- Various Displacement Well Response Testing -

A Well Performance Testing Methodology to Identify Nonlinear Formation-Controlled Flow

presented*) at the International Conference on Groundwater in Fractured Rock, May 21-24, 2012, Prague

M.A. Zenner

Freie Universität Berlin, Institut für Geologische Wissenschaften, Arbeitsbereich Hydrogeologie

Malteserstraße 74-100, Haus B, 12249 Berlin, Germany

e-mail: mzenner@zedat.fu-berlin.de

Poster Identcode #8

Poster Identcode #8

Abstract

Over the last decades well response tests were extensively used to obtain estimates of the hydraulic conductivity of porous and fractured formations. Traditionally, well response tests are often performed by employing just one initial displacement H_0. For many years we have investigated the information that might be deduced from initiating well response tests by various initial displacements H_0. This work summarizes the major findings of our investigations and shows that under favourable conditions various displacement well response testing allows for an identification and differenttiation of tubing-controlled and formation-controlled nonlinear flow processes. Test settings shown in this presentation relate to two wells, one of which is completed in a coarse sand aquifer in Berlin, while the other one is located in a fractured limestone formation close to the town of Harzheim in the German Eifel-area. The potential of identifying formation-controlled nonlinear flow by various displacement well response testing is elucidated to be promising at characterizing fractured formations envisioned for ground water and potentially for geothermal energy exploitation. The presented methodology should also be useful at characterizing the tightness of fractured reservoir cap rocks and nuclear waste repositories.

Introduction

Well response testing has evolved to a frequently applied field technique when estimates of the hydraulic conductivity of the subsurface are required. Traditionally, slug tests are conducted by using just one initial displacement H_0. Classical linear theories developed for the analysis of these tests do not allow for a dependency of overdamped normalized head data on the initial displacement H_0 but suggest that overdamped normalized head responses collapse onto a unique curve. Based on experience such response curves should either be convex or linear in shape when plotted in a Hvorslev-style semi-logarithmic format. Concave normalized head responses are generally not predicted by classical linear well response test theories nor is a shift in time of response curves when employing different initial displacements H_0.

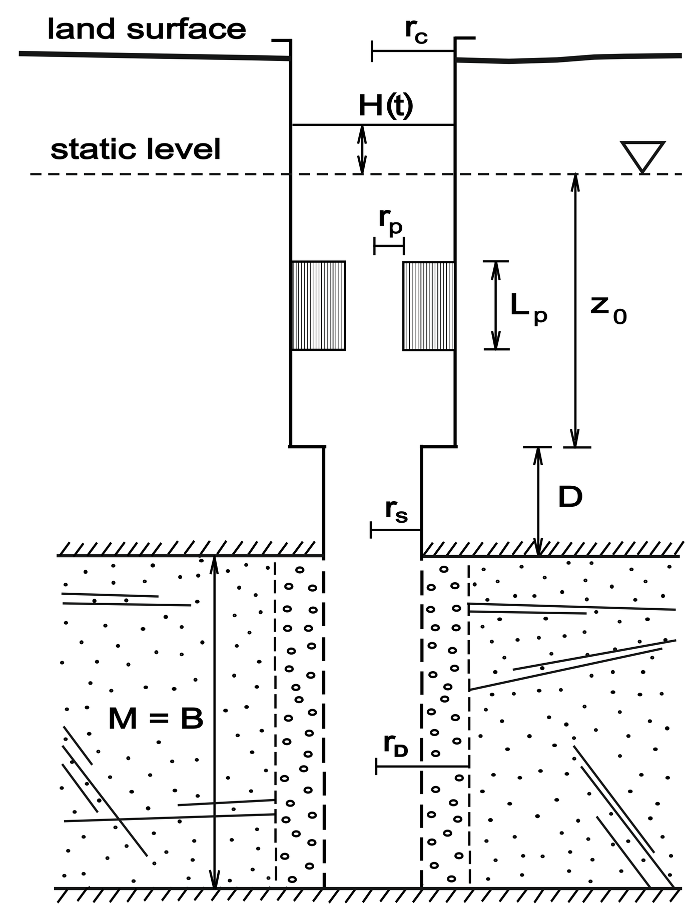

Fig. 1: Schematic of a finite-diameter well with a packer (shaded) placed inside the well's casing.

