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.

[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.

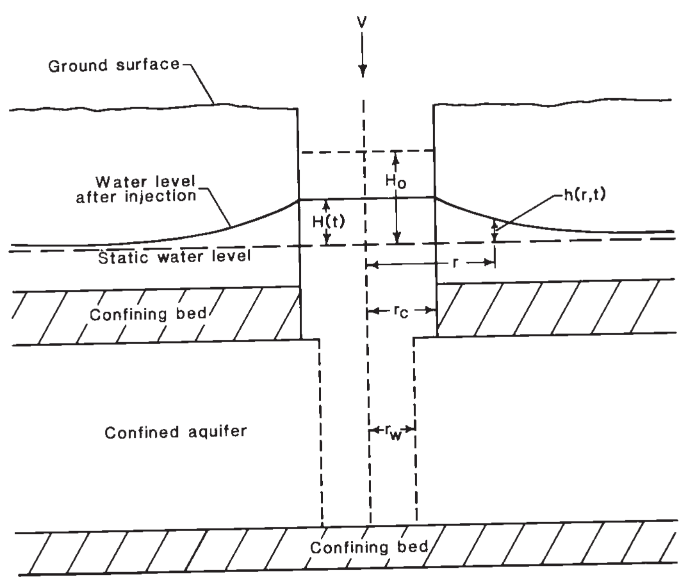

FIG. 1 Cross Section Through a Well in Which a Slug of Water is Suddenly Injected

[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}
	1.00	0.9771	0.9920	0.9969	0.9985	0.9992
10^{-3}	2.15	0.9658	0.9876	0.9949	0.9974	0.9985
	4.64	0.9490	0.9807	0.9914	0.9954	0.9970
	1.00	0.9238	0.9693	0.9853	0.9915	0.9942
10^{-2}	2.15	0.8860	0.9505	0.9744	0.9841	0.9883
	4.64	0.8293	0.9187	0.9545	0.9701	0.9781
	1.00	0.7460	0.8655	0.9183	0.9434	0.9572
10^{-1}	2.15	0.6289	0.7782	0.8538	0.8935	0.9167
	4.64	0.4782	0.6436	0.7436	0.8031	0.8410
	1.00	0.3117	0.4598	0.5729	0.6520	0.7080
10^{0}	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
	1.00	0.03065	0.03780	0.04821	0.06355	0.08378
	1.40	0.02092	0.02414	0.02844	0.03492	0.04426
10^{1}	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
	1.00	0.002577	0.002618	0.002653	0.002688	0.002725
10^{2}	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}
	1	0.9994	0.9996	0.9996	0.9997	0.9997
	2	0.9989	0.9992	0.9993	0.9994	0.9995
10^{-3}	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
	1	0.9956	0.9965	0.9971	0.9975	0.9978
	2	0.9919	0.9934	0.9944	0.9952	0.9958
10^{-2}	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
	1	0.9655	0.9712	0.9753	0.9784	0.9807
	2	0.9361	0.9459	0.9532	0.9587	0.9631
10^{-1}	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
	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
10^{0}	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
	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
10^{1}	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
	1	0.002763	0.002803	0.002845	0.002890	0.002938
10^{2}	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

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(**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.

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(**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.