905694E−01	−8.376400E−01	7.115125E + 01	−3.768776E−03
8.696264E−01	−8.156531E−01	7.905694E + 01	−3.348259E−03
9.486833E−01	−7.939129E−01	8.696264E + 01	−3.012294E−03
1.106797E + 00	−7.516347E−01	9.486833E + 01	−2.739666E−03
1.264911E + 00	−7.114323E−01	1.106797E + 02	−2.315479E−03
1.423025E + 00	−6.735824E−01	1.264911E + 02	−2.006129E−03
1.581139E + 00	−6.381472E−01	1.423025E + 02	−1.769696E−03
1.739253E + 00	−6.050646E−01	1.581139E + 02	−1.583084E−03
1.897367E + 00	−5.742069E−01	1.739253E + 02	−1.432076E−03
2.213594E + 00	−5.185081E−01	1.897367E + 02	−1.307343E−03
2.529822E + 00	−4.831462E−01	2.213594E + 02	−1.113382E−03
2.846050E + 00	−4.270546E−01	2.529822E + 02	−9.695169E−04
...	...	2.846050E + 02	−8.585304E−04

$$T = [(\beta g)/L_e]^{1/2}\, r_s^{\,2} S = [(4.9 \times 10^9)(9.8\ \text{m/s}^2)/19.2\ \text{m}]^{1/2} \qquad (26)$$

$$(0.051\ \text{m})^2\,(8 \times 10^{-5}) = 0.01\ \text{m}^2/\text{s}$$

8.7.7 This example is included to show the application of the method. Because of the difference between the values of L_e exceeds 20 %, this test would not be considered a successful application of this test method.

9. Report

9.1 Prepare the report including the following information. The final report of the analytical procedure will include information from the report on test method selection, Guide D 4043, and the field testing procedure, Test Method D 4044.

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the slug test method for determining transmissivity and storativity. Summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well, and the method of measurement and of effecting a change in head. Discuss the rationale for selecting this test method.

9.1.2 *Hydrogeologic Setting*—Review information available on the hydrogeology of the site; interpret and describethe hydrogeology of the site as it pertains to the method selected for conducting and analyzing an aquifer test method. Compare hydrogeologic characteristics of the site as it conforms and differs from assumptions made in the solution to the aquifer test method.

9.1.3 *Equipment*—Report the field installation and equipment for the aquifer test method. Include in the report, well construction information, diameter, depth, and open interval to the aquifer, and location of control well and pumping equipment. The construction, diameter, depth, and open interval of observation wells should be recorded.

9.1.3.1 Report the techniques used for observing water levels, pumping rate, barometric changes, and other environmental conditions pertinent to this test method. Include a list of measuring devices used during the test method; the manufacturers name, model number, and basic specifications for each major item; and the name and date of the last calibration, if applicable.

9.1.4 *Test Procedures*—Report the steps taken in conducting the pretest and test phases. Include the frequency of head measurements made in the control well, and other environmental data recorded before and during the procedure.

9.1.5 *Presentation and Interpretation of Test Results*:

TABLE 7 Values of the Dimensionless Water Level Displacement, w', Versus Dimensionless Time, t, for Construction of Type Curves, $\zeta = 2.0$ and $\alpha = 199761$

t	w'	t	w'
3.162278E−02	−9.995504E−01	3.162278E + 00	−4.954981E−01
3.636619E−02	−9.993964E−01	3.952847E + 00	−4.198530E−01
3.952847E−02	−9.992824E−01	4.269075E + 00	−3.936005E−01
4.269075E−02	−9.991596E−01	4.743416E + 00	−3.578603E−01
4.743416E−02	−9.989589E−01	5.375872E + 00	−3.161236E−01
5.375872E−02	−9.986610E−01	6.324555E + 00	−2.640067E−01
6.324555E−02	−9.981509E−01	7.115125E + 00	−2.283612E−01
7.115125E−02	−9.976692E−01	7.905694E + 00	−1.984082E−01
7.905694E−02	−9.971377E−01	8.696264E + 00	−1.731322E−01
8.696264E−02	−9.965578E−01	9.486833E + 00	−1.517201E−01
9.486833E−02	−9.959308E−01	1.106797E + 01	−1.179834E−01
1.106797E−01	−9.945412E−01	1.264911E + 01	−9.327095E−02
1.264911E−01	−9.929793E−01	1.423025E + 01	−7.493612E−02
1.423025E−01	−9.912556E−01	1.581139E + 01	−6.116444E−02
1.581139E−01	−9.893797E−01	1.739253E + 01	−5.069464E−02
1.739253E−01	−9.873613E−01	1.897367E + 01	−4.263949E−02
1.897367E−01	−9.852094E−01	2.213594E + 01	−3.142780E−02
2.213594E−01	−9.805395E−01	2.529822E + 01	−2.431526E−02
2.529822E−01	−9.754347E−01	2.846050E + 01	−1.959156E−02
2.846050E−01	−9.699542E−01	3.162278E + 01	−1.631463E−02
3.162278E−01	−9.641512E−01	3.636619E + 01	−1.300164E−02
3.636619E−01	−9.549461E−01	3.952847E + 01	−1.144921E−02
3.952847E−01	−9.498965E−01	4.269075E + 01	−1.023206E−02
4.269075E−01	−9.380387E−01	4.743416E + 01	−8.833366E−03
5.375872E−01	−9.179758E−01	5.375872E + 01	−7.480425E−03
6.324555E−01	−8.968434E−01	6.324555E + 01	−6.093618E−03
7.115125E−01	−8.791796E−01	7.115125E + 01	−5.282479E−03
7.905694E−01	−8.616598E−01	7.905694E + 01	−4.663663E−03
8.696264E−01	−8.444851E−01	8.696264E + 01	−4.175479E−03
9.486833E−01	−8.274940E−01	9.486833E + 01	−3.780257E−03
1.106797E + 00	−7.948821E−01	1.106797E + 02	−3.179076E−03
1.264911E + 00	−7.639855E−01	1.264911E + 02	−2.743153E−03
1.423025E + 00	−7.347865E−01	1.423025E + 02	−2.412451E−03
1.581139E + 00	−7.071872E−01	1.581139E + 02	−2.152957E−03
1.739253E + 00	−6.738222E−01	1.739253E + 02	−1.943876E−03
1.897367E + 00	−6.562890E−01	1.897367E + 02	−1.771827E−03
2.213594E + 00	−6.103452E−01	2.213594E + 02	−1.468741E−03
2.529822E + 00	−5.819047E−01	2.529822E + 02	−1.308454E−03
2.846050E + 00	−5.304684E−01	2.846050E + 02	−1.157121E−03