In the past, we have often observed concave head response curves when plotting acquired well response test data in a normalized Hvorslev-style format. These response curves were usually shifted in time for varying initial displacements H_0. We consider classical linear well response test theories inadequate at describing such test data.

Model Development

In order to gain more insight about the processes governing our data, we developed a nonlinear well response test model for fully penetrating finite-diameter wells (Zenner, 2008, 2009). This model accounts for three major nonlinear flow processes: a) a water column height depending on the actual head displacement H(t), b) nonlinear wellbore-internal head losses due to turbulent flow and inertial effects at radius changes along the flow path inside the well casing, and c) a rate-dependent skin effects to accommodate near-wellbore nonlinear flow inside the tested formation:

$$-\left(H+z_0+\left[\frac{r_c^2}{r_p^2}-1\right]L_p+\left[\frac{3}{8}B+D\right]\frac{r_c^2}{r_s^2}\right)\frac{d^2H}{dt^2}-gH \qquad (1)$$

$$+\frac{1}{2}\left[\left(\frac{r_c^2}{2r_sB}\right)^2-1+\xi_{\text{loss}}-\left(f_p\frac{L_pr_c^4}{2r_p^5}+f_s\frac{Dr_c^4}{2r_s^5}+f_c\frac{z_0-L_p+H}{2r_c}\right)sign\left(\frac{dH}{dt}\right)\right]\left(\frac{dH}{dt}\right)^2$$

$$-g\pi r_c^2\left(B_2+C\left(\pi r_c^2\right)^{p-1}\left|\frac{dH}{dt}\right|^{p-1}\right)\frac{dH}{dt}-\frac{gr_c^2}{2\pi^2T}\int_0^t\frac{\partial^2H}{\partial\tau^2}\int_0^\infty\frac{1-e^{-\frac{4T(t-\tau)x^2}{Sr_D^2}}}{x^3\left[J_1^2(2x)+Y_1^2(2x)\right]}dxd\tau=0$$

Model eq. (1) relates to the schematic of Fig. 1. The initial conditions read:

$$\frac{dH(t=0)}{dt}=0 \qquad H(t=0)=0 \qquad (2)$$

The above single porosity compartment convolution-type model (eq. 1) is based upon the principle of mechanical energy conservation of the water contained within the well and assumes that farfield flow away from the well is cylindrically convergent and Darcian. This model will be applied subsequently to two test problems to differentiate between tubing-controlled and formation-controlled nonlinear flow processes. The key to arrive at such a differentiation is to conduct several well response tests initiated by differing initial displacements H_0 and to describe wellbore-internal nonlinear head losses by known head loss formulas from steady-state pipe hydraulics. The resulting procedure essentially is the slug test analogue to classical well performance testing by step-rate pumping.

Example No.1: Coarse Sand Aquifer

The first application of the above model (eq. 1) demonstrates the applicability of Colebrook and Borda-Carnot-type head loss formulas from steady-state pipe hydraulics to characterize nonlinear wellbore-internal head losses in the course of a well response test. On August 29, 2006 a set of twelve packer-induced well response tests was conducted at well B-7004, which is located north of Berlin-Tempelhof Airport, Germany. 7"-well B-7004 fully penetrates a confined medium to coarse-sand aquifer, which is over- and underlain by confining marl (Fig. 2). The aquifer thickness is M = 21.0 m. The remaining geometrical parameters specifying the well-aquifer system are given as follows: $r_c = r_s = 0.085$ m, $z_0 = 17.27$ m, D = 0 m.

