Wellbore Skin Effect in Slug-Test Data Analysis for Low-Permeability Geologic Materials

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Abstract

The wellbore skin effect on slug-test results was analyzed using numerical simulation and field tests for a well at progressive stages of development. The numerical simulation is based on a composite flow model that incorporates a zone of disturbed formation surrounding the wellbore. Field tests were performed on a water-bearing clayey silt formation at a ground-water remediation site in Wisconsin. Based on the numerical simulation, the radius of investigation was examined. The results show that the early-time and late-time data reflect ground-water flow in the wellbore skin and undisturbed formation, respectively.

Both the numerically simulated and the field slug-test data define a downward concave curve on a semilog plot of time versus the logarithm of dimensionless head. For the Hvorslev (1951) and Bouwer and Rice (1976) methods, the late-time segment of the simulated data yields estimates of hydraulic conductivity close to the value defined in the flow model. When a wellbore skin exists, the data curve in a plot of the logarithm of time versus the dimensionless head is shifted horizontally along the time axis. This shift leads to an inaccurate determination of hydraulic conductivity based on the Cooper et al. (1967) method. In the plots of time versus dimensionless head derivatives, the data curve geometry depends on the hydraulic properties of the wellbore skin. Consequently, the wellbore skin effect can be identified and eliminated using derivative-based type curve methods.

For low-permeability materials, the effect of wellbore skin on estimates of hydraulic conductivity can be minimized through use of the late-time data. However, proper well installation and development appears to be the most effective and practical solution.

Introduction

During well installation, a wellbore skin of finite thickness can develop between the well and formation. Auger rotation and retrieval can smear silt- and clay-sized sediments on the borehole wall. The smearing produces a positive wellbore skin that has lower hydraulic conductivity than the undisturbed formation (Driscoll, 1986; Paul, 1987). Conversely, extensive well development removes fine silt and clay particles from the surrounding formation, increases its hydraulic conductivity, and consequently forms a negative wellbore skin. For slug tests, the presence of a wellbore skin is one of several important factors that compromise model assumptions and thus affect the accuracy of slug-test results (Palmer and Paul, 1987).

When a wellbore skin exists, slug-test results can be more indicative of the hydraulic properties of the skin rather than those of the formation (Palmer and Paul, 1987; Faust and Mercer, 1984). Based on numerical modeling results, Hyder and Butler (1995) demonstrated that in the presence of a positive wellbore skin, the Bouwer and Rice (1976) method introduces error in the hydraulic conductivity estimate of more than two orders of magnitude. Moench and Hsieh (1985) and Faust and Mercer (1985) concluded that in a semilog plot of the logarithm of time versus dimensionless head, the type curves of Cooper et al. (1967) are horizontally shifted depending on the hydraulic conductivity of the wellbore skin. This shift leads to an inaccurate estimate of hydraulic conductivity.

Because the early-time data reflect wellbore storage, Bouwer (1989) suggested use of the intermediate-time data in data analysis based on the Bouwer and Rice (1976) method. However, in a numerical analysis to assess wellbore skin effects, Sageev (1986) concluded that for the Cooper et al. (1967) type curve method, intermediate-time data are the most sensitive to the skin effect. Furthermore, Jones (1993) observed that for unweathered Wisconsinan till in Iowa, late-time data yield hydraulic conductivity estimates comparable with the pumping test results. Apparently, these studies indicate that the wellbore skin effect can be minimized by using the proper data segment in the data analysis for low-permeability geologic materials. However, no agreement has been made in literature nor in practice on which data segment yields hydraulic conductivity estimates with little or no influence from the wellbore skin effect.

In this investigation, a numerical model was constructed for slug tests in a confined aquifer of low hydraulic conductivity. Simulations were conducted to assess the wellbore skin effect on dimensionless head in the slug-test well and the adjacent formation. Additionally, slug tests and a pumping test were performed in a semiconfined water-bearing clayey silt formation at a ground-water remediation site in Wisconsin. Both the numerical modeling and the field test results are presented to illustrate proper data selection and analysis techniques for low-permeability geologic materials.

Methods

Field Slug Test and Pumping Test

Contaminated ground water exists at a ground-water remediation site in Wisconsin. The semiconfined water-bearing formation is composed of interlayered clay and clayey silt. At the site, a ground-water monitoring system consists of twelve 5.1 cm diameter monitoring wells installed using hollow stem augers. For the purpose of performing a pumping test, a 10.2 cm diameter pumping well and three 5.1 cm diameter observation wells were installed using the same drilling method (Figure 1). Pre-existing monitoring well MW-2A was incorporated into the observation well network. The pumping well and four observa-

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tion wells were spaced at approximately 3.05 meter intervals and screened across the entire aquifer thickness.

