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A novel analytical solution for a slug test conducted in a well with a finite-thickness skin

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Abstract

An aquifer containing a skin zone is considered as a two-zone system. A mathematical model describing the head distribution is presented for a slug test performed in a two-zone confined aquifer system. A closed-form solution for the model is derived by Laplace transforms and Bromwich integral. This new solution is used to investigate the effects of skin type, skin thickness, and the contrast of skin transmissivity to formation transmissivity on the distributions of dimensionless hydraulic head. The results indicate that the effect of skin type is marked if the slug-test data is obtained from a radial two-zone aquifer system. The dimensionless well water level increases with the dimensionless positive skin thickness and decreases as the dimensionless negative skin thickness increases. In addition, the distribution of dimensionless well water level due to the slug test depends on the hydraulic properties of both the wellbore skin and formation zones.
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Keywords: Ground water; Slug test; Confined aquifer; Skin effect; Laplace transforms; Closed-form solution

1. Introduction

A slug test is one of the aquifer test methods commonly used to investigate aquifer parameters. The test involves an instantaneous removal/injection of a small volume of water from/into a well [7]. An instantaneous head change is thus imposed within a well and the recovery/falloff of water level is continuously measured using a pressure transducer that connects to a data logger. The aquifer parameters, e.g., transmissivity and storativity, can then be obtained if the slug-test data is analyzed.

Ferris and Knowles [12] originally introduced the analysis procedure from slug-test data. They derived an approximate solution for describing the water level change within the test well. The transmissivity is estimated based on a straight line, which represents residual head versus inverse time. Employing an electrical analog model of the well-aquifer system, Bredehoeft et al. [4] demonstrated that Ferris and Knowles' approximation is valid only for very late test time. Using the modified Thiem equation for the unconfined and steady state conditions, Bouwer and Rice [3] presented a procedure for determining the hydraulic conductivity or transmissivity for the unconfined aquifers. Using results from an electric analog model, they obtained two empirical formulas related to the effective radius for the partially and fully penetrating wells. Later, Bouwer [2] provided information on using Bouwer and Rice's method for testing the validity of falling level tests, the application of the method to the confined aquifers, the effect of well diameter, and the computer processing of field data. Cooper et al. [8] obtained a solution including the well storage analogous to a heat conduction problem provided by Carslaw and Jaeger [6]. Cooper et al. [8] applied their solution to a ground-water flow system and made a

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Nomenclature

T	Transmissivity
S	Storativity
r	Radial distance from the centerline of the well
r_w	Radius of the well
r_c	Radius of the standpipe
r_s	Radial distance from the well centerline to the outer skin envelope
t	Time from the start of the test
H	Hydraulic head distribution
H_0	Initial hydraulic head in the wellbore skin and formation zones
$\overline{H}$	Hydraulic head in the Laplace domain
q^2	pS/T
p	Laplace variable
$J_0(\cdot)$, $Y_0(\cdot)$	Bessel functions of the first and second kinds of order zero
$J_1(\cdot)$, $Y_1(\cdot)$	Bessel functions of the first and second kinds of order one
$I_0(\cdot)$, $K_0(\cdot)$	Modified Bessel functions of the first and second kinds of order zero
$I_1(\cdot)$, $K_1(\cdot)$	Modified Bessel functions of the first and second kinds of order one
κ	$\sqrt{T_1S_2/T_2S_1}$
ζ	T_2/T_1
η	S_2/S_1
α	$S_2r_w^2/r_c^2$
β	T_2t/r_c^2
ρ	r/r_w
ρ_c	r_c/r_w
ρ_s	r_s/r_w
$\bar{h}$	$\overline{H}/H_0$
h	H/H_0
λ_1^2	$\zeta p/\eta$
λ_2^2	p

Subscripts

1, 2	Wellbore skin, formation

family of type curves. They used a matching approach for the slug-test data to estimate aquifer parameters. However, the aquifer parameters obtained by this technique may be very rough because the shape of a type curve is rather insensitive to the value of aquifer storage [19], especially, if the storage is very small. Kipp [17] constructed a set of type curves that enables the well water level response data from the slug tests to be analyzed if the inertial parameter is large. Pandit and Miner [23] provided an automatic fitting procedure to determine the aquifer parameters when analyzing the slug-test data obtained from a confined aquifer. Marschall and Barczewski [20] presented an analysis of slug tests in the frequency domain for evaluating the solution of Cooper et al. [8]. Their solution is in terms of Kelvin functions [18], and the slug-test data is transformed using numerical Fourier transforms to determine aquifer parameters. Such an approach can avoid evaluating the integrand, which is an oscillatory function and difficult to evaluate.

Using the infinitesimally thin skin concept, Ramey and Agarwal [24] reported a solution to the drill-stem test (DST) problem with an inversion integral and related short- and long-time approximating forms. The skin effect describing the damage or improvement to the region surrounding a well is represented by a skin factor. Ramey et al. [25] presented semi- and double-log type curves, which combine the effects of the well storage and wellbore skin, to determine the formation permeability and skin effect by analyzing the slug-test data. Faust and Mercer [11] provided an infinite-aquifer solution for the response of slug tests to investigate the effect of a finite-thickness skin. They assumed that the skin has a much lower permeability than that of the adjacent formation. Under this condition, the skin effect can lead to very low estimates of hydraulic conductivity if using the type-curve fitting method of Cooper et al. [8]. Moench and Hsieh [21] commented on the evaluation of slug tests in a finite-thickness skin by Faust and Mercer [11]. They showed that when the specific storage of the skin is negligibly small, the finite-thickness skin solution becomes equivalent to the infinitesimally thin skin solution. Under a finite-thickness skin condition, the skin properties control the early time response, whereas the formation properties relate to the late time response. Further, Sageev [26] investigated the effects of the well storage and wellbore skin in a confined aquifer system. He obtained a similar result to that of Moench and Hsieh [21]. Karasaki et al. [16] developed various slug-tests models and related solutions for linear flow, radial flow with boundaries, two zone, and concentric composite aquifer systems. They provided type curves for each solution and noted that slug tests suffer the problem of non-uniqueness in matching the test data to type curves. Butler and Healey [5] investigated the estimate of hydraulic conductivity obtained through the pumping or slug test. They indicated that the hydraulic conductivity estimate from a pumping test is, on the average, larger than that from a series of slug test in the same formation.

An aquifer is considered as a radial two-zone (or composite) system if the formation properties near the well is apparently changed due to the well drilling or development. Well drilling causes the invasion of drilling

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