The sliding-head packer used to conduct the well response tests allows for using straight inner packer flow-through tubes of differing radii r_p and lengths L_p (Tab. 1). Head losses at radius changes along the flow path inside the wellbore were accounted for by Borda-Carnot-type head loss formulas, aggregated by minor loss coefficient ξ_{loss}, while turbulence within the well was modeled by Colebrook-formulas quantifying the Darcy-Weisbach friction factors f_p, f_s, and f_c of the three pipe sections of radii r_p, r_s, and r_c, respectively (Zenner, 2008). The measured head responses of ten of the conducted well response tests are shown in Fig. 3. The reproducibility of the head data was verified by two more tests (not shown). Consistent model fits of all data could be achieved by using an aquifer storage coefficient of $S=2\cdot10^{-4}$ and a hydraulic conductivity value of k_r=$9.4\cdot10^{-4}$ m/sec. A skin effect was not accounted for (B_2=0, C=0). As is evident from Fig. 3, the nonlinear head loss formulas from steady-state pipe hydraulics allow approximating the concave response curves over a broad range of test settings. These formulas may thus be considered to be sufficiently accurate at modeling wellbore-internal nonlinear flow processes in the course of transient well response tests.

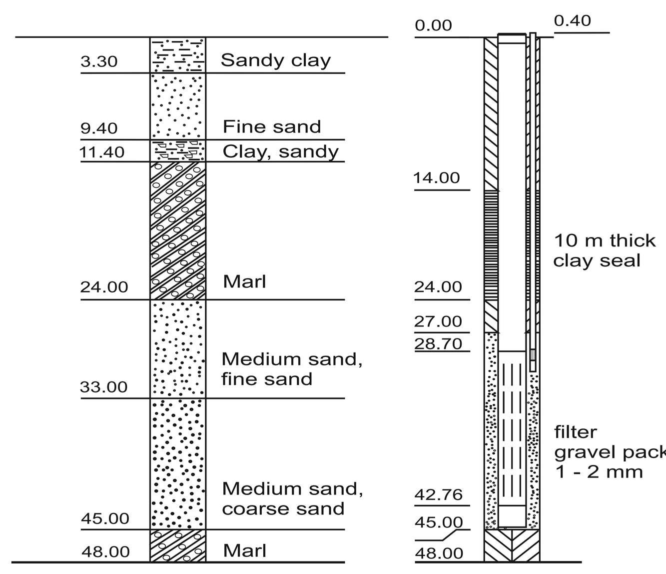

Fig. 2: Simplified geological profile and well construction plan of well B-7004.

Tab. 1: Radii and lengths of the three packer flow through pipes and initial heads used to induce the ten slug tests shown in Fig. 3.

Test Identifier	r_p (m)	L_p (m)	H_0 (m)
B7004/1	0.025	1.774	3.96
B7004/2	0.025	1.774	1.35
B7004/3	0.025	9.774	4.15
B7004/4	0.025	9.774	1.35
B7004/5	0.014	1.774	4.12
B7004/6	0.014	1.774	1.33
B7004/7	0.0055	1.774	4.09
B7004/8	0.0055	1.774	1.33
B7004/11	0.014	9.774	4.21
B7004/12	0.014	9.774	1.36

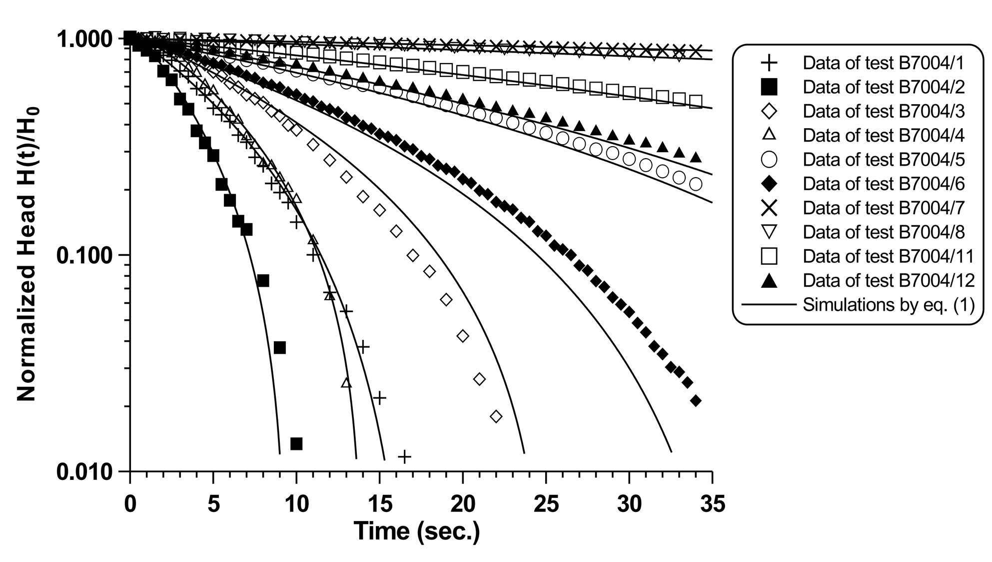

Fig. 3: Normalized head responses of ten packer-induced well response tests conducted on August 29, 2006, at well B-7004. Different packer flow-through pipes were used to initiate the tests. All tests can be modeled using unique aquifer parameters.