Falling head slug tests were performed in the pumping well and in the 13 monitoring and observation wells. A data logger equipped with pressure transducers was used to record water-level changes during the slug tests. Each test lasted approximately 1100 seconds with varying time intervals between readings. To detect wellbore skin effects, three slug tests were performed for monitoring well MW-6 (Figure 1). The first test was run immediately following well installation. The second test was performed after the well was fully developed according to the U.S. EPA guidelines. The third slug test was conducted following further well development, during which a substantial amount of water, fine silt, and clay sediments were removed from the well. For the convenience of description, these three slug tests are labeled as MW-6A, MW-6B, and MW-6C for the absent, complete, and extensive well development, respectively.

A pumping test was conducted in an area approximately 100 meters away from the slug-test well MW-6 (Figure 1). A submersible diaphragm pump was used to pump the well at a rate of 0.025 liters/second. The pumping rate was monitored with a rotameter and electronically maintained throughout the test. Water levels in the pumping well and observation wells were measured and recorded using the data logger and pressure transducers. The pumping test consisted of 19.5 hours of well pumping followed by 10 hours of recovery.

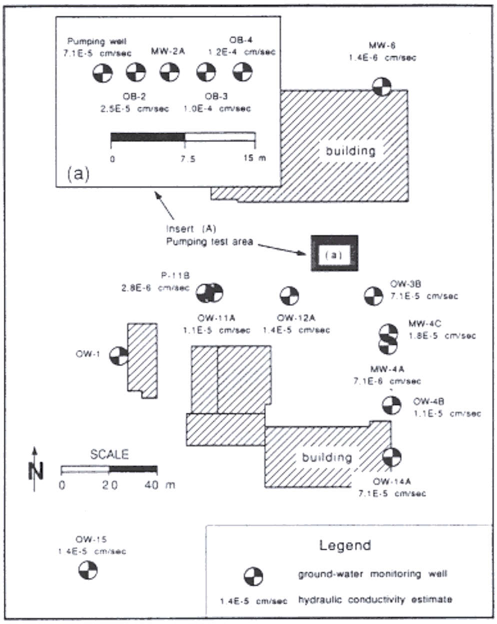

Fig. 1. Estimates of hydraulic conductivity using late-time slug-test data for the 13 monitoring wells and the pumping well at a ground- [illegible]

Numerical Model Definition

A numerical model was constructed and used to examine slug-test performance. For the well and aquifer configurations shown on Figure 2, the following assumptions are incorporated into the flow model: (1) vertical flow gradients are negligible; (2) aquifer is homogeneous and isotropic; and (3) aquifer properties remain constant throughout the test. Under these assumptions, the flow equations can be written as:

$$\frac{\partial^2 h_s}{\partial r^2} + \frac{1}{r}\frac{\partial h_s}{\partial r} = \frac{S_s}{T_s}\frac{\partial h_s}{\partial t} \qquad (r_w \leq r \leq r_s) \tag{1}$$

and

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (r_s \leq r \leq \infty) \tag{2}$$

where the subscripts s and w represent wellbore skin and testing well, respectively; r is distance from the well; t is time since initiation of the head change; S is storativity; T is transmissivity; and h is dimensionless head defined as:

$$h = \frac{H_o - H_{(t)}}{H_o - H_i} \tag{3}$$

where H_o is hydraulic head at ambient conditions. H_i and $H_{(t)}$ represent the head at time zero and at time t, respectively.

Initial and boundary conditions of the partial differential equations are as follows:

$$r_c^2\left(\frac{\partial h}{\partial t}\right)_{t=0} = 2\,K_s b r_w\left(\frac{\partial h}{\partial r}\right)_{r=rw} \tag{4}$$

$$K_s\left(\frac{\partial h_s}{\partial t}\right)_{r=rs} = K\left(\frac{\partial h}{\partial t}\right)_{r+rs} \tag{5}$$

