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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[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.

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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^2T^{-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)**.

$$\frac{d}{dt}\int_{-m}^{0} \pi r_s^2 p v_d z = [-pv_2^2 + p_1 - p_2 - pgm]\pi r_s^2 \tag{3}$$

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)**.

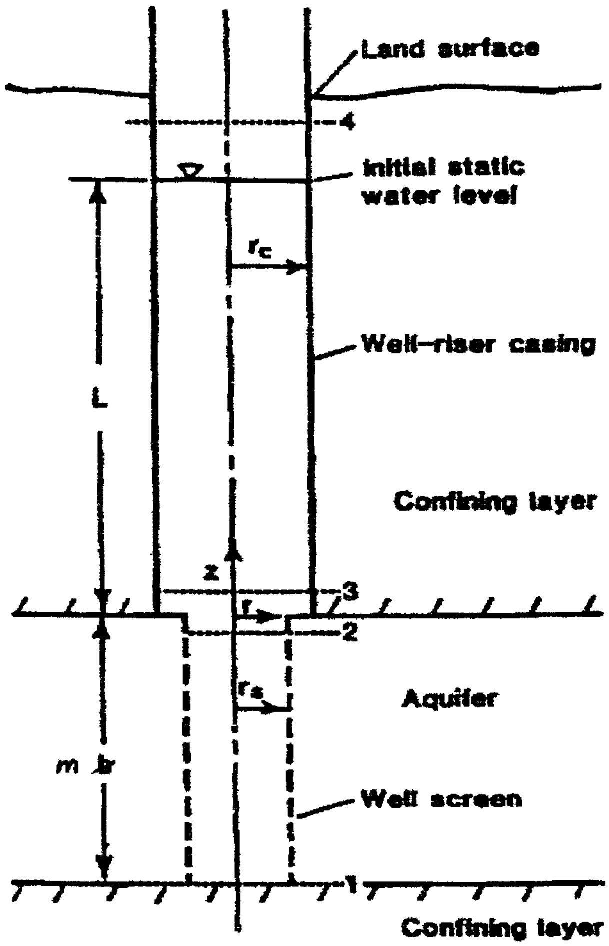

FIG. 1 Well and Aquifer Geometry

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:

$$d = \gamma/(g/L)^{1/2} \tag{21}$$

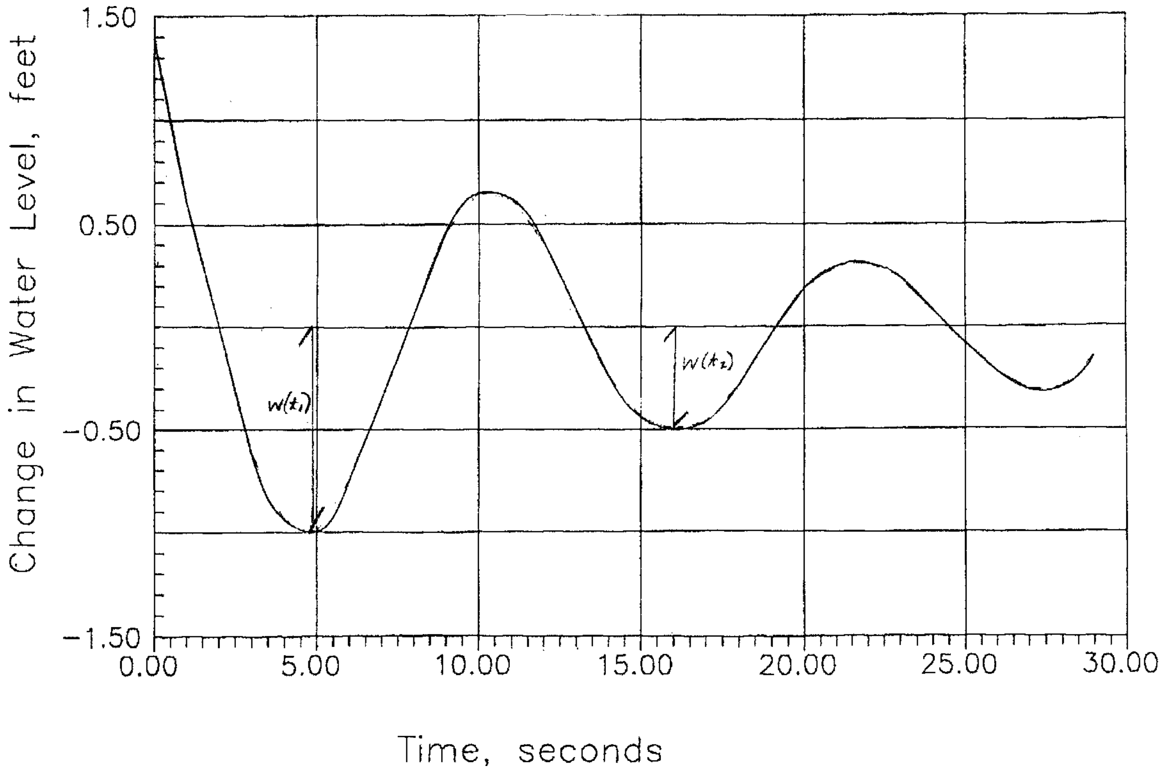

FIG. 2 Underdamped Response of Water Level to a Sudden Change in Head

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

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