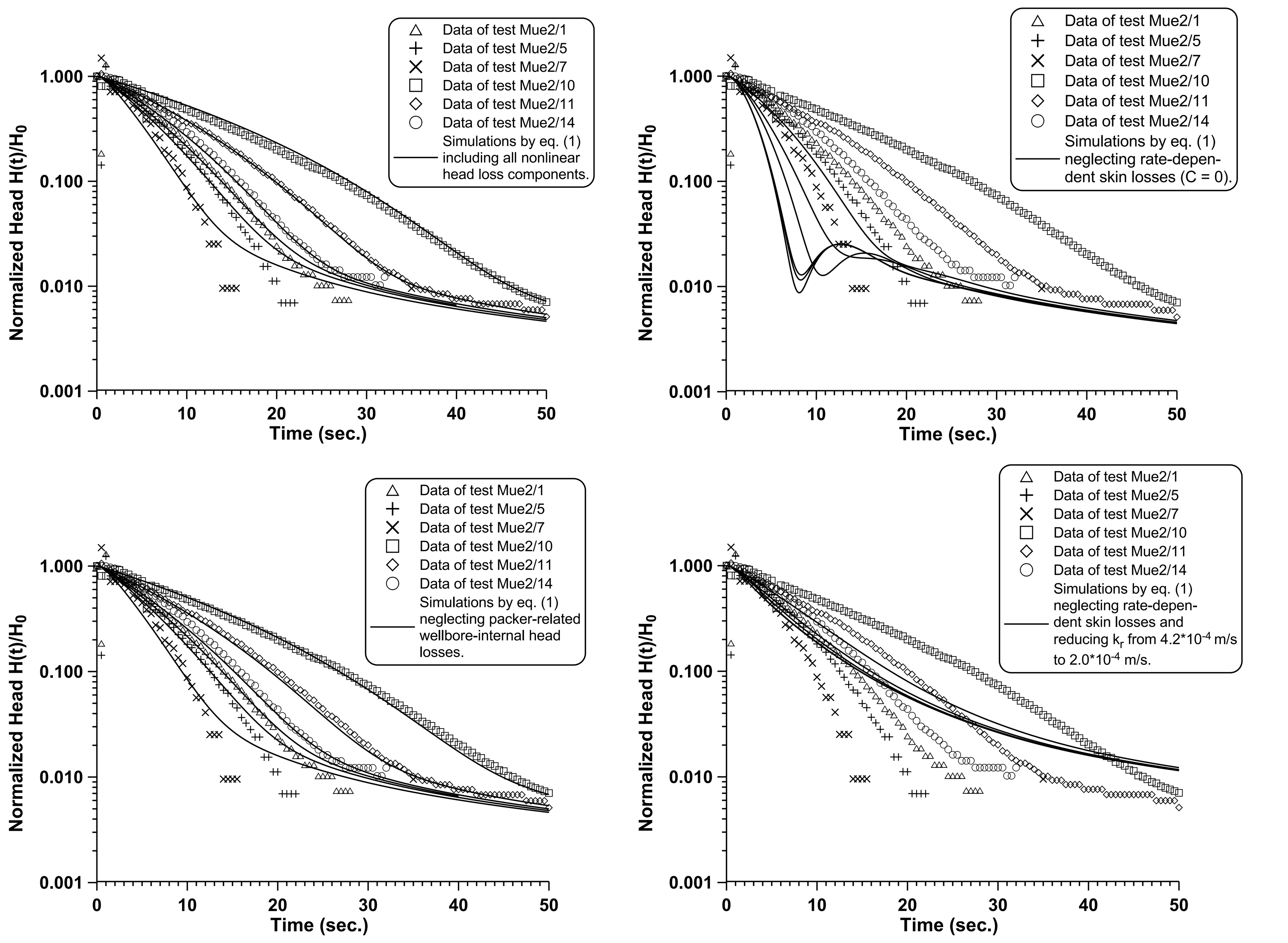

Fig. 5: Normalized head responses of ten well response tests conducted on October 25, 2006, at well Münster-eifelbohrung B2. The tests were initiated by different solid cylinders as well as by the sliding head packer used at well B-7004. All tests can satisfactorily be modeled using unique aquifer parameters when all nonlinear head loss components are acknowledged (left upper plot).

Example No.2: Fractured Limestone Aquifer

The previous test example showed that nonlinear wellbore-internal flow processes can be accounted for by head loss formulas rooted in steady-state pipe hydraulics. These formulas are used now to discriminate between nonlinear flow characteristics originating inside the wellbore and inside the tested formation, respectively. The current test example refers to a set of ten well response tests conducted on October 25, 2006 at well Münstereifelbohrung B2, which was completed in a Devonian limestone formation close to the small town of Harzheim at the western national border of Germany. The tested limestone formation is known to be fractured according to hydrogeological investigations at nearby waterworks Urfey. The geological profile and