$$h(\infty, t) = 0 \tag{6}$$

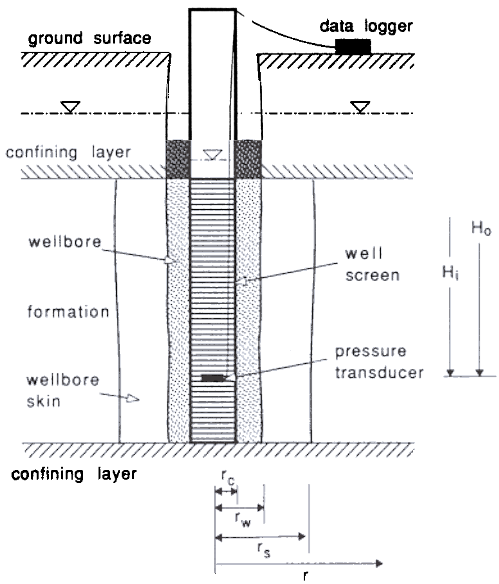

Fig. 2. Schematic diagram showing conceptualized slug test in a well surrounded by wellbore skin of a finite thickness. In the numerical simulation, the hydraulic conductivity and storativity are, respectively, 1.8 × 10^{-6} cm/sec and 0.01 for a positive wellbore skin, 1.8 × 10^{-5} cm/sec and 0.01 for undisturbed formation, and 1.8 × 10^{-4} cm/sec and 0.1 for a negative wellbore skin. Other modeling parameters include: r_c = 5.08 cm; r_w = 9.15 cm; and r_s = 30.5 cm.

$$h_t = h_w \qquad \text{at } r = r_w \tag{7}$$

$$h_o = 1 \qquad \text{at } r \leq r_w \text{ and } t = 0 \tag{8}$$

$$h_o = 0 \qquad \text{at } r > r_w \text{ and } t = 0 \tag{9}$$

where r_c is standpipe radius, and K is hydraulic conductivity.

Flow equations (1) and (2) were solved using the finite-element method under the initial and boundary conditions specified in equations (4) to (9). Other modeling parameters were determined with reference to the water-bearing formation at the remediation site. Based on the slug test and pumping test results, the approximately 6 to 7 meter-thick water-bearing formation has an average hydraulic conductivity of 1.8×10^{-5} cm/second and a storativity of 0.01.

As shown on Figure 2, the flow model accounts for the wellbore skin effect in a disturbed zone immediately surrounding the wellbore. The thickness of the disturbed zone depends on well installation and development methods. For model simplicity, the disturbed zone was assumed to have a thickness of 21.4 cm (9.1 cm $< r <$ 30.5 cm). When a positive wellbore skin is present, the zone was taken to have a decreased hydraulic conductivity at 1.8×10^{-6} cm/second and a storativity of 0.01. For a negative wellbore skin, the zone was assumed to have an increased hydraulic conductivity of 1.8×10^{-4} cm/second and a storativity of 0.1. When neither a negative, nor a positive wellbore skin exists, hydraulic conductivity and storativity of the zone were taken to be equal to those of the undisturbed formation.

Results

During the field pumping test, measurable drawdown occurred in the pumping well and in the nearest observation well OB-2. The time-drawdown data for OB-2 were analyzed using the Neuman (1975) method. which yields transmissivity and storativity estimates of 0.22 m^2/day and 0.01, respectively. The corresponding hydraulic conductivity is 1.2×10^{-4} cm/sec for a water-saturated thickness of 7.0 m in the pumping test area.

Pumping and recovery data for the pumping well and observation well OB-2 were analyzed using the Jacob method (Cooper and Jacob, 1946). The transmissivity estimates are 0.12 and 0.13 m^2/day for the pumping well and 0.55 and 0.48 m^2/day for the observation well OB-2. Based on the transmissivity and saturated thickness, the hydraulic conductivity of the formation was calculated. The average hydraulic conductivity is 1.8×10^{-4} cm/sec.

For the slug tests, hydraulic conductivity was estimated using the late-time data and the Bouwer and Rice (1976) method. The results show that hydraulic conductivity is greater in the pumping test area than in the other parts of the site (Figure 1). In the pumping test area, hydraulic conductivity estimates range from 2.5×10^{-5} to 1.2×10^{-4} cm/sec with an average of 7.9×10^{-5} cm/sec. These results are similar to the hydraulic conductivity values determined from the pumping test. In contrast, hydraulic conductivity values in other areas of the site range from 1.4×10^{-6} to 7.1×10^{-5} cm/sec with an average of 1.8×10^{-5} cm/sec (Figure 1).

Table 1 presents a partial list of the dimensionless head data for the three slug tests performed in the monitoring well MW-6. Based on the late-time data and the Bouwer and Rice (1976) method, hydraulic conductivity was determined to be 1.4×10^{-6}, 5.3×10^{-6}, and 1.4×10^{-6} cm/sec for MW-6A, MW-6B, and MW-6C, respectively. The value for complete well development (MW-6B) is approximately four times higher than the estimates for the slug tests at the absent and extensive well development (MW-6A and MW-6C).