TABLE 8 Values of the Dimensionless Water Level Displacement, w', Versus Dimensionless Time, t, for Construction of Type Curves, $\zeta = 3.0$ and $\alpha = 299642$

t	w'	t	w'
3.162278E−02	−9.995713E−01	3.162278E + 00	−6.252020E−01
3.636619E−02	−9.994208E−01	3.636619E + 00	−5.849806E−01
3.952847E−02	−9.992801E−01	3.952847E + 00	−5.599474E−01
4.269075E−02	−9.991903E−01	4.269075E + 00	−5.362293E−01
4.743416E−02	−9.989957E−01	4.743416E + 00	−5.029083E−01
5.375872E−02	−9.987081E−01	5.375872E + 00	−4.623004E−01
6.324555E−02	−9.982186E−01	6.324555E + 00	−4.085330E−01
7.115125E−02	−9.977595E−01	7.115125E + 00	−3.693645E−01
7.905694E−02	−9.972559E−01	7.905694E + 00	−3.345921E−01
8.696264E−02	−9.967096E−01	8.696264E + 00	−3.036493E−01
9.486833E−02	−9.961227E−01	9.486833E + 00	−2.760565E−01
1.106797E−01	−9.948334E−01	1.106797E + 01	−2.293403E−01
1.264911E−01	−9.934017E−01	1.264911E + 01	−1.918026E−01
1.423025E−01	−9.918402E−01	1.423025E + 01	−1.614586E−01
1.581139E−01	−9.901608E−01	1.581139E + 01	−1.367944E−01
1.739253E−01	−9.883746E−01	1.739253E + 01	−1.166434E−01
1.897367E−01	−9.864919E−01	1.897367E + 01	−1.000984E−01
2.213594E−01	−9.824744E−01	2.213594E + 01	−7.513561E−02
2.529822E−01	−9.781767E−01	2.529822E + 01	−5.783395E−02
2.846050E−01	−9.736570E−01	2.846050E + 01	−4.561932E−02
3.162278E−01	−9.689648E−01	3.162278E + 01	−3.683581E−02
3.636619E−01	−9.616917E−01	3.636619E + 01	−2.783159E−02
3.952847E−01	−9.580948E−01	3.952847E + 01	−2.365551E−02
5.375872E−01	−9.340335E−01	4.269075E + 01	−2.045240E−02
6.324555E−01	−9.189910E−01	4.743416E + 01	−1.690262E−02
7.115125E−01	−9.066885E−01	5.375872E + 01	−1.366930E−02
7.905694E−01	−8.946509E−01	6.324555E + 01	−1.061295E−02
8.696264E−01	−8.828959E−01	7.115125E + 01	−8.959150E−03
9.486833E−01	−8.714239E−01	7.905694E + 01	−7.762188E−03
1.106797E + 00	−8.492890E−01	8.696264E + 01	−6.854400E−03
1.264911E + 00	−8.281398E−01	9.486833E + 01	−6.140890E−03
1.423025E + 00	−8.078648E−01	1.106797E + 02	−5.088277E−03
1.581139E + 00	−7.883699E−01	1.264911E + 02	−4.346830E−03
1.739253E + 00	−7.623399E−01	1.423025E + 02	−3.795249E−03
1.897367E + 00	−7.514388E−01	1.581139E + 02	−3.368423E−03
2.213594E + 00	−7.169161E−01	1.739253E + 02	−3.028188E−03
2.529822E + 00	−6.978197E−01	1.897367E + 02	−2.750489E−03
2.846050E + 00	−6.540089E−01	2.213594E + 02	−2.324282E−03

9.1.5.1 *Data*—Present tables of data collected during the test.

9.1.5.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.1.5.3 Show calculation of transmissivity and coefficient of storage.

9.1.5.4 Evaluate the overall quality of the test on the basis of the adequacy of instrumentation and observations of stress and response and the conformance of the hydrogeologic conditions and the performance of the test to the assumptions (see 5.1).

10. Precision and Bias

10.1 *Precision*—It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses.

10.2 *Bias*—No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 aquifer; aquifer tests; ground water; hydraulic conductivity; observation wells; slug test; storage coefficient; transmissivity

TABLE 9 Values of the Dimensionless Water Level Displacement, w', Versus Dimensionless Time, t, for Construction of Type Curves, $\zeta = 4.0$ and $\alpha = 399523$

t	w'	t	w'
3.636619E−02	−9.994397E−01	3.162278E + 00	−7.016959E−01
3.952847E−02	−9.993315E−01	3.636619E + 00	−6.675513E−01
4.269075E−02	−9.992153E−01	3.952847E + 00	−6.459305E−01
4.743416E−02	−9.990266E−01	4.269075E + 00	−6.252068E−01
5.375872E−02	−9.987391E−01	4.743416E + 00	−5.956538E−01
6.324555E−02	−9.982789E−01	5.375872E + 00	−5.588830E−01
7.115125E−02	−9.978410E−01	6.324555E + 00	−5.087715E−01
7.905694E−02	−9.973634E−01	7.115125E + 00	−4.711058E−01
8.696264E−02	−9.968485E−01	7.905694E + 00	−4.367299E−01
9.486833E−02	−9.962983E−01	8.696264E + 00	−4.053004E−01
1.106797E−01	−9.951003E−01	9.486833E + 00	−3.765203E−01
1.264911E−01	−9.937850E−01	1.106797E + 01	−3.259029E−01
1.423025E−01	−9.923664E−01	1.264911E + 01	−2.831426E−01
1.581139E−01	−9.908572E−01	1.423025E + 01	−2.468765E−01
1.739253E−01	−9.892689E−01	1.581139E + 01	−2.160073E−01
1.897367E−01	−9.876121E−01	1.739253E + 01	−1.896467E−01
2.213594E−01	−9.841292E−01	1.897367E + 01	−1.670685E−01
2.529822E−01	−9.804724E−01	2.213594E + 01	−1.309732E−01
2.846050E−01	−9.766928E−01	2.529822E + 01	−1.040662E−01
3.162278E−01	−9.728306E−01	2.846050E + 01	−8.380617E−02
3.636619E−01	−9.669495E−01	3.162278E + 01	−6.840166E−02
3.952847E−01	−9.630034E−01	3.636619E + 01	−5.170694E−02
5.375872E−01	−9.453851E−01	3.952847E + 01	−4.360799E−02
6.324555E−01	−9.339662E−01	4.269075E + 01	−3.723898E−02
7.115125E−01	−9.246968E−01	4.743416E + 01	−3.004421E−02
7.905694E−01	−9.156473E−01	5.375872E + 01	−2.343231E−02
8.696264E−01	−9.068039E−01	6.324555E + 01	−1.727746E−02
9.486833E−01	−8.981501E−01	7.115125E + 01	−1.407907E−02
1.106797E + 00	−8.813505E−01	7.905694E + 01	−1.186523E−02
1.264911E + 00	−8.651446E−01	8.696264E + 01	−1.025799E−02
1.423025E + 00	−8.494578E−01	9.486833E + 01	−9.042727E−03
1.581139E + 00	−8.342370E−01	1.106797E + 02	−7.328027E−03
1.739253E + 00	−8.194373E−01	1.264911E + 02	−6.172593E−03
1.897367E + 00	−8.050439E−01	1.423025E + 02	−5.337797E−03
2.213594E + 00	−7.773380E−01	1.581139E + 02	−4.704649E−03
2.529822E + 00	−7.509616E−01	1.739253E + 02	−4.207132E−03
2.846050E + 00	−7.257946E−01	1.897367E + 02	−3.805443E−03
...	...	2.213594E + 02	−3.168381E−03
...	...	2.529822E + 02	−2.755521E−03
...	...	2.846050E + 02	−2.421855E−03

