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Comparative analyses of pumping tests conducted in layered rhyolitic volcanic formations

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SUMMARY

The rhyolitic volcanic formations are modeled as multilayer flow systems composed of high permeability fractured zones separated by less permeable depth intervals referred to as matrix zones. The multilayer or linear cross flow model is applied which considers lateral flow in all units. The vertical cross flow between the model layers is calculated as the product of the head difference and the vertical inter-layer conductance. The axi-symmetrical well flow simulation software WT (i) applies either analytical or numerical drawdown simulators in the formation, (ii) assumes uniform well bore drawdown conditions in the pumping wells, and (iii) considers drawdown driven induced flow in the observation well. The interpretation of the pumping-recovery test in the well Megyaszó K-9 (Hungary) includes 7 low permeability and 6 screened water yielding zones and applies analytical method to compute the formation response. The benchmark Drill Hole Wash pumping test (Nevada) with pumped and monitoring open boreholes involves 5 fracture and 8 matrix zones. The radial formation heterogeneity is approximated by the bi-zonal flow domain and numerical method is used for drawdown simulation in the formation. Appropriate agreement with the measured drawdown data (both tests) and flow logging data (Drill Hole Wash) is achieved. Computer aided calibration is used for the parameter estimation. The results of the presented evaluations are compared with outputs of independent analyses.

1. Introduction

Rhyolitic formations comprising segments of lava flow, tuff and ash-flow may be utilized as the source of water supply (Megyaszó, Hungary) or can be selected as the geologic environment to host underground repository site for nuclear wastes (Drill Hole Wash, Nevada, USA). In such areas the volcanic rocks are frequently subject to hydrogeologic testing via pumping from screened wells or open boreholes. In thick formations several, high permeability fractured or porous depth intervals may be present, while the rest of the volcanic sequence exhibits low permeability. In this paper the low permeability sections are called matrix zones, whereas the water yielding high permeability sections are referred to as fracture zones. The location of fracture zones, the permeability variation, the availability of observation wells and flow logging survey should be considered in testing and interpretation. The presently available computer modeling tools allow for simulating well tests in layered or fissured formations by assuming unsteady, axi-symmetrical flow around the operating well using analytical solutions (Hemker and Post, 2010), numerical methods (Ruud and Kabala, 1997; Lebbe, 1999) or both techniques (Székely, 2013). The latter software is used in the present study. The WT (previously TEST) software is designed to simulate discharge/recharge/recovery, constant head, slug as well as packer tests considering linear cross flow between the model layers or diffusive cross flow through the aquitards (Hemker and Randall, 2010). It has been successfully applied to evaluate field tests conducted in sedimentary (Mukhopadhyay et al., 1994; Székely, 1992, 2013) and fissured granite (Székely, 2013a; Székely and Galsa, 2006) formations. The wellbore simulator of the WT software includes the following effects: (i) laminar and/or turbulent skin loss with depth and time variant parameters; (ii) turbulent axial friction loss; (iii) variable static level of the screened model layers; and (iv) induced flow controlled drawdown in the observation wells. The latter flow option is used in processing the second case study.

The purpose of this study is to document 3D well flow analyses in fractured formations under different hydrogeologic and testing conditions with results strongly influenced by the data availability. The WT software allowed for applying the geology conform,

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Nomenclature

b	thickness of model layers (m)
c	hydraulic resistance of model layers (d)
j	downward counter of fracture zones
k	downward counter of model layers
K_h	hydraulic conductivity in horizontal direction (m/d)
K_v	hydraulic conductivity in vertical direction (m/d)
Q_j	yield of the jth fracture zone (m^3/d)
r	distance (m)
R_{far}	distance to the circular interface between the near and far zones (m)
$s_k(r,t)$	drawdown in model layer k (m)
S_s	specific storativity (m^{-1})
S_y	specific yield, dimensionless
t	elapsed time (d)
T	transmissivity (m^2/d)
T_{near}	transmissivity of the near zone (m^2/d)
T_{far}	transmissivity of the far zone (m^2/d)
T_j	transmissivity of the jth fracture zone in the near zone (m^2/d)
δ	mean absolute deviation between the measured and simulated drawdown data (m)

multi-layered hydrostratigraphic model and selecting the most appropriate solution options. The results of parameter estimation have been confirmed in two ways. The average hydraulic conductivity or the overall transmissivity of the presumably isotropic water yielding sections agree well with the data obtained by independent analytical methods developed for single aquifers or fractures. The axi-symmetrical analytical and the equivalent 3D numerical simulations of the first case study with the multilayer formation model yielded close well bore drawdown.

