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Modeling cross-hole slug tests in an unconfined aquifer

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ABSTRACT

A modified version of a published slug test model for unconfined aquifers is applied to cross-hole slug test data collected in field tests conducted at the Widen site in Switzerland. The model accounts for water-table effects using the linearized kinematic condition. The model also accounts for inertial effects in source and observation wells. The primary objective of this work is to demonstrate applicability of this semi-analytical model to multi-well and multi-level pneumatic slug tests. The pneumatic perturbation was applied at discrete intervals in a source well and monitored at discrete vertical intervals in observation wells. The source and observation well pairs were separated by distances of up to 4 m. The analysis yielded vertical profiles of hydraulic conductivity, specific storage, and specific yield at observation well locations. The hydraulic parameter estimates are compared to results from prior pumping and single-well slug tests conducted at the site, as well as to estimates from particle size analyses of sediment collected from boreholes during well installation. The results are in general agreement with results from prior tests and are indicative of a sand and gravel aquifer. Sensitivity analysis show that model identification of specific yield is strongest at late-time. However, the usefulness of late-time data is limited due to the low signal-to-noise ratios.

1. Introduction

Slug tests are a common tool in hydrogeology for hydraulic characterization of aquifers because they are quick, obviate the need for waste water disposal, require less equipment, and are not as labor intensive as pumping tests. Fundamentally, they involve instantaneous (step) perturbation of fluid pressure in an interval followed by continuous monitoring of the pressure change as it dissipates by fluid flow through the aquifer. This is typically achieved by either dropping a slug mass into a well (Cooper et al., 1967) or pneumatically pressurizing the water column in a well (Butler, 1998; Malama et al., 2011), a configuration referred to as a single well test. Several mathematical models are available in the hydrogeology literature for analyzing confined (Cooper et al., 1967; Bredehoeft and Papadopulos, 1980; Zurbuchen et al., 2002; Butler and Zhan, 2004) and unconfined (Bouwer and Rice, 1976; Springer and Gelhar, 1991; Hyder et al., 1994; Spane, 1996; Zlotnik and McGuire, 1998; Malama et al., 2011) aquifer slug test data under the Darcian flow regime. Consideration of slug tests under non-Darcian flow regimes may be found in Quinn et al. (2013) and Wang et al. (2015).

Slug tests have the advantage of only involving limited contact with and minimal disposal of effluent formation water. As such, they have found wide application for characterizing heterogeneous formations at contaminated sites (Shapiro and Hsieh, 1998) and for investigating flow in fractured rock (Quinn et al., 2013; Ji and Koh, 2015; Ostendorf et al., 2015). However, the small volumes of water involved impose a physical limit on the volume of the formation interrogated during tests (Shapiro and Hsieh, 1998; Beckie and Harvey, 2002) because the resulting pressure perturbations often do not propagate far enough to be measurable in observation wells. As a result, hydraulic parameters estimated from single well slug-test data can only be associated with the formation volume within the immediate vicinity of the source well (Beckie and Harvey, 2002; Butler, 2005).

Cross-hole (or multi-well) slug tests are less common but have been applied to interrogate relatively large formation volumes in what has come to be known as hydraulic tomography (Yeh and Liu, 2000; Illman et al., 2009). For example, Vesselinov et al. (2001) and Illman and Neuman (2001) used pneumatic cross-hole injection tests to hydraulically characterized a fractured

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Nomenclature

a_i	finite Hankel transform parameter [–]
B	aquifer initial thickness [L]
b_s	length of source well test interval [L]
C_w	coefficient of wellbore storage [L^2]
d/d_o	depth of top of source/observation well test interval below watertable [L]
g	acceleration due to gravity [$L\,T^{-2}$]
H	hydraulic head change from equilibrium position in source well [L]
H_0	initial slug input [L]
K	formation hydraulic conductivity [$L\,T^{-1}$]
K_r	radial formation hydraulic conductivity [$L\,T^{-1}$]
K_z	vertical formation hydraulic conductivity [$L\,T^{-1}$]
K_{skin}	skin hydraulic conductivity [$L\,T^{-1}$]
l/l_o	depth of bottom of source/observation well test interval below watertable [L]
L/L_{obs}	characteristic length for source/observation well damping term [L]
$L_e/L_{e,\mathrm{obs}}$	characteristic length for source/observation well oscillatory term [L]
p	Laplace transform parameter [–]
r	radial coordinate, out from center of source well [L]
R	domain radius, out from center of source well [L]
r_c	radius of source well tubing at water-table [L]
r_w	radius of source well at test interval [L]
s	hydraulic head change from initial conditions [L]
S_s	specific storage [L^{-1}]
S_y	specific yield [–]
t	time since slug initiation [T]
T_c	characteristic time ($T_c = B^2/\alpha_{r,1}$) [T]
z	vertical coordinate, down from water-table [L]
$\alpha_{r,i}$	hydraulic diffusivity of i^{th} zone [$L^2\,T^{-1}$]
γ_s	source well damping coefficient [T^{-1}]
ν	kinematic viscosity of water [$L^2\,T^{-1}$]

