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Analysis of partially penetrating slug tests in a stratified formation by alternating piezometer and tube methods

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SUMMARY

In partially penetrating slug tests, hydraulic conductivity (K) estimates might not necessarily be valid because of vertical flows in heterogeneous formations. We assess the error in hypothetical stratified formations by numerical sensitivity analysis, and propose an effective method for compensation by incorporating two types of casing configuration (piezometer and tube). The hypothetical stratified formation consists of completely horizontal layers, each 1 m thick; the permeability is different between, but not within, layers. In this study, conductivity estimates in the piezometer and tube methods are calculated by assigning various patterns of conductivity to the test, upper, and lower layers: K_T, K_U, and K_L. The effect of vertical flow becomes significant when K_T is small relative to K_U or K_L, and K_L is more important than K_U because the base of the borehole is open to the lower formation. The conductivity ratios (estimate over actual value) are treated as approximately linearly dependent on logarithms of K_T/K_U and K_T/K_L, so that conductivity estimates can be straightforwardly derived from one piezometer measurement and two tube measurements at the top and bottom of the screen. The linear relations are evaluated and constant parameters are determined under specific conditions. This study also recommends alternating piezometer and tube methods in the drilling procedure because the actual variation of K with depth is larger than that found using isolated measurements, as shown in a field study of alluvial fan gravel deposits in Sapporo, Japan.

1. Introduction

Slug tests are employed in both practical engineering and scientific studies to determine in situ hydraulic conductivity, K, by measuring the recovery of head in a single borehole after artificially raising or lowering the water level in the well. Although slug tests are sensitive to artificial and natural conditions in the well (e.g., Black, 2010), they are useful because they are simpler, cost less, and require less equipment than multiple pumping tests. It is also common for slug tests to have a logistical advantage, especially in groundwater contamination investigations. One reason is that slug tests can be conducted without removing or adding water, by lowering a solid piece of metal, called a slug, into a well, which does not disturb the site of suspected contamination. Another reason is that slug test results are related mainly to permeability on a small scale, and thus local information is directly relevant to preferential flow paths for contamination plumes. In addition, a series of slug tests at multiple depths aids in interpreting vertical variations of K. When such vertical profiles are interpolated among different locations, three dimensional distributions of K can be obtained for an individual site. Various previous studies have shown the spatial variability in K obtained from slug test analyses (Zlotnik and Zurbuchen, 2003; Zemansky and McElwee, 2005; Ross and McElwee, 2007; Leek et al., 2009; Cardiff et al., 2011).

Analytical solutions for slug tests have been available since the work of Hvorslev (1951), and theoretical and numerical studies have contributed to the practical application of slug tests in a variety of conditions for target aquifers (e.g., confined or unconfined), well types (e.g., fully or partially penetrating wells), falling head data (e.g., normally overdamped or nonlinear oscillatory head data), and borehole configurations (e.g., skin or no skin effects), as summarized by Butler (1997). Even in the last decade, analytical solutions of slug tests have been developed, for example, for highly permeable formations (Butler and Zhan, 2004), varying pressure conditions (Chen and Wu, 2006), and unconfined aquifers with