The low transmissivity (T = 55.8 m^2/d) water supply well Megyaszó K-9 (Fig. 1) is basically screened in the Sarmathian rhyolite tuff at depth 180.8–355.1 m, however, two of six permeable zones are located in the 113 m thick saturated section of the overlying Pannonian sandy-clayey formation. The Tortonian clay represents the no-flow lower boundary. The seven days long pumping-recovery test has been conducted at variable rate without flow logging measurements and observation wells. The limited data availability reduced the number of parameters and necessitated several assumptions on properties of model layers constituting the formation. By contrast the high transmissivity (T = 381.2 m^2/d) open borehole UE-25b#1 at the Drill Hole Wash test (Moench, 1984) discharged the Tertiary volcanic rocks at sufficiently larger depth between 471 and 1219.2 m (Fig. 3). The constant rate pumping lasted almost 3 days and the head variations in the pumping and one monitoring borehole were measured. The interpretation involved borehole flow measurements in the pumping borehole. The extended set of observation data sufficiently reduced the number of simplifying assumptions and allowed for a more comprehensive well test data analysis.

In this study the software WT applies the multilayer or linear cross flow model (Hemker, 1999; Hemker and Randall, 2010) to approximate the flow in the formation. This model assumes lateral flow along and vertical cross flow between the model layers. The anisotropic model layers exhibit depth variant hydraulic conductivities K_h and K_v m/d in horizontal and vertical directions, respectively. The vertical cross flow between layers $k-1$ and k is controlled by the hydraulic resistances c_{k-1}, and c_k with $c = b/K_v$. The specific linear vertical cross flow $q_l(r,t)$ m/d at distance r m and time t d is calculated as $q_l(r,t) = 2(c_{k-1} + c_k)^{-1}\,[s_{k-1}(r,t) - s_k(r,t)]$ where $s_{k-1}(r,t)$, $s_k(r,t)$ m denote the drawdown in layers $k-1$ and k, respectively; the term $2(c_{k-1} + c_k)^{-1}$ is called vertical inter-layer conductance.

The software WT uses the analytical technique based on the numerical Laplace inversion (Hemker, 1999a) and the axi-symmetrical numerical finite difference FD method by Székely (Székely and Galsa, 2006). In case study 2 the drawdown response of the formation is calculated with the effect of variable well radius. The method of transient, uniform (depth invariant) wellbore drawdown (uniform well-face drawdown or UWD by Hemker, 1999a) is applied in the pumping well or borehole. In both case studies water table condition is considered in the predefined 1 m thick low permeability top layer, whereas a no flow boundary is assumed at the bottom of the flow domain. Model calibration via nonlinear multi-regression analysis (Székely, 2013) is used to estimate the hydraulic parameters. All the water yielding zones are open to the pumping wellbore/borehole. This discharge option generates a close drawdown in and a limited vertical flow between the fracture zones. The absence of drawdown measurements and the low vertical flow in the interbedded matrix zones reduce the accuracy of the calibrated parameters of those intervals.

The results of the parameter estimation are compared with data obtained by independent analytical tools (Moench, 1984; Kruseman and De Ridder, 1994, software MLU by Hemker and Randall, 2010, Aquifer Test Pro by Schlumberger Water Services, 2011) as well as multilayer numerical simulation (software FLOW by Székely, 2008). The comparison confirmed base results of the multilayer analyses conducted with the software WT.

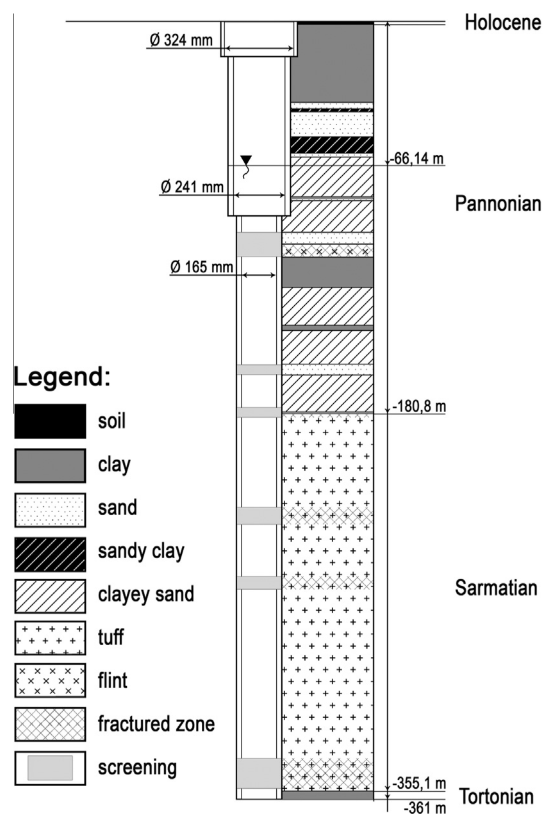

Fig. 1. Hydrostratigraphic section of the well Megyaszó K-9.