TABLE 10 Values of the Dimensionless Water Level Displacement, w', Versus Dimensionless Time, t, for Construction of Type Curves, $\zeta = 5.0$ and $\alpha = 499404$

t	w'	t	w'
3.162278E−02	−9.995993E−01	3.162278E + 00	−7.522230E−01
3.636619E−02	−9.994555E−01	3.636619E + 00	−7.227334E−01
3.952847E−02	−9.993500E−01	3.952847E + 00	−7.039170E−01
4.269075E−02	−9.992370E−01	4.269075E + 00	−6.857313E−01
4.743416E−02	−9.990540E−01	4.743416E + 00	−6.595645E−01
5.375872E−02	−9.987858E−01	5.375872E + 00	−6.266026E−01
6.324555E−02	−9.983344E−01	6.324555E + 00	−5.809008E−01
7.115125E−02	−9.979164E−01	7.115125E + 00	−5.458994E−01
7.905694E−02	−9.974631E−01	7.905694E + 00	−5.134182E−01
8.696264E−02	−9.969772E−01	8.696264E + 00	−4.832304E−01
9.486833E−02	−9.964608E−01	9.486833E + 00	−4.551380E−01
1.106797E−01	−9.953459E−01	1.106797E + 01	−4.045587E−01
1.264911E−01	−9.941348E−01	1.264911E + 01	−3.604938E−01
1.423025E−01	−9.928421E−01	1.423025E + 01	−3.219817E−01
1.581139E−01	−9.914807E−01	1.581139E + 01	−2.882303E−01
1.739253E−01	−9.900617E−01	1.739253E + 01	−2.585794E−01
1.897367E−01	−9.885951E−01	1.897367E + 01	−2.324735E−01
2.213594E−01	−9.855521E−01	2.213594E + 01	−1.890850E−01
2.529822E−01	−9.824077E−01	2.529822E + 01	−1.550702E−01
2.846050E−01	−9.792032E−01	2.846050E + 01	−1.282238E−01
3.162278E−01	−9.759688E−01	3.162278E + 01	−1.069007E−01
3.636619E−01	−9.711069E−01	3.636619E + 01	−8.264429E−02
3.952847E−01	−9.678791E−01	3.952847E + 01	−7.033634E−02
4.269075E−01	−9.607577E−01	4.269075E + 01	−6.035508E−02
5.375872E−01	−9.536742E−01	4.743416E + 01	−4.871115E−02
6.324555E−01	−9.445502E−01	5.375872E + 01	−3.762513E−02
7.115125E−01	−9.371475E−01	6.324555E + 01	−2.698853E−02
7.905694E−01	−9.299074E−01	7.115125E + 01	−2.139780E−02
8.696264E−01	−9.228118E−01	7.905694E + 01	−1.755806E−02
9.486833E−01	−9.158457E−01	8.696264E + 01	−1.482285E−02
1.106797E + 00	−9.022552E−01	9.486833E + 01	−1.280765E−02
1.264911E + 00	−8.890648E−01	1.106797E + 02	−1.007026E−02
1.423025E + 00	−8.762274E−01	1.264911E + 02	−8.316009E−03
1.581139E + 00	−8.637098E−01	1.423025E + 02	−7.096335E−03
1.739253E + 00	−8.442461E−01	1.581139E + 02	−6.196777E−03
1.897367E + 00	−8.395387E−01	1.739253E + 02	−5.503989E−03
2.213594E + 00	−8.164029E−01	1.897367E + 02	−4.952866E−03
2.529822E + 00	−8.075058E−01	2.213594E + 02	−4.129436E−03
2.846050E + 00	−7.728430E−01	2.529822E + 02	−3.542355E−03
...	...	2.846050E + 02	−3.102085E−03

REFERENCES

(**1**) Kipp, K. L., Jr., “Type Curve Analysis of Inertial Effects in the Response of a Well to a Slug Test,” *Water Resources Research*, Vol 21, No. 9, 1985, pp. 1397–1408.

(**2**) Bird, R. B., W. E. Stewart, and E. N. Lightfoot, Transport Phenomena, John Wiley, New York, 1960.

(**3**) Cooper, H. H., Jr., Bredehoeft, J. D., and Papadopulos, I. S., “Response of a Finite-Diameter Well to an Instantaneous Charge of Water,” *Water Resources Research*, Vol 3, No. 1, 1967, pp. 263–269.

(**4**) van der Kamp, Garth, “Determining Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case,” *Water Resources Research*, Vol 12, No. 1, 1976, pp. 71–77.

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Standard Test Method for (Analytical Procedure) Determining Hydraulic Conductivity of an Unconfined Aquifer by Overdamped Well Response to Instantaneous Change in Head (Slug)[1]

This standard is issued under the fixed designation D 5912; 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.

ϵ^1 NOTE—Note 5 was added editorially in December 1996.

1. Scope

1.1 This test method covers the determination of hydraulic conductivity from the measurement of inertial force free (overdamped) response of a well-aquifer system to a sudden change in water level in a well. Inertial force free response of the water level in a well to a sudden change in water level is characterized by recovery to initial water level in an approximate exponential manner with negligible inertial effects.

1.2 The analytical procedure in this test method is used in conjunction with the field procedure in Test Method D 4044 for collection of test data.

1.3 *Limitations*—Slug tests are considered to provide an estimate of hydraulic conductivity. The determination of storage coefficient is not possible with this test method. Because the volume of aquifer material tested is small, the values obtained are representative of materials very near the open portion of the control well.

NOTE 1—Slug tests are usually considered to provide estimates of the lower limit of the actual hydraulic conductivity of an aquifer because the test results are so heavily influenced by well efficiency and borehole skin effects near the open portion of the well. The portion of the aquifer that is tested by the slug test is limited to an area near the open portion of the well where the aquifer materials may have been altered during well installation, and therefore may significantly effect the test results. In some cases the data may be misinterpreted and result in a higher estimate of hydraulic conductivity. This is due to the reliance on early time data that is reflective of the hydraulic conductivity of the filter pack surrounding the well. This effect was discussed by Bouwer.[2] In addition, because of the reliance on early time data, in aquifers with medium to high hydraulic conductivity, the early time portion of the curve that is useful for this data analyses is too short (for example, <10 s) for accurate measurement; therefore, the test results begin to greatly underestimate the true hydraulic conductivity.