Based on the composite flow model, numerical simulations were conducted for slug tests in the presence of the positive wellbore skin, undisturbed formation, and the negative wellbore skin. Each simulation yielded values of dimensionless head in the tested well and surrounding formation at the time from zero to 1100 seconds (Tables 2 and 3).

Discussions

For the water-bearing clayey silt formation at the remediation site, the pumping and slug tests yielded similar estimates of hydraulic conductivity only when the late-time ($t > 250$ seconds) slug-test data are used in the analysis. Similar observations have been derived in a comparison of the pumping and slug-test results for low-permeability Wisconsinan till in Iowa (Jones, 1993). Assuming that the pumping test results are accurate, the agreement indicates that the late-time slug test data are most indicative of ground-water flow in the undisturbed low-permeability formations. Therefore, using the late-time data may reduce the wellbore skin effect on the slug-test results. This possibility is examined in the following discussion.

Table 1. Selected Dimensionless Head Data for the Three Slug Tests in Monitoring Well MW-6

Well development					
Absent (MW-6A)				*Extensive (MW-6C)*	
t (sec)	*h*	*t (sec)*	*h*	*t (sec)*	*h*
	1.0000				1.0000
	0.9110				0.5186
	0.8856				0.5161
	0.8941				0.5112
	0.9025				0.5087
	0.8856				0.5087
	0.8856				0.5062
	0.8856				0.5062
	0.8856				0.5037
	0.8856				0.5037
	0.8856				0.5037
	0.8856				0.5037
	0.8856				0.5012
	0.8856				0.5012
	0.8856				0.5012
	0.8856				0.5012
	0.8856				0.4988
	0.8814				0.4988
	0.8814				0.4963
	0.8814				0.4963
	0.8771				0.4963
	0.8771				0.4963
	0.8729				0.4963
	0.8729				0.4963
	0.8729				0.4963
	0.8686				0.4938
	0.8686				0.4938
	0.8686				0.4913
	0.8644				0.4913
	0.8602				0.4888
	0.8602				0.4864
	0.8559				0.4839
	0.8517				0.4839
	0.8475				0.4814

Table 2. Selected Dimensionless Head Data in the Tested Well Computed for the Three Numerically Simulated Slug Tests*

Undisturbed formation		*Positive wellbore skin*		*Negative wellbore skin*	
t (sec)	*h*	*t (sec)*		*t (sec)*	*h*
	1.0000		1.0000		1.0000
	0.9801		0.9978		0.8179
	0.9632		0.9957		0.6905
	0.9484		0.9937		0.5979
	0.9351		0.9916		0.5281
	0.9230		0.9896		0.4738
	0.8966		0.9848		0.3799
	0.8739		0.9802		0.3195
	0.8538		0.9757		0.2772
	0.8356		0.9714		0.2457
	0.8188		0.9673		0.2211
	0.8032		0.9633		0.2014
	0.7887		0.9594		0.1852
	0.7750		0.9556		0.1716
	0.7497		0.9485		0.1500
	0.7268		0.9417		0.1336
	0.7057		0.9352		0.1207
	0.6862		0.9291		0.1103
	0.6680		0.9232		0.1019
	0.6056		0.9017		0.0802
	0.5550		0.8828		0.0694
	0.5126		0.8657		0.0636
	0.4763		0.8501		0.0603
	0.4447		0.8356		0.0583
	0.3811		0.8033		0.0555
	0.3328		0.7750		0.0539
	0.2949		0.7497		0.0526
	0.2644		0.7268		0.0515
	0.2395		0.7057		0.0506
	0.2187		0.6861		0.0497
	0.2012		0.6678		0.0489

*In the modeling, hydraulic conductivity and storativity are, respectively, 1.8E(−5) cm/sec and 0.01 for undisturbed formation, 1.8E(−4) cm/sec and 0.1 for the negative wellbore skin, and 1.8E(−6) and 0.01 for the positive wellbore skin.

Radius of Influence of a Slug Test

Based on the numerical simulation data, dimensionless head profiles across the slug-test well were constructed (Figure 3). For the undisturbed formation, dimensionless head change during the early time is limited to the formation immediately adjacent to the wellbore (Figure 3a). The dimensionless head at a distance of 30.5 cm from the well is only 0.001 at 20 seconds. As well recovery proceeds, head changes propagate farther into the formation. At 900 seconds, for example, dimensionless head exceeds 0.055 in the formation 61 cm from the well.

