Designation: D6034 – 17

Standard Test Method (Analytical Procedure) for Determining the Efficiency of a Production Well in a Confined Aquifer from a Constant Rate Pumping Test[1]

This standard is issued under the fixed designation D6034; 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 describes an analytical procedure for determining the hydraulic efficiency of a production well in a confined aquifer. It involves comparing the actual drawdown in the well to the theoretical minimum drawdown achievable and is based upon data and aquifer coefficients obtained from a constant rate pumping test.

1.2 This analytical procedure is used in conjunction with the field procedure, Test Method D4050.

1.3 The values stated in inch-pound units are to be regarded as standard, except as noted below. The values given in parentheses are mathematical conversions to SI units, which are provided for information only and are not considered standard.

1.3.1 The gravitational system of inch-pound units is used when dealing with inch-pound units. In this system, the pound (lbf) represents a unit of force (weight), while the unit for mass is slugs.

1.4 *Limitations*—The limitations of the technique for determination of well efficiency are related primarily to the correspondence between the field situation and the simplifying assumption of this test method.

1.5 All observed and calculated values shall conform to the guidelines for significant digits and round established in Practice D6026, unless superseded by this standard.

1.5.1 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 date to be commensurate with these considerations. It is beyond the scope of this standard to consider significant digits used in analysis method for engineering design.

1.6 *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:*[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

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

D5521 Guide for Development of Groundwater Monitoring Wells in Granular Aquifers

D6026 Practice for Using Significant Digits in Geotechnical Data

3. Terminology

3.1 *Definitions*—For definitions of common terms used in this test method, see Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *well efficiency, n*—the ratio, usually expressed as a percentage, of the measured drawdown inside the control well divided into the theoretical drawdown which would occur in the aquifer just outside the borehole if there were no drilling damage, that is, no reduction in the natural permeability of the sediments in the vicinity of the borehole.

3.3 *Symbols:*

3.3.1 *Symbols and Dimensions:*

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

[1] This test method 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**

3.3.2.1 *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 soil and rock mechanics and soil science.

3.3.3 K_r—hydraulic conductivity in the plane of the aquifer, radially from the control well (horizontal hydraulic conductivity) [LT^{-1}].

3.3.4 K_z—hydraulic conductivity normal to the plane of the aquifer (vertical hydraulic conductivity) [LT^{-1}].

3.3.5 $K_0\ (x)$—modified Bessel function of the second kind and zero order [nd].

3.3.6 Q—discharge [L^3T^{-1}].

3.3.7 S—storage coefficient [nd].

3.3.8 T—transmissivity [L^2T^{-1}].

3.3.9 s_r—drawdown in the aquifer at a distance *r* from the control well [*L*].

3.3.10 s_f—drawdown which would occur in response to pumping a fully penetrating well [*L*].

3.3.11 r_w—borehole radius of control well [*L*].

3.3.12 s_{rw}—theoretical drawdown which would occur in the aquifer just outside the borehole if there were no drilling damage, that is, no reduction in the natural permeability of the sediments in the vicinity of the borehole [*L*].

3.3.13 s_w—drawdown measured inside the control well [*L*].

3.3.14 u—$(r^2S)/(4Tt)$[nd].

3.3.15 $W(u)$—an exponential integral known in hydrology as the Theis well function of *u* [nd].

3.3.16 A—K_z/K_r, anisotropy ratio [nd].

3.3.17 b—thickness of aquifer [*L*].

3.3.18 d—distance from top of aquifer to top of screened interval of control well [*L*].

3.3.19 d'—distance from top of aquifer to top of screened interval of observation well [*L*].

3.3.20 f_s—incremental dimensionless drawdown component resulting from partial penetration [nd].

3.3.21 l—distance from top of aquifer to bottom of screened interval of control well [*L*].

3.3.22 l'—distance from top of aquifer to bottom of screened interval of observation well [*L*].

3.3.23 r—radial distance from control well [*L*].

3.3.24 t—time since pumping began [*T*].