1.4 The values stated in SI units are to be regarded as the 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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[3]

D 4043 Guide for Selection of Aquifer-Test Methods in Determining Hydraulic Properties by Well Techniques[3]

D 4044 Test Method (Field Procedure) for Instantaneous Change in Head (Slug Test) for Determining Hydraulic Properties of Aquifers[3]

D 4104 Test Method (Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Test)[3]

3. Terminology

3.1 *Definitions*—For definitions of terms used in this test method, see Terminology D 653.

3.2 *Symbols:Symbols and Dimensions:*

3.2.1 *A [nd]*—coefficient that is a function of L/r_w and is determined graphically.

3.2.2 *B [nd]*—coefficient that is a function of L/r_w and is determined graphically.

3.2.3 *C [nd]*—coefficient that is a function of L/r_w and is determined graphically.

3.2.4 *D [L]*—aquifer thickness.

3.2.5 *H [L]*—distance between static water level and the base of open interval of the well.

3.2.6 *L [L]*—length of well open to aquifer.

3.2.7 *rc [L]*—inside diameter of the portion of the well casing in which the water level changes.

3.2.8 R_e[L]—effective radius, determined empirically based on the geometry of the well, over which y is dissipated.

3.2.9 r_w[L]—radial distance from well center to original undisturbed aquifer.

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved Feb. 10, 1996. Published June 1996.

[2] Bouwer, H., and Rice, R. C., "A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells," *Water Resources Research*, Vol 12, No. 3, 1976, pp. 423–428.

[3] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.10 t_f[T]—time at end point of straight-line portion of graph.

3.2.11 t_0[T]—time at beginning of straight-line portion of graph.

3.2.12 y_f[L]—head difference at end point of straight-line portion of graph.

3.2.13 y_0[L]—head difference at beginning of straight-line portion of graph.

4. Summary of Test Method

4.1 This test method describes the analytical procedure for analyzing data collected following an instantaneous change in head (slug) test in an overdamped well. The field procedures in conducting a slug test are given in Test Method D 4044. The analytical procedure consists of analyzing the recovery of water level in the well following the change in water level induced in the well.

4.2 *Solution*—The solution given by Bouwer and Rice[2] follows:

$$K = \frac{r_c^2 \ln(R_e/r_w)}{2L} \frac{1}{(t_f - t_0)} \ln \frac{y_0}{yf} \qquad (1)$$

where:

if $D > H$

$$\ln(R_e/r_w) = \left[\frac{1.1}{\ln(H/r_w)} + \frac{A + B \ln[(D - H)/r_w]}{L/r_w}\right]^{-1} \qquad (2)$$

if $D = H$

$$\ln R_e/r_w = \left[\frac{1.1}{\ln(H/r_w)} + \frac{C}{L/r_w}\right]^{-1} \qquad (3)$$

NOTE 2—Other analytical solutions are given by Hvorslev[4] and Cooper et al;[5,6] however, they may differ in their assumptions and applicability.

NOTE 3—Bouwer[2] provided discussion of various applications and observations of the procedure described in this test method.

NOTE 4—Test Method D 4104 describes the analytical solution following Cooper et al.[5]

NOTE 5—The use of the symbol K for the term hydraulic conductivity is the predominant usage in ground-water literature by hydrogeologists, whereas, the symbol k is commonly used for this term in soil and rock mechanics and soil science.

5. Significance and Use

5.1 *Assumptions of Solution*:

5.1.1 Drawdown (or mounding) of the water table around the well is negligible.

5.1.2 Flow above the water table can be ignored.

5.1.3 Head losses as the water enters or leaves the well are negligible.

5.1.4 The aquifer is homogeneous and isotropic.

5.2 *Implications of Assumptions*:

5.2.1 The mathematical equations applied ignore inertial effects and assume that the water level returns to the static level in an approximate exponential manner.

5.2.2 The geometric configuration of the well and aquifer are shown in Fig. 1, that is after Fig. 1 of Bouwer and Rice.[2]

5.2.3 For filter-packed wells, Eq 1 applies to cases in which the filter pack remains saturated. If some of the filter pack is dewatered during testing, r_c^2 should be replaced by the following:

$$r_c\,(corrected) = [(1 - n)r_a^{\,2} + nr_w^{\,2}]^{0.5} \qquad (4)$$

where:

n = short-term specific yield of the filter pack,

r_a = uncorrected well casing radius, and

r_w = borehole radius.

NOTE 6—Short term refers to the duration of the slug test.

6. Procedure

6.1 The overall procedure consists of conducting the slug test field procedure (see Test Method D 4044) and analysis of the field data that is addressed in this test method.

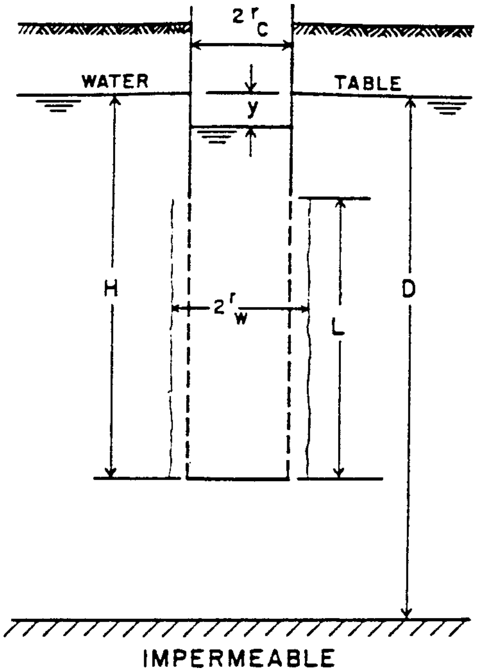
6.2 The water level data are corrected so that the difference between the original static water level and the water level during the test is known. This difference in water level at time "t" is denoted as "y_t".

6.3 The dimensionless coefficients of A, B, and C are determined graphically based on their relationship with L/r_w. An example of the curves relating A, B, and C to L/r_w is given in Fig. 2, that is after Fig. 3 of Bouwer and Rice.[2]

7. Calculation

7.1 Determine $\ln\,(R_e/r_w)$ using Eq 2 or Eq 3, as appropriate.

7.2 Plot at a semilogarithmic scale the relationship of "y" on the log scale versus elapsed time on the arithmetic scale.



NOTE 1—See Fig. 1 of Footnote 2.