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Nomenclature

a_1, b_1, c_1, a_2, c_{2U}, b_2, and c_{2L}	empirical parameters determined by numerical simulation
d_c	diameter of well casing (L)
d_s	diameter of well screen in the piezometer method (L)
H	drawdown of hydraulic head in the well during slug tests (L)
H_0	initial drawdown of hydraulic head at slug tests (L)
H_1	drawdown of hydraulic head at the beginning time for analysis (L);
H_2	drawdown of hydraulic head at the end time for analysis (L)
L	length of screen interval in the piezometer method (L)
K	hydraulic conductivity (LT^{-1})
K_i	hydraulic conductivity in the ith layer from the top to the bottom of the numerical model ($L\,T^{-1}$)
K_L	hydraulic conductivity in the lower adjoining layer ($L\,T^{-1}$)
K_{Li}	hydraulic conductivity in the ith layer upper from the test layer ($L\,T^{-1}$)
K_r	radial component of hydraulic conductivity ($L\,T^{-1}$)
K_T	hydraulic conductivity in the layer to be tested by the piezometer method ($L\,T^{-1}$)
K_U	hydraulic conductivity in the upper adjoining layer ($L\,T^{-1}$)
K_{Ui}	hydraulic conductivity in the ith layer upper from the test layer ($L\,T^{-1}$)
K_z	vertical component of hydraulic conductivity ($L\,T^{-1}$)
$\widetilde{K}_{HV}$	estimate of hydraulic conductivity in the piezometer method ($L\,T^{-1}$)
$\widetilde{K}_{HV}$	hydraulic conductivity estimate obtained by the piezometer method ($L\,T^{-1}$)
$\widetilde{K}_{SL}$	hydraulic conductivity estimate obtained by the lower tube method ($L\,T^{-1}$)
$\widetilde{K}_{SU}$	hydraulic conductivity estimate obtained by the upper tube method ($L\,T^{-1}$)
$\widetilde{K}_T$	hydraulic conductivity estimate obtained by alternating the piezometer and tube methods ($L\,T^{-1}$)
n	total number of horizontal layers consisting of the formation
r	radial coordinate with origin at base of well (L)
P	capillary pressure (L)
Q_g	groundwater discharge rate during slug tests into the well ($L^3\,T^{-1}$)
R_U	logarithm of ratio of upper adjoining conductivity to target conductivity; K_U/K_T
R_L	logarithm of ratio of lower adjoining conductivity to target conductivity; K_L/K_T
$\widetilde{R}_L$	estimated logarithm of ratio of lower conductivity to target conductivity
S_s	specific storage coefficient (L^{-1})
S_w	degree of saturation (%)
t	time (T)
T	time interval for slug test analysis (T)
T_0	basic time lag at which a normalized head of 0.37 (T)
z	vertical coordinate (L)
α	dimensionless storage parameter, $(2d_s^2S_sL)/d_c^2$
α_L	ratio of estimate by the piezometer method to by the upper tube method, $\frac{\widetilde{K}_{HV}}{\widetilde{K}_{SU}}$
α_U	ratio of estimate by the piezometer method to by the lower tube method, $\frac{\widetilde{K}_{HV}}{\widetilde{K}_{SL}}$
θ	volumetric water content
ψ	square root of the anisotropy ratio over the aspect ratio, $\frac{\sqrt{K_z/K_r}}{2L/d_s}$

wellbore inertial effects and well skins (Malama et al., 2011). However, most previous studies of slug tests have been based on the assumption of homogeneity: that is, any flow parameters are constant. This idealized view of formations is not necessarily realistic in nature, and hydraulic properties are often variable to a considerable degree in geologic settings. For example, K in coarse mixtures ranges over several orders of magnitude, depending on grain sizes and the volume fractions of each component (Koltermann and Gorelick, 1995). However, to our knowledge, only a few studies have discussed the application of slug tests in naturally heterogeneous formations. Karasaki et al. (1988) presented rigorously analytic solutions of fully penetrating slug tests in a formation that contains two layers of different permeability with no vertical flows. In this case, slug test results entirely agreed with those from a homogeneous formation, for which K was the thickness-weighted arithmetic average, when the vertical flows were neglected. Due to the complexity of aquifer and boundary conditions, numerical approaches offer more flexibility than theoretical studies for handling vertical flow. For example, Beckie and Harvey (2002) numerically examined fully penetrating slug tests with stochastic realizations of K, and used the solution reported by Cooper et al. (1967) for simulated head recovery data in each realization. As a result, these solutions approximately corresponded to the geometric means of K in the support volume of slug tests, but were close to the arithmetic means when the characteristic scale of heterogeneity (correlation scale of K) increased. On the other hand, partially penetrating slug tests are more affected by vertical flows from the lower adjoining layers than fully penetrating slug tests. As an example of a typical field study, Shapiro and Hsieh (1998) performed double-packer slug tests in the crystalline fractured rock of central New Hampshire. They found that the water responses in the analytical models are different from the measured responses, probably due to non-radial flow in the vicinity of the borehole. Yu and Lloyd (1992) used several optimization procedures to compensate for the effects of vertical flows in double-packer slug test results under the assumption of multiple layered systems. The effect of vertical flow in partially penetrating slug tests was discussed through a comparison between semi-analytical and conventional solutions (Hyder et al., 1994). Hyder et al. found that the effect was large for small aspect ratios $2L/d_s$, where L is the screen interval length and d_s is the borehole diameter, as shown later in Fig. 2. Furthermore, Butler et al. (1994) used numerical simulation to evaluate the effect in a horizontally layered formation. They considered the case of multi-level double-packer slug tests and assumed that the hypothetical formation contained horizontal layers of various thicknesses, but with two types of K. They found that slug test results corresponded approximately to a thickness-weighted average of K in cases where the test interval spans a number of layers. The conclusion matches that of the study of fully penetrating slug tests described above. The study also revealed that considerable error may be introduced into the estimate of K, owing to the effects of adjoining layers, when the test interval length was of the order of the average layer thickness. However, this study examined only one set of permeabilities, and the effects of adjoining layers were not examined for various patterns of K variation. In addition, the