unsaturated rock formation with dimensions of $30 \times 30 \times 30\ \mathrm{m}^3$. Barker and Black (1983) presented evidence of measurable pressure responses in observation wells several meters from the source well. Audouin and Bodin (2008) reported cross-hole slug tests conducted in fractured rock, where they collected data in observations wells at radial distances 30 to about 120 m from the source well, and observed maximum peak amplitudes ranging from 5 to 20 cm. This demonstrated empirically that slug test pressure perturbations can propagate over relatively large distances beyond the immediate vicinity of the source well, albeit for fractured rocks, which have high hydraulic diffusivities. Brauchler et al. (2010) attempted to intensively apply cross-hole slug tests to obtained a detailed image of confined aquifer heterogeneity. They used the model of Butler and Zhan (2004) to estimate aquifer hydraulic conductivity, specific storage and anisotropy. Cross-hole slug tests in unconfined aquifers, neglecting wellbore inertial effects, have been reported by Spane (1996), Spane et al. (1996), and Belitz and Dripps (1999) for source-to-observation well distances not exceeding 15 m.

Recently Paradis and Lefebvre (2013) and Paradis et al. (2014, 2015) analyzed synthetic cross-hole slug test data using a model for over-damped observation well responses. The need, therefore, still exists to analyze field data and characterize high permeability heterogeneous unconfined aquifers using cross-hole slug tests where source and observation well inertial effects may not be neglected. Malama et al. (2011) developed a slug test model for unconfined aquifers using the linearized kinematic condition of Neuman (1972) at the water-table, and accounting for inertial effects of the source well. They analyzed data from single-well tests performed in a shallow unconfined aquifer. This work extends the application of the model of Malama et al. (2011) to multi-well tests and to response data collected in observation wells. The data analyzed were collected at multiple vertical intervals in an observation well about 4 m from the source well, which itself was perturbed at multiple intervals. The model and data are used to estimate hydraulic conductivity, specific storage, and specific yield. The sensitivity of predicted model behavior to these parameters is also analyzed. In the following, the mathematical model is presented, the multi-level multi-well tests are described, and data analyzed. The work concludes with an analysis of the sensitivity coefficients for the hydraulic and well characteristic parameters.

2. Slug test model

Malama et al. (2011) developed a model for formation and source well response to slug tests performed in unconfined aquifers using the linearized kinematic condition at the water-table. The model allows for estimation of specific yield in addition to hydraulic conductivity and specific storage. The model also accounts for source-well wellbore storage and inertial effects. Wellbore storage in the source well is treated in the manner of Cooper et al. (1967). A schematic of the conceptual model used to derive the semi-analytical solution is shown in Fig. 1. Whereas the solution of (Malama et al., 2011) was obtained for and applied to source wells, here a more complete solution is presented that applies to observation wells. The complete aquifer response for both source and observation wells is given by (see Appendix A and Malama et al. (2011) for details)

$$\hat{\bar{s}}_D = \hat{\bar{u}}_D \begin{cases} \left[1 - \hat{\bar{v}}_D(d_D)\right]\hat{\bar{f}}_1(z_D) & \forall z_D \in [0, d_D] \\ 1 - \hat{\bar{v}}_D & \forall z_D \in [d_D, l_D] \\ \left[1 - \hat{\bar{v}}_D(l_D)\right]\hat{\bar{f}}_2(z_D) & \forall z_D \in [l_D, 1], \end{cases} \tag{1}$$

where $\hat{\bar{s}}_D$ is the double Laplace-Hankel transform of the dimensionless formation head response $s_D = s/H_0$, $d_D = d/B$ and $l_D = l/B$ are dimensionless depths to the top and bottom of the test interval, $z_D = z/B$ ($z \in [0, B]$) is dimensionless depth below the water-table, B is initial saturated thickness,

$$\hat{\bar{u}}_D = \frac{C_D(1 - p\overline{H}_D)}{\kappa\eta^2\xi_w \mathrm{K}_1(\xi_w)}, \tag{2}$$

$$\hat{\bar{v}}_D = \frac{\Delta_0(d_D)}{\Delta_0(1)} \cosh\left(\eta z_D^*\right) + \sinh\left(\eta_D^*\right) \frac{\Delta_0'(z_D)}{\eta\Delta_0(1)}, \tag{3}$$

$$\hat{\bar{f}}_1(z_D) = \frac{\Delta_0'(z_D)}{\Delta_0'(d_D)}, \tag{4}$$

$$\hat{\bar{f}}_2(z_D) = \frac{\cosh\left(\eta z_D^*\right)}{\cosh\left(\eta l_D^*\right)}, \tag{5}$$

$$\Delta_0(z_D) = \sinh(\eta z_D) + \varepsilon\cosh(\eta z_D), \tag{6}$$