3.3.25 E—well efficiency [nd].

4. Summary of Test Method

4.1 This test method uses data from a constant rate pumping test to determine the well efficiency. The efficiency is calculated as the ratio of the theoretical drawdown in the aquifer just outside the well bore (s_{r_w}) to the drawdown measured inside the pumped well (s_w). The theoretical drawdown in the aquifer (s_{r_w}) is determined from the pumping test data by either extrapolation or direct calculation.

4.2 During the drilling of a well, the hydraulic conductivity of the sediments in the vicinity of the borehole wall is reduced significantly by the drilling operation. Damaging effects of drilling include mixing of fine and coarse formation grains, invasion of drilling mud, smearing of the borehole wall by the drilling tools, and compaction of sand grains near the borehole. The added head loss (drawdown) associated with the permeability reduction due to drilling damage increases the drawdown in the pumped well and reduces its efficiency (see Fig. 1). Well development procedures help repair the damage (see Guide D5521) but generally cannot restore the sediments to their original, natural permeability.

4.2.1 Additional drawdown occurs from head loss associated with flow through the filter pack, through the well screen and vertically upward inside the well casing to the pump intake. While these drawdown components contribute to inefficiency, they usually are minor in comparison to the head loss resulting from drilling damage.

4.2.2 The well efficiency, usually expressed as a percentage, is defined as the theoretical drawdown, also called aquifer drawdown, which would have occurred just outside the well if there were no drilling damage divided by the actual drawdown inside the well. The head losses contributing to inefficiency generally are constant with time while aquifer drawdown gradually increases with time. This causes the computed efficiency to increase slightly with time. Because the efficiency is somewhat time dependent, usually it is assumed that the well efficiency is the calculated drawdown ratio achieved after one day of continuous pumping. It is acceptable, however, to use other pumping times, as long as the time that was used in the efficiency calculation is specified. The only restriction on the pumping time is that sufficient time must have passed so that wellbore storage effects are insignificant. In the vast majority of cases, after one day of pumping, the effects of wellbore storage have long since become negligible.

4.2.3 Efficiency is also somewhat discharge dependent. Both the aquifer drawdown and the inefficiency drawdown can include both laminar (first order) and turbulent (approximately second order) components. Because the proportion of laminar versus turbulent flow can be different in the undisturbed aquifer than it is in the damaged zone and inside the well, the aquifer

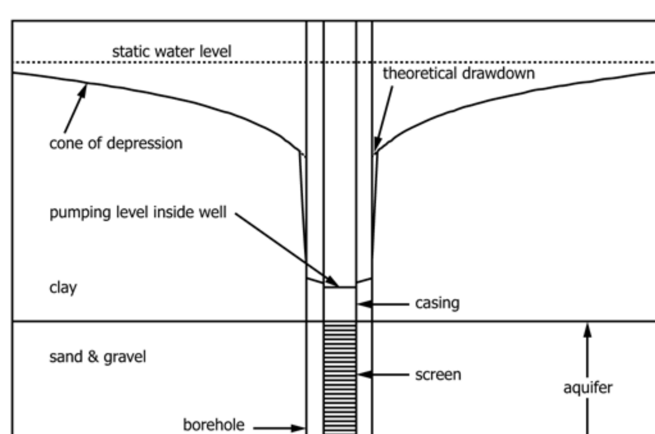

FIG. 1 Illustration of Drawdown Inside and Outside Pumping Well

drawdown and inefficiency drawdown can increase at different rates as Q increases. When this happens, the calculated efficiency is different for different pumping rates. Because of this discharge dependence, efficiency testing usually is performed at or near the design discharge rate.

4.3 The drawdown in the aquifer around a well pumped at a constant rate can be described by one of several equations.

4.3.1 For fully penetrating wells, the Theis equation (**1**)[3] is used.

$$s_r = \frac{Q}{4\pi T} W(u) \tag{1}$$

where:

$$W(u) = \int_u^\infty \frac{e^{-x}}{x}\, dx \tag{2}$$

and

$$u = \frac{r^2 S}{4Tt} \tag{3}$$

4.3.2 For sufficiently small values of u, the Theis equation may be approximated by the Cooper-Jacob equation (**2**).

$$s_r = \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2 S}\right) \tag{4}$$

4.3.2.1 Examples of errors in this approximation for some u values are as follows:

u	Error
0.01	0.25 %
0.03	1.01 %
0.05	2.00 %
0.10	5.35 %

4.3.3 For partially penetrating wells, the drawdown can be described by either the Hantush equation (**3-5**) or the Kozeny equation (**6**).