When a wellbore skin exists, ground-water flow for time less than 20 seconds is restricted to the zone of disturbed formation (Figures 3b and 3c). As shown on Figure 3b, the influence of a positive wellbore skin is significant throughout a slug test. The dimensionless head in the skin ranges from 0.0008 to 0.874 at 20 seconds, and remains greater than 0.136 at 900 seconds. During the test, the gradient of dimensionless head remains significant in the skin. At 900 seconds, for example, the gradient ranges from 0.013 to 0057 cm^{-1}. The significant dimensionless head and its gradient in the skin indicate that even in late times, ground-water flow into or from the well depends on hydraulic properties of both the formation and the positive wellbore skin.

In the presence of a negative wellbore skin, water-level recovery in the well is accelerated in early times and significantly decelerated in late times (Figure 3c). Dimensionless head in the well decreases rapidly to 0.32 in the first 20 seconds, and remains at 0.05 at 900 seconds. Furthermore, the head difference between the well and the skin diminishes with time. The dimensionless head in the skin ranges from 0.0008 to 0.32 at 20 seconds, and from 0.0482 to 0.0496 at 900 seconds. The gradient at 900 seconds decreases significantly to a range of 2.5×10^{-5} to 1.05×10^{-3} cm^{-1}. The small dimensionless head and its gradient indicate that during late times, the negative skin with an increased hydraulic conductivity becomes a part of the wellbore.

Correlations of t Versus log(h)

Slug-test data for low-permeability geologic materials generally define a downward concave curve in a plot of time versus the logarithm of dimensionless head. For both the Hvorslev (1951) and Bouwer and Rice (1976) methods, the hydraulic conductivity estimate is positively related to the slope of a data array in the semilog plot.

As shown on Figure 4a, both the early-time and intermediate-time data have different slopes in the plot depending on hydraulic conductivity of the wellbore skin. Only the late-time data for $t > 400$ seconds yield consistent slopes in the plot that are less influenced by the presence of a wellbore skin. In the case of undisturbed formation surrounding the wellbore, the slope is -1.056×10^{-3} $second^{-1}$, from which the Bouwer and Rice (1976) method yields a hydraulic conductivity of 1.6×10^{-5} cm/sec. This estimate is close to the value of 1.8×10^{-5} cm/sec defined in the numerical model.

In the presence of a positive and negative wellbore skin, the slopes are -1.997×10^{-4} $second^{-1}$ and -3.053×10^{-4} $second^{-1}$,

Table 3. Selected Dimensionless Head Data Calculated in the Well and Adjacent Formation*

Distance	*Undisturbed formation Time (sec)*					*Negative wellbore skin Time (sec)*					*Positive wellbore skin Time (sec)*				
r (cm)	*20*	*100*	*300*	*600*	*900*	*20*	*100*	*300*	*600*	*900*	*20*	*100*	*300*	*600*	*900*
0	0.8739	0.668	0.4447	0.2949	0.2187	0.9802	0.9232	0.8356	0.7497	0.6861	0.3195	0.1019	0.0583	0.0526	0.0497
9.1	0.874	0.668	0.4447	0.2949	0.2187	0.9802	0.9232	0.8356	0.7497	0.6861	0.3196	0.1019	0.0583	0.0526	0.0497
15.2	0.2312	0.3789	0.3212	0.2381	0.1866	0.0122	0.1271	0.2893	0.3596	0.3748	0.1291	0.0841	0.0573	0.0523	0.0495
30.5	0.0008	0.0605	0.1379	0.1449	0.1316	0	2E-05	0.0019	0.0115	0.0224	0.0008	0.0374	0.0532	0.0506	0.0482
61.0	0	0.0002	0.0133	0.0406	0.0547	0	0	4E-05	0.0011	0.0041	0	0.0001	0.0068	0.0159	0.0202
91.4	0	0	0.0004	0.006	0.0146	0	0	0	6E-05	0.0005	0	0	0.0002	0.0027	0.0058
121.9	0	0	0	0.0005	0.0025	0	0	0	0	4E-05	0	0	0	0.0002	0.0011
152.4	0	0	0	2E-05	0.0003	0	0	0	0	0	0	0	0	1E-05	0.0001

*Dimensionless head $< 1E(-6)$ is assigned to be zero.