FIG. 1 Geometry and Symbols of a Partially Penetrating, Partially Perforated Well in Unconfined Aquifer with Gravel Pack or Developed Zone Around Perforated Section

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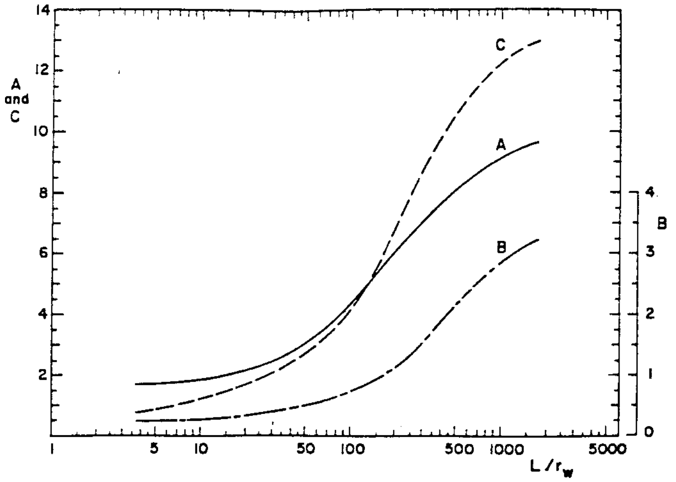
[4] Hvorslev, M. J., "Time Lag and Soil Permeability in Ground-Water Observations," Waterways Experiment Station, Corps of Engineers, *U.S. Army, Bulletin No. 36*, 1951.

[5] Cooper, H. H., Jr., Bredehoeft, J. D., and Papadopulos, I. S., "Response of a Finite-Diameter Well to an Instantaneous Change in Water," *Water Resources Research*, Vol 3, No. 1, 1967, pp. 263–269.

[6] Bouwer, H., "The Bouwer-Rice Slug Test—An Update," *Ground Water*, Vol 27, No. 3, 1989, pp. 304–309.



NOTE 1—See Fig. 3 of Footnote 2.

FIG. 2 Curves Relating Coefficients *A, B*, and *C* to L/r_w

7.3 Determine the straight-line portion of the graph.

7.4 Determine the end point values of the straight-line portion of the graph and substitute along with value for *ln* (R_e/r_w) determined in 7.1, into Eq 1.

NOTE 7—An example of the plot of this test method is given in Fig. 3. The data used to prepare the plot is presented in Table 1. Table 1 also presents the well configuration data and the corresponding values of *A, B*, and *C*.

8. Report

8.1 Prepare a report including the information described in this section. The final report of the analytical procedure will include information from the report on the test method selection (see Guide D 4043) and the field testing procedure (see Test Method D 4044).

8.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the slug test method for determining hydraulic conductivity. Summarize the field hydrogeologic conditions and field equipment and instrumentation including the construction of the control well, and the method of measurement and of effecting a change in head. Discuss the rationale for selecting the method used (see Guide D 4043).

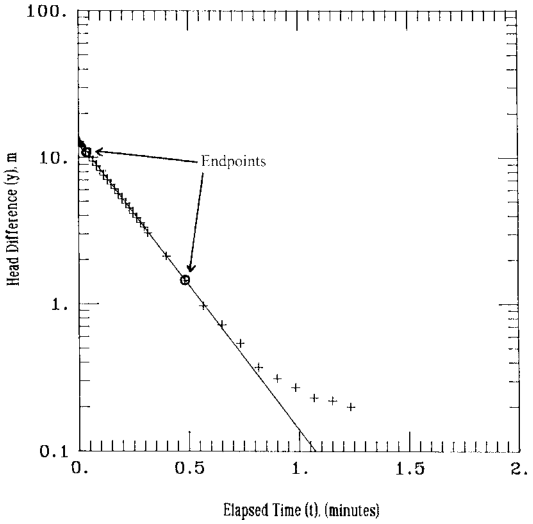


FIG. 3 Sample Plot of Slug Test Data

TABLE 1 Sample Slug Test Data[A][B]

NOTE 1—*A* and *B* are not used since $D = H$.

NOTE 2—Endpoint values are highlighted.

Elapsed Time, min	Head Difference, m
0.0034	12.86
0.0067	12.71
0.0100	12.40
0.0134	12.13
0.0167	11.96
0.0334	10.94
0.0500	10.15
0.0667	9.45
0.0834	8.80
0.1000	8.16
0.1167	7.05
0.1334	6.54
0.1500	6.10
0.1667	5.64
0.1834	5.21
0.2000	4.85
0.2167	4.51
0.2334	4.14
0.2500	3.88
0.2667	3.59
0.2834	3.35
0.3000	3.06
0.3167	2.12
0.4001	1.45
0.4834	0.97
0.5667	0.72
0.6501	0.54
0.7334	0.37
0.8167	0.31
0.9001	0.27
1.0667	0.23
1.1501	0.22
1.2334	0.20

[A] Well configuration data, m: $Rc = 0.0833$, $Rw = 0.1615$, $D = 41.5$, $L = 8$, and $H = 41.5$.

[B] Coefficients (dimensionless): *A* = n/a, *B* = n/a, and $C = 2.624$.

8.1.2 *Hydrogeologic Setting*—Review information available on the hydrogeology of the site; interpret and describe the hydrogeology of the site as it pertains to the method selected for selected for conducting and analyzing an aquifer test. Compare hydrogeologic characteristics of the site as it conforms and differs from the assumptions made in the solution to the aquifer test method.

8.1.3 *Equipment*—Report the field installation and equipment for the aquifer test. Include in the report, well construction information, diameter, depth, and open interval to the aquifer, and location of control well. Include a list of measuring devices used during the test; the manufacturer's name, model number, and basic specifications for each major item; and the name and date of the last calibration, if applicable.

8.1.4 *Test Procedures*—Report the steps taken in conducting the pretest and test phases. Include the frequency of head measurements made in the control well and other environmental data recorded before and during the test procedure.

8.1.5 *Presentation and Interpretation of Test Results*:

8.1.5.1 *Data*—Present tables of data collected during the test.

8.1.5.2 *Data Plots*—Present data plots used in analysis of the data.

8.1.5.3 Show calculation of hydraulic conductivity.

8.1.5.4 Evaluate the overall quality of the test on the basis of the adequacy of instrumentation and observations of stress and response and the conformance of the hydrogeologic conditions and the performance of the test to the assumptions (see 5.1).

9. Precision and Bias

9.1 It is not practical to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent on ambient stresses. No statement can be made about the bias because no true reference values exist.

10. Keywords

10.1 aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; slug test

Designation: D 5920 – 96

AMERICAN SOCIETY FOR TESTING AND MATERIALS
100 Barr Harbor Dr., West Conshohocken, PA 19428

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

This standard is issued under the fixed designation D 5920; 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 D 4043 and Test Method D 4050.

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:*

D 653 Terminology Relating to Soil, Rock, and Contained Fluids[2]

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques[2]

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well[2]

3. Terminology

3.1 *Definitions:*

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *aquifer, unconfined*—an aquifer that has a water table.

3.1.3 *control well*—a well by which the head and flow in the aquifer is changed by pumping, injecting, or imposing a constant change of head.

3.1.4 *drawdown*—the vertical distance the static head is lowered due to removal of water.

3.1.5 *head, static*—the height above a standard datum the surface of a column of water can be supported by the static pressure at a point.

3.1.6 *hydraulic conductivity— field aquifer test*, the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.7 *observation well*—a well open to all or part of an aquifer.

3.1.8 *piezometer*—a device used to measure static head at a point in the subsurface.

3.1.9 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.1.10 *transmissivity*—the volume of water of the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 For definitions of other terms used in this test method, see Terminology D 653.

