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

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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.

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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

Condition	Answer	Test Methods
FRACTURED AQUIFER	—yes→	**Fractured Aquifer, Sec. 5.3.6** Gringarten and Ramey (33) Barenblatt et al (34) Boulton and Streltsova (35) Moench (36)
↓ no		
SINGLE AQUIFER	—no→	**Multiple Aquifers, Sec. 5.3.5** Bennett and Patten (28) Hantush (29) Neuman and Witherspoon (30, 31) Javendel and Witherspoon (32)
↓ yes		
ISOTROPIC AQUIFER	—no→	**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)
↓ yes		
LATERAL BOUNDARY	—yes→	**Bounded Aquifer, Sec. 5.3.4** Ferris et al (25) Lohman (27) Stallman (26) D 5270
↓ no		
CONFINED AQUIFER	—no→	**Unconfined Aquifer, Sec. 5.4** Constant Discharge, Sec. 5.3.1: Boulton (37, 38, 39); Neuman (40, 41, 42); D 18.21.92.01; D 18.21.04.94.09 Slug Test, Sec. 5.4.2: Bouwer and Rice (43); Bouwer (44); D 18.21.04.94.02; D 18.21.95.01; D 5785
↓ yes		
LEAKY AQUIFER	—no→	**Confined Aquifer, Sec. 5.3.1** Constant Discharge, Sec. 5.2.1.1: Theis (1); D 5472; D 4106; D 4105; Cooper and Jacob (2); Jacob (3); D5269 Slug Test Sec. 5.3.1.4: Hvorslev (12); Cooper et al (14); D 4104; D 18.21.04.92; D 18.21.04.95.01; D4631 Variable Discharge, Sec. 5.2.1.2: Stallman (4); Hantush (6); Abu-Zied and Scott (8); Aron and Scott (8); Lai et al (9); Moench (5); Birsoy and Summers (45) Constant Head Sec. 5.3.1.3: Jacob and Lohman (10); Hantush (6); Rushton and Rathod (11); D 18.21.91.02; D4630
↓ yes		
STORAGE IN CONFINING	—no→	**Without Storage, Sec. 5.3.2.1** Hantush and Jacob (19)
	yes →	**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

[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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