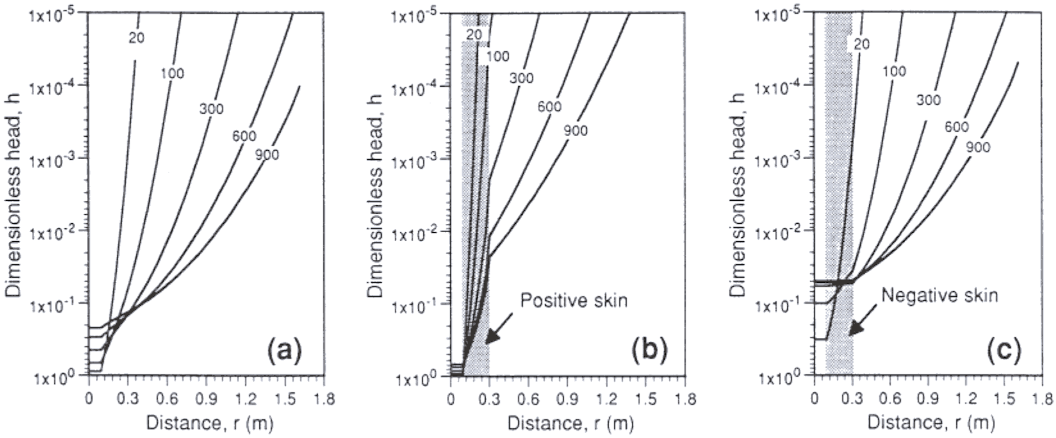

Fig. 3. Axisymmetric profile of dimensionless head across the tested well and formation at 20, 100, 300, 600, and 900 seconds: (a) in situ formation; (b) positive wellbore skin; and (c) negative wellbore skin. Patterned area indicates wellbore skin.

respectively (Figure 4a). The corresponding hydraulic conductivity estimates are 2.6×10^{-6} cm/sec and 3.9×10^{-6} cm/sec using the Bouwer and Rice (1976) method. These values are approximately five to seven times lower than the hydraulic conductivity of the formation.

Similar observations can be made for the field slug-test data. As shown on Figure 4b, the late-time ($t > 200$ seconds) data yield similar slopes in the plot for different degrees of well development. The slopes for absent, complete, and extensive well development are -3.521×10^{-5}, -1.258×10^{-4}, and -3.770×10^{-5} second^{-1}, respectively. Based on the Bouwer and Rice (1976) method, the corresponding estimates of hydraulic conductivity are 5.3×10^{-6}, and 1.4×10^{-6}, and 5.3×10^{-6} cm/sec.

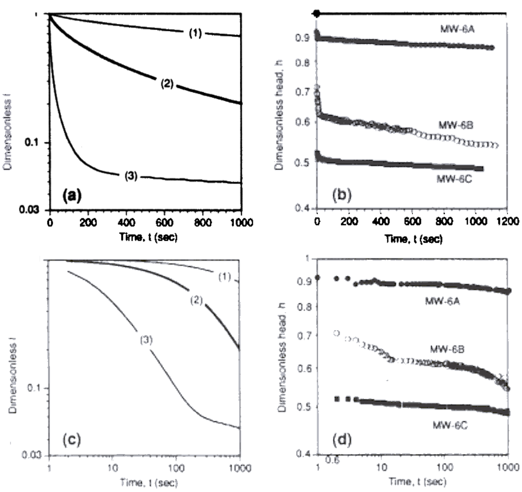

Fig. 4. Correlations between time and dimensionless head for the numerically simulated (a and c) and field-measured (b and d) slug-test data. Labels 1, 2, and 3 refer to, respectively, positive wellbore skin, undisturbed formation, and negative wellbore skin. MW-6A, MW-6B, and MW-6C are field slug tests at absent, complete, and extensive well development, respectively.

The smaller slope in the case of a positive wellbore skin is likely to be a result of retarded water-level recovery in the well. As shown on Figure 3b, dimensionless head and hydraulic gradient remain significant in the positive wellbore skin even during late times. Ground-water flow is a function of both the formation and the positive wellbore skin. Consequently, retardation of water-level recovery in the well results in a smaller slope in the semilog plot (Figure 3) and lower hydraulic conductivity estimates using the Bouwer and Rice (1976) and Hvorslev (1951) methods.

In the presence of a negative wellbore skin, the smaller slope of late-time data is related to the increased wellbore size and storage effect. During early times, storage release from the negative wellbore skin accelerates water-level recovery in the well and leads to a deeply concave curve in the semilog plot (Figure 4a). As the water-level recovery proceeds, the hydraulic gradient between the well and negative wellbore skin decreases (Figure 3c). The skin, which has an enhanced hydraulic conductivity and storativity, essentially becomes a part of the wellbore. The storage effect of the positive skin reduces the water-level recovery rate in the late times, leading to the smaller slope and lower hydraulic conductivity estimates.