3.2 *Symbols: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.

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

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[1] This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

Current edition approved Feb. 10, 1996. Published June 1996.

[2] *Annual Book of ASTM Standards*, Vol 04.08.

3.2.6.1 *Discussion*—The use of the symbol *K* for the hydraulic conductivity is the predominant usage in ground water 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.

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 D 4043 on the basis of the hydrologic characteristics of the site. The field test (Test Method D 4050) 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

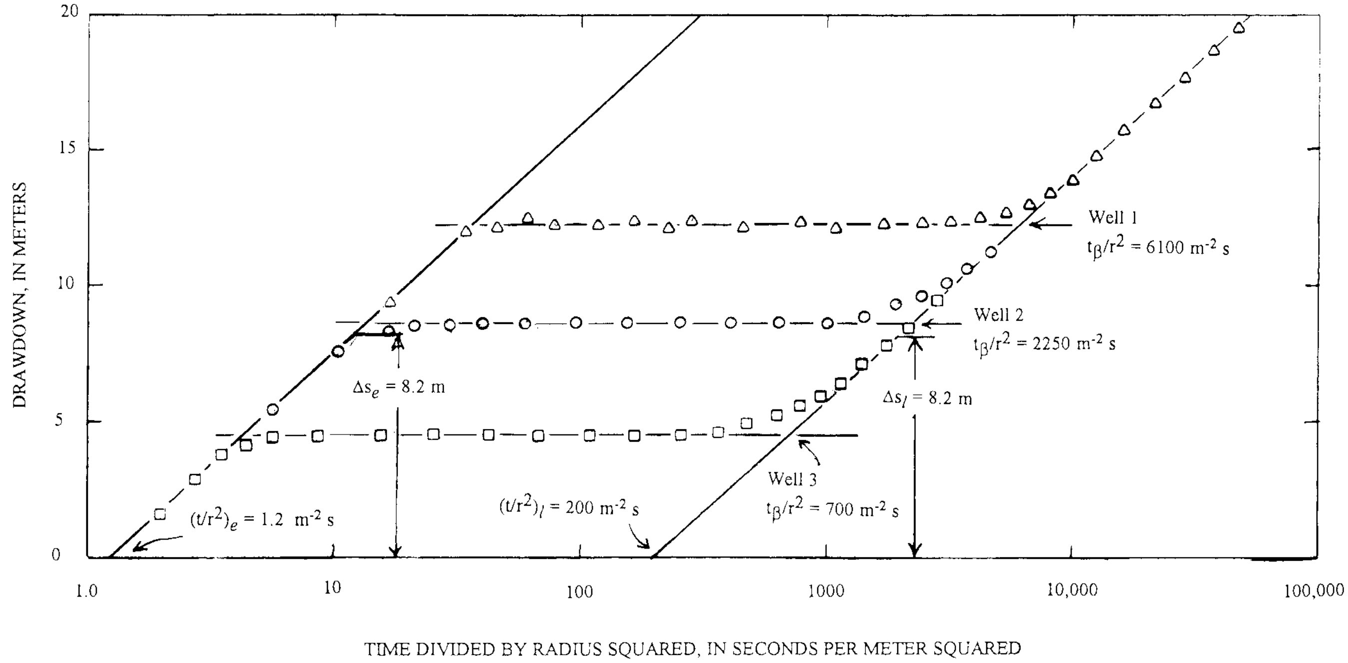

FIG. 1 Aquifer-Test Analysis, Example Two

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.

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

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

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

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

and:

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

and the terms γ_0 and $\gamma_n$are the roots of the following equations:

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

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

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

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

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:

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

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

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:

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

and:

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

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 D 4106 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 D 4106 provides guidance in correcting for the reduction in saturated thickness. According to Neuman **(1)** such adjustments should be made only for late-time values.

6. Apparatus

6.1 *Analysis*—Analysis of data from the field procedure (see Test Method D 4050) 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.

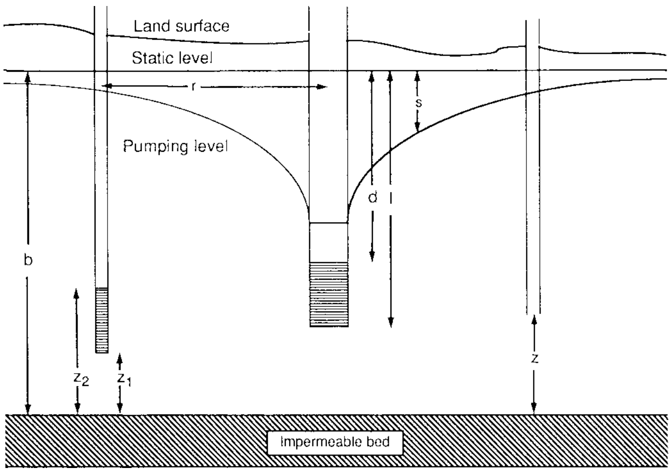

FIG. 2 Cross Section Through a Discharging Well Screened in Part of an Unconfined Aquifer

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

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 D 4050), 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 *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).

8.1.1.1 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.

8.1.1.2 Holding the axes parallel, overlay the data plot on the type curves. Match as many of the early time-drawdown

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 $\sigma = 10^{-2}$.

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}

t_y	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
1×10^{-4}	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}
2×10^{-4}	...	...	...	...	...	7.81×10^{-2}	4.80×10^{-2}	3.15×10^{-2}	2.16×10^{-2}	1.53×10^{-2}
3.5×10^{-4}	...	...	...	...	1.03×10^{-1}	7.83×10^{-2}	4.81×10^{-2}	3.16×10^{-2}	2.17×10^{-2}	1.54×10^{-2}
6×10^{-4}	...	...	...	...	1.04×10^{-1}	7.85×10^{-2}	4.84×10^{-2}	3.18×10^{-2}	2.19×10^{-2}	1.56×10^{-2}
1×10^{-3}	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}
2×10^{-3}	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}
3.5×10^{-3}	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}
6×10^{-3}	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}
1×10^{-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}
2×10^{-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}
3.5×10^{-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}
6×10^{-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}
1×10^{-1}	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}
2×10^{-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}
3.5×10^{-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}
6×10^{-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}
1×10^{0}	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}
2×10^{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}
3.5×10^{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}
6×10^{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}
1×10^{1}	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}
2×10^{1}	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}
3.5×10^{1}	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}
6×10^{1}	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}
1×10^{2}	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 $\sigma = 10^{-2}$.