4.3.3.1 The Hantush equation is similar to the Theis equation but includes a correction factor for partial penetration.

$$s_r = \frac{Q}{4\pi T} \left(W(u) + f_s\right) \tag{5}$$

4.3.3.2 According to Hantush, at late pumping times, when $t > b^2 S/(2TA)$, f_s can be expressed as follows:

$$f_s = \frac{4b^2}{\pi^2 (l-d)(l'-d')} \sum_{n=1}^{\infty} \left(\frac{1}{n^2}\right) K_0\left(\frac{n\pi r\sqrt{K_z/K_r}}{b}\right) \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right]\left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right)\right] \tag{6}$$

4.3.3.3 The Kozeny equation is as follows:

$$s_r = \frac{s_f}{\frac{l-d}{b}\left(1 + 7\sqrt{\frac{r}{2(l-d)}}\cos\frac{\pi(l-d)}{2b}\right)} \tag{7}$$

4.3.3.4 In this equation, s_f is the drawdown for a fully penetrating well system and can be computed from Eq 1-4. While easier to compute than the Hantush equation, the Kozeny equation is not as accurate. It does not incorporate pumping time or anisotropy and assumes that the screen in the control well reaches either the top or the bottom of the aquifer.

4.3.4 The presence of a positive boundary (for example, recharge) causes the drawdown in the aquifer to be less than predicted by Eq 1-6, while a negative boundary (for example, the aquifer pinching out) results in more drawdown. The boundary-induced increases or decreases in drawdown usually can be determined from the pumping test data. These increases/decreases can be combined with calculations using Eq 1-7 to determine the drawdown just outside the well bore.

4.4 The efficiency of a production well is calculated as follows:

$$E = \frac{s_{r_w}}{s_w} \tag{8}$$

where:

s_w = denominator, the drawdown measured inside the well, and
s_{rw} = numerator, must be determined from field data.

Two procedures are available for determining s_{rw}—extrapolation and direct calculation.

4.4.1 *Extrapolation*—Extrapolation can be used to determine s_{r_w} if data from two or more observation wells are available. Distance drawdown data can be plotted from these wells on either log-log or semilog graphs. If a log-log plot is used, the Theis type curve is used to extrapolate the drawdown data to the borehole radius to determine s_{r_w}. If a semilog plot is used, extrapolation is done using a straight line of best fit. The semilog method can be used only if the u value for each observation well is sufficiently small that the error introduced by the log approximation to the Theis equation is minimal.

4.4.1.1 For partially penetrating wells, the observation wells must be located beyond the zone affected by partial penetration, that is, at a distance r from the pumped well such that:

$$r \geq \frac{1.5b}{\sqrt{K_z/K_r}} \tag{9}$$

4.4.1.2 The extrapolated drawdown obtained in this case is s_f, the theoretical drawdown, which would have occurred just outside the borehole of a fully penetrating pumped well. The aquifer drawdown corresponding to partial penetration is then computed with the Hantush equation as follows:

$$s_{r_w} = s_f + \frac{Q}{4\pi T} f_s \tag{10}$$

4.4.1.3 The second term on the right-hand side of Eq 10 represents the incremental aquifer drawdown caused by partial penetration.

4.4.1.4 Using the Kozeny equation, the aquifer drawdown for partial penetration is computed from Eq 7 with r set equal to the borehole radius r_w:

$$s_{r_w} = \frac{s_f}{\frac{l-d}{b}\left(1 + 7\sqrt{\frac{r_w}{2(l-d)}}\cos\frac{\pi(l-d)}{2b}\right)} \tag{11}$$

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