Correlations of log(t) Versus h and log(t) Versus log(h)

In the log-log or semilog plot of dimensionless head versus time, slug-test data for low-permeability materials define "Z"-shape curves as shown on Figures 4c and 5. The log-log correlation is employed in the Nguyen and Pinder (1984) method, which relates storativity inversely to the slope of a linear curve segment (C_3). The correlation in the semilog plot is used in the Cooper et al. (1967) type curve method to determine the matching time value at $\beta = 1$. Hydraulic conductivity is inversely related to the matching time value, and storativity equals that of the matched type curve (Cooper et al., 1967).

Inspection of Figure 4c indicates that in the log-log plot, the numerically simulated data curves in the presence of a wellbore skin are horizontally shifted along the time axis relative to the data curve of undisturbed formation. This shift is less evident for the field data (Figure 4d). Despite the horizontal shift, the slope of the intermediate-time data remains unchanged. Consequently,

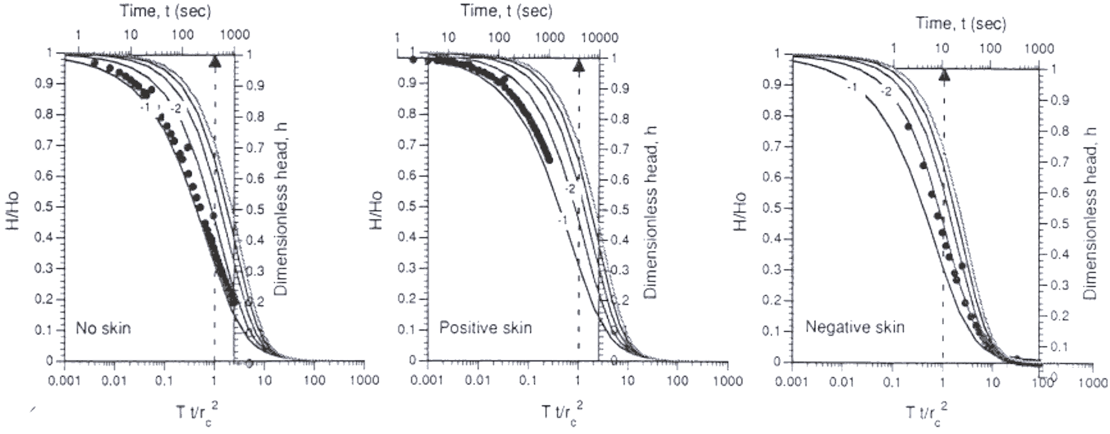

Fig. 5. Numerically simulated data in the semilog plot of dimensionless head versus the logarithm of time. Also shown are selected Cooper et al. (1967) type curves. Other labels in the diagram: −1 and −2 are the values of the parameter log(α).

the storativity estimate based on the Nguyen and Pinder (1984) method appears insensitive to the presence of a wellbore skin.

The wellbore skin effect on the Cooper et al. (1967) type curve method was examined using the numerical modeling data. As shown on Figure 5, the simulated data curves in the presence of negative and positive wellbore skins are shifted along the time axis relative to the data curve for undisturbed formation. This observation is consistent with the conclusions of Faust and Mercer (1984, 1985) and Sageev (1986).

The shifting changes the matching time value τ and subsequently affects the estimation of hydraulic conductivity (Figure 5). In response to the presence of a positive wellbore skin, the numerically simulated data are shifted to the left in the semilog plot. As a result, the time matching value is overestimated by approximately 10 times (Figure 5b), and hydraulic conductivity is significantly underestimated using the Cooper et al. (1967) method. The opposite conclusion can be derived for the influence of a negative wellbore skin. Additionally, as shown on Figure 5, the presence of either a positive or negative wellbore skin does not affect the data curve geometry. Therefore, the matched type curve and the storativity estimates remain relatively unchanged.

It is important to note that the horizontal shifting in both the semilog and log-log plots cannot be practically detected. The effect of a wellbore skin on hydraulic conductivity estimates is difficult to quantify using the Cooper et al. (1967) method. When existence of a wellbore skin is suspected, the type curve methods such as the Sageev (1986) that account for the wellbore skin effect should be employed in the data analysis.

Correlations of t Versus $\Delta h/\Delta t$

Correlations between time (t) and dimensionless head derivative ($\Delta h/\Delta t$) are used in slug-test models (i.e., Onur and Reynolds, 1988; Nguyen and Pinder, 1984; Ostrowski and Kloska, 1989). In the Nguyen and Pinder (1984) method, the hydraulic conductivity estimate is inversely related to the slope of a linear data segment (C_4) in the log-log plot. As shown on Figures 6a and 6b, the data curve geometry varies as a function of the hydraulic properties of a wellbore skin. Only the late-time data segment yields consistent slopes.