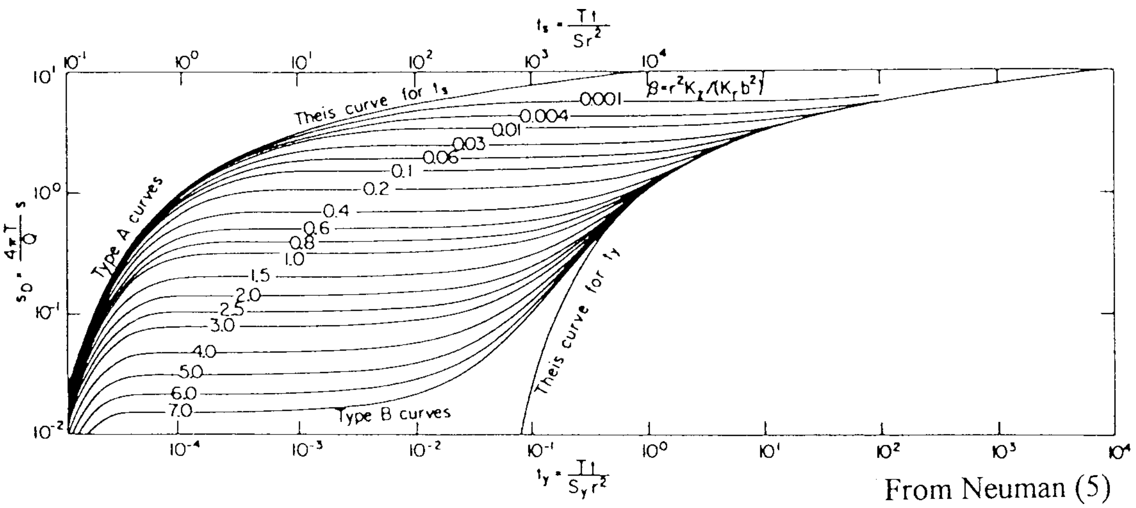
data as possible to the left-most part of the type curve (Type A curves). Select an early-time match point, and record the values of s, t/r^2, s_D and t_s. Moving the data plot horizontally, match as many as possible of the late-time data to the right-most part of the type curves (Type B curves) and 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.

8.1.1.3 Repeat the procedure in 8.1.1.2 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.

8.1.1.4 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:

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

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



From Neuman (5)

NOTE 1—From Ref **(5)**.

FIG. 3 Type Curves for Fully Penetrating Wells

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

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

The anisotropy can be calculated from:

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

and the vertical permeability from:

$$K_z = \alpha K_r \tag{15}$$

8.1.1.5 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.

8.1.1.6 For the example, the transmissivity from Eq 10 is:

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

and the specific yield from Eq 11 is:

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

The storage coefficient, from Eq 11 is:

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

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:

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

8.1.2 *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.

8.1.2.1 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 D 4105.

$$T = 2.30\ Q/4\pi\Delta s_l \tag{16}$$

$$S_y = 2.25\ T\ (t/r^2)_l \tag{17}$$

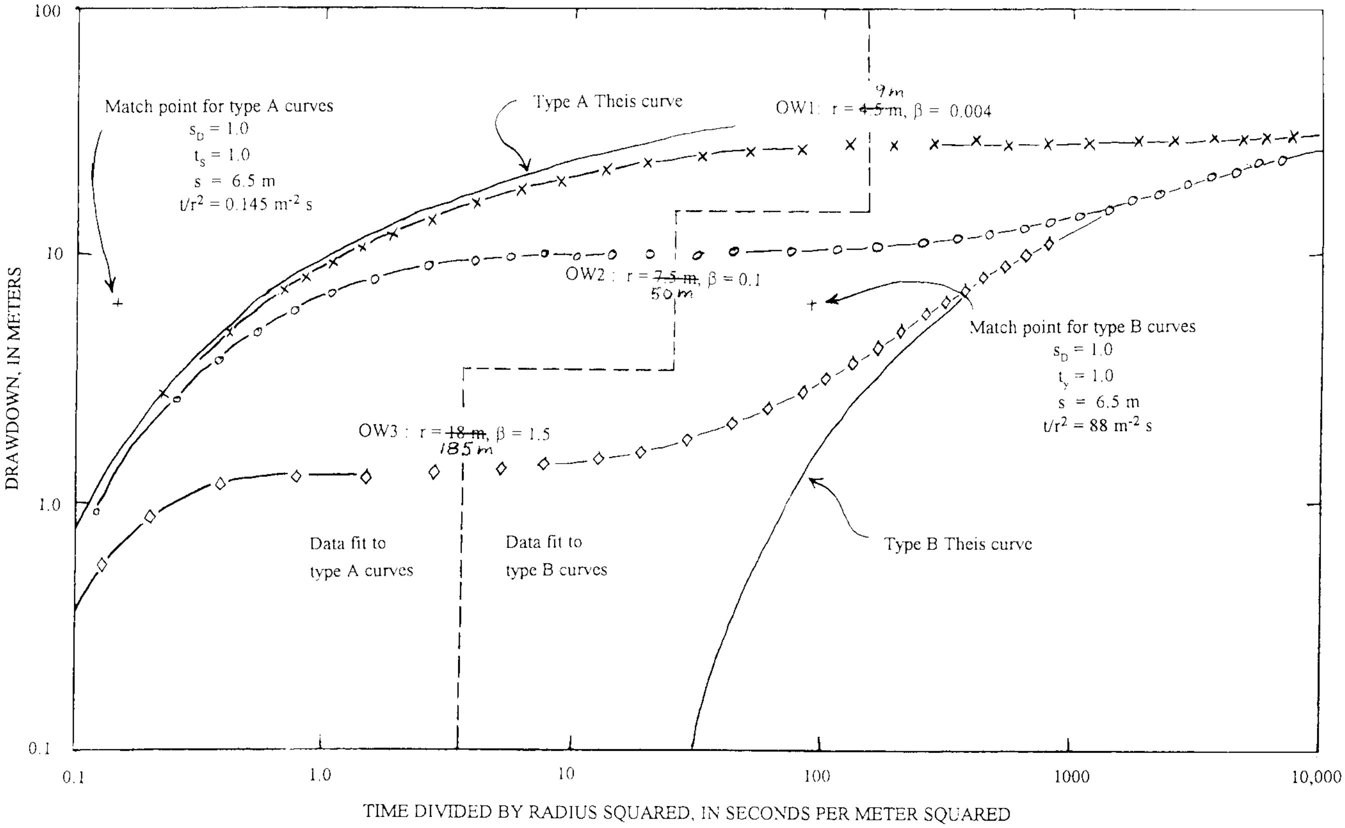


FIG. 4 Aquifer-Test Analysis, Example 1

8.1.2.2 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:

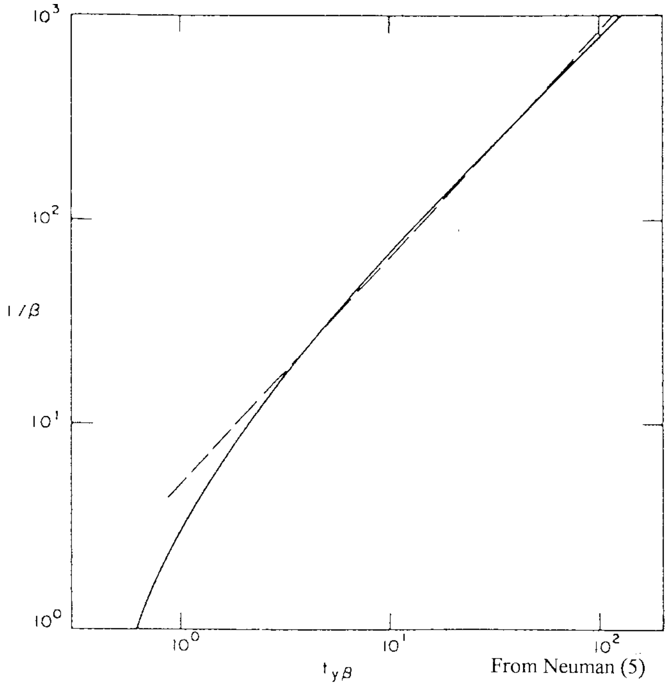
$$t_{y\beta} = (T/S_y)(t_{\beta}/r^2) \tag{18}$$

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 8.1.1.3.

