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

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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:

3.2.1 b [L]—aquifer thickness.

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

[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.

3.2.2.1 *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:

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

$$s' = \frac{Q}{4\pi T}\,ln(t/t') \qquad (3)$$

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 constant rate $Q_1, Q_2 \ldots Q_n$.

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.