The log-log correlation of head derivatives versus time is used in the Ostrowski and Kloska (1989) type curve method. Sageev (1986) and Spane and Wurstner (1993) observed that type curves utilizing head derivatives have distinct geometries as a function of the hydraulic properties of the wellbore skin.

Similar observations can be made on both the numerically simulated and the field data. As shown on Figures 6c and 6d, the data curve geometry for the undisturbed formation is distinctively different from those in the presence of a positive or negative wellbore skin. When a positive wellbore skin exists, the dimensionless head derivative is small and fairly constant throughout a slug test. The small head derivative reflects retardation of water-level recovery in the well as the result of lower

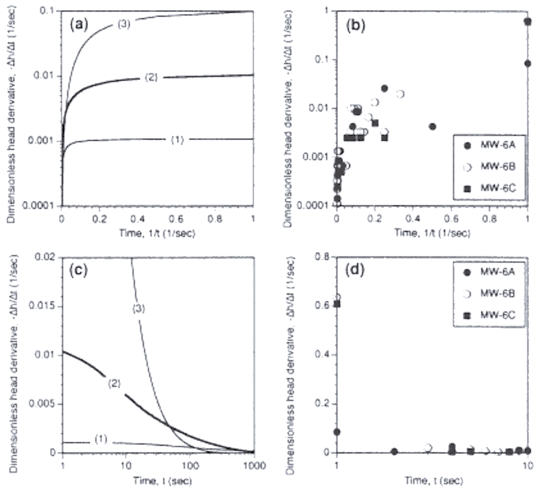

Fig. 6. Correlations of time versus dimensionless head derivative for the numerically simulated (a and c) and field-measured (b and d) slug-test data. Labels 1, 2, and 3 refer to, respectively, positive wellbore skin, undisturbed formation, and negative wellbore skin. MW-6A, MW-6B, and MW-6C are field slug tests at absent, complete, and extensive well development, respectively.

hydraulic conductivity of the positive skin (Figure 3b). Conversely, the dimensionless head derivative in the presence of a negative wellbore skin is large in the beginning of a slug test and rapidly decreases with time. This variation is considered to reflect the increased storage effect in the negative skin.

Conclusions

Numerical modeling and field slug-test results both demonstrate that a wellbore skin significantly affects water-level recovery at the well in low-permeability geologic materials. Water-level recovery is retarded in the presence of a positive wellbore skin compared to the undisturbed formation. Ground-water flow in early times is restricted in the skin. When a negative wellbore skin exists, water-level recovery is accelerated in the early time and decelerated in the late time due to the effects of enhanced skin storage. In all cases, the late-time data are closely reflective of ground-water flow in the undisturbed aquifer formation.

In the plot of time versus the logarithm of dimensionless head, the slope of late-time data is least affected by the existence of a wellbore skin. Based on the late-time data, the Hvorslev (1951) and Bouwer and Rice (1976) methods yield hydraulic conductivity estimates close to and slightly lower than the actual value of the formation. The underestimation is believed to be the result of delayed water-level recovery in the presence of a positive wellbore skin, or the increased storage effect of a negative skin.

In the semilog plot of dimensionless head versus the logarithm of time, the existence of a wellbore skin has no significant influence on the data curve geometry. Consequently, matched type curve and storativity estimates using the Cooper et al. (1967) method are insensitive to the skin effect. Additionally, a wellbore skin causes horizontal shifting of the data curve along time axis. When a negative wellbore skin exists, the shifting results in an apparently large matching time value and consequently a lower hydraulic conductivity estimate. The opposite conclusion can be made for the effect of a negative wellbore skin. It is important to note that the shifting and subsequent incorrect estimate of hydraulic conductivity cannot be detected and quantified using the Cooper et al. (1967) method. Under such circumstances, use of the Sageev (1986) type curve method is required to account for the skin effect.

Compared to dimensionless head, head derivatives are more sensitive to the presence of a wellbore skin. In the semilog plot utilizing the derivatives, slug-test data curves have distinctive geometries for the presence of undisturbed formation, negative and positive wellbore skin. Consequently, the skin effect can be identified and eliminated.

Nomenclature

H_o	hydraulic head at ambient condition.
H_i	hydraulic head at time zero.
$H_{(t)}$	hydraulic head at time t.
K	hydraulic conductivity.
r	distance from center of the slug-test well.
r_c	radius of the standpipe.
r_w	radius of the wellbore.
r_s	radius of the wellbore skin.
S	storativity.
t	time since the initiation of a head change in well.
T	transmissivity.

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