TABLE 3 Values of 1/β and $t_{y\beta}$ used in plotting Fig. 5, (1)

1/β	$t_{y\beta}$
2.50×10^{-1}	4.52×10^{-1}
1.67×10^{-1}	4.55×10^{-1}
2.00×10^{-1}	4.59×10^{-1}
2.50×10^{-1}	4.67×10^{-1}
3.33×10^{-1}	4.81×10^{-1}
4.00×10^{-1}	4.94×10^{-1}
5.00×10^{-1}	5.13×10^{-1}
6.67×10^{-1}	5.45×10^{-1}
1.00×10^{0}	6.11×10^{-1}
1.25×10^{0}	6.60×10^{-1}
1.67×10^{0}	7.39×10^{-1}
2.50×10^{0}	8.93×10^{-1}
5.00×10^{0}	1.31×10^{0}
1.00×10^{1}	2.10×10^{0}
1.67×10^{1}	3.10×10^{0}
3.33×10^{1}	5.42×10^{0}
1.00×10^{2}	1.42×10^{1}
2.50×10^{2}	3.22×10^{1}
1.00×10^{3}	1.23×10^{2}

[A] Values were obtained from Ref **(2)** by setting $\sigma = 10^{-9}$.



From Neuman (5)

NOTE 1—From Ref **(1)**.

FIG. 5 Values of 1/β Versus $t_{y\beta}$ for Fully Penetrating Wells

8.1.2.3 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:

$$T = 2.30\, Q/4\pi\Delta s_e \tag{19}$$

$$S = 2.25\, T\,(t/r^2)_e \tag{20}$$

8.1.2.4 The slope of the line should be the same as the one computed in 8.1.2.1; that is, the transmissivity should be the same. If not, the type-curve method in 8.1.1 must be used to compute the storage coefficient.

8.1.2.5 A hypothetical example of the use of the semilogarithmic method is shown in Fig. 1. In this example a control well is discharged at 0.01 $m^3\,s^{-1}$, and water levels are measured in a fully penetrating observation Well One (r = 4.5 m), Well Two (r = 7.5 m), and Well Three (r = 18 m). The change in drawdown over one log cycle of time for the late data, Δs_l, is 8.2 m. The intersection of a line through the late data with the $s = 0$ axis, $(t/r^2)_l$, is 200 $m^{-2}s$. The transmissivity and specific yield calculated from Eq 16 and Eq 17 are as follows:

$$T = 2.30\, Q/4\pi\Delta s_l = (2.30 \times 0.01\ m^3\, s^{-1})/(4 \times 3.14 \times 8.2\ m) = 2.23 \times 10^{-4}\ m^2\, s^{-1}$$

$$S_y = 2.25\, T\,(t/r^2)_l = 2.25\,(2.23\times 10^{-4}\ m^2\, s^{-1})(200\ m^{-2}\, s) = 0.10$$

8.1.2.6 From the intersection of the horizontal parts of the data plot with the late-time part, a value of t_β/r^2 of 6100 $m^{-2}s$ was determined for Well One, 2250 $m^{-2}s$ for Well Two, and 700 $m^{-2}s$ for Well Three. From Eq 18, a value of $t_y\beta$ is calculated for Well One as follows:

$$t_{y\beta} = (T/S_y)(t_\beta/r^2) = [(2.23 \times 10^{-4}\ m^2 s^{-1})/](6100\ m^{-2}s) = 14$$

Similar calculations yield values of $t_y\beta$ of 5 for Well Two and 1.6 for Well Three. From Fig. 5 an approximate value of 100 is estimated for 1/β for Well One, 31 for Well Two, and 6 for Well Three.

8.1.2.7 The change in drawdown for one log cycle of time divided by radius squared for early time data, Δs_e, is 8.2 m. The transmissivity calculated from the early data using Eq 19 is therefore the same as that calculated from the late data:

$$T = 2.30\, Q/4\pi\Delta s_e = (2.30 \times 0.01\ m^3 s^{-1})/(4 \times 3.14 \times 8.2\ m) = 2.23 \times 10^{-4}\ m^2 s^{-1}$$

8.1.2.8 The intersection of the early data with the horizontal axis at $s = 0$, $(t/r^2)_e$, is 1.2 $m^{-2}s$, so from Eq 20 the storage coefficient is as follows:

$$S = 2.25\, T\,(t/r^2)_e = 2.25\,(2.23 \times 10^{-4} m^2 s^{-1})(1.2\ m^{-2}s) = 6 \times 10^{-4}$$

9. Report

9.1 *Preparation*—Prepare a report including the following information. The report of the analysis will include information from the field testing procedure.

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the Neuman method for an unconfined, anisotropic aquifer. Summarize the field geohydrologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells and piezometers, the method of measurement of discharge and water levels, and the duration of the test and pumping rates. Discuss the rationale for selecting the Neuman method.

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site. Interpret and describe the hydrogeology of the site as it pertains to the selection of this test method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Scope of Aquifer Test*:

9.1.3.1 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened interval, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells or piezometers.

9.1.3.2 *Instrumentation*—Report the field instrumentation for observing water levels, pumping rate, barometric pressure changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test; the manufacturer's name, model number, and basic specifications for each major item; and the name and date of the last calibration, if applicable.

9.1.3.3 *Testing Procedures*—State the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.4 *Presentation and Interpretation of Test Results*:

9.1.4.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for pretest trends, and calculation of drawdown and residual drawdown.

9.1.4.2 *Data Plots*—Present data plots used in analysis of the data. Show data plots with all values of β, all match points, and all match-point values.

9.1.4.3 Evaluate qualitatively the overall accuracy of the test on the basis of the adequacy of instrumentation and observations of stress and response, and the conformance of the hydrogeologic conditions and the conformance of the test to the assumptions of this test method.

10. Precision and Bias

10.1 *Precision*—It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses.

10.2 *Bias*—No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 anisotropic aquifers; aquifers; aquifer tests; control wells; ground water; hydraulic properties; observation wells; transmissivity; unconfined aquifers

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