Designation: D4105/D4105M – 20

Standard Practice for (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 D4105/D4105M; 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 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 practice is a shortcut procedure used to apply the Theis nonequilibrium method. The Theis method is described in Practice D4106.

1.2 This practice, along with others, is used in conjunction with the field procedure given in Test Method D4050.

1.3 *Limitations*—The limitations of this practice are primarily related to the correspondence between the field situation and the simplifying assumptions of this practice (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 All observed and calculated values shall conform to the guidelines for significant digits and rounding established in Practice D6026.

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

1.5 *Units*—The values stated in either SI Units or inch-pound units are to be regarded separately as standard. The values in each system may not be exact equivalents; therefore each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the standard. Reporting of results in units other than SI shall not be regarded as nonconformance with this practice.

1.6 *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 the 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 the 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.*

1.7 *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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D653 Terminology Relating to Soil, Rock, and Contained Fluids

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

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

[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 Groundwater and Vadose Zone Investigations.

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

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

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

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

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions:*

3.1.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *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—dimensionless storage coefficient.

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.

3.2.12 u—dimensionless time parameter.

4. Summary of Practice

4.1 This practice describes an analytical procedure for analyzing data collected during a withdrawal or injection well test. The field procedure (see Test Method D4050) 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:

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

where:

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

and:

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

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:

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

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

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

and:

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

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**)

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

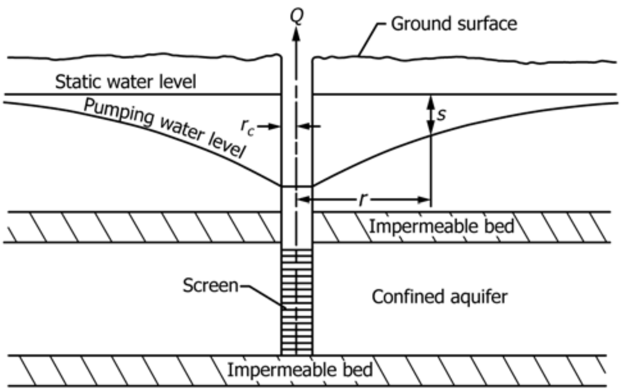

FIG. 1 Cross Section Through a Discharging Well in a Nonleaky Confined Aquifer

$$r = \frac{1.5b}{\sqrt{\frac{K_z}{K_{xy}}}} \tag{7}$$

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:

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

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:

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

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

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

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.

NOTE 2—The quality of the result produced by this standard is dependent on the competence of the personnel performing it, and the suitability of the equipment and facilities used. Agencies that meet the criteria of Practice D3740 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with Practice D3740 does not in itself assure reliable results. Reliable results depend on many factors; Practice D3740 provides a means of evaluating some of those factors.

NOTE 3—The injection of water into an aquifer may be regulated or require regulatory approvals. Withdrawal of contaminated waters may require that the removed water be properly treated prior to discharge.

6. Apparatus

6.1 Analysis of data from the field procedure (see Test Method D4050) by this practice 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 *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