the construction plan of well Münstereifelbohrung B2 are shown in Fig. 4. The tested limestone formation is overlain by confining marlstone, while a confining base was not reached by drilling. The aquifer thickness employed for test analysis is M = 12.0 m. The remaining geometrical parameters specifying the well-aquifer system are given as follows: r_c=r_s=0.0625 m, z_0=31.77 m, D=0 m, r_D=0.120 m. Five tests were conducted in withdrawal mode using solid slugs of different volumes

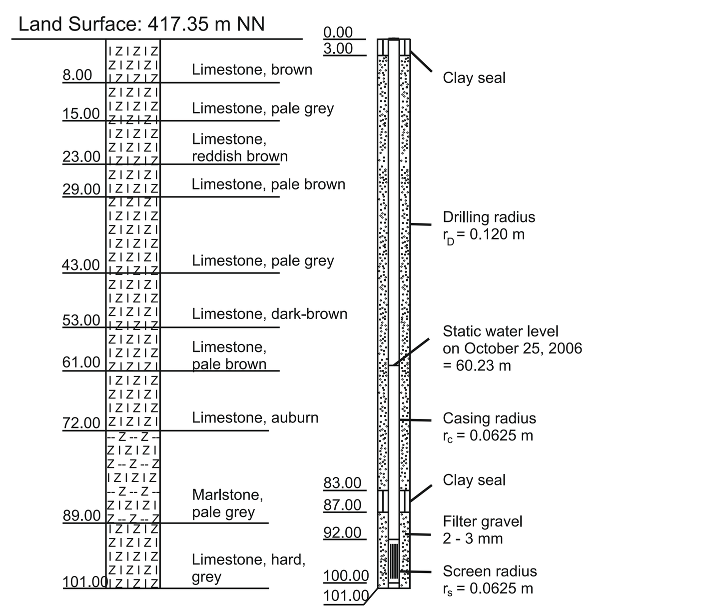

Fig. 4: Geological profile and well construction plan of well Münstereifelbohrung B2.

Tab. 2: Geometrical characteristics for the five slug withdrawal tests (Mue2/1, Mue2/3, Mue2/5, Mue2/6, Mue2/7) and the packer-induced slug injection tests.

Test Identifier	r_p (m)	L_p (m)	H_0 (m)
Mue2/1	-	-	- 0.715
Mue2/3	-	-	- 0.715
Mue2/5	-	-	- 0.475
Mue2/6	-	-	- 0.129
Mue2/7	-	-	- 0.129
Mue2/10	0.025	1.774	+ 7.470
Mue2/11	0.025	1.774	+ 2.420
Mue2/12	0.025	1.774	+ 2.530
Mue2/14	0.025	1.774	+ 1.020
Mue2/15	0.025	1.774	+ 7.370

and five tests in injection mode using the same packer employed for the previously shown tests at well B-7004. The respective geometrical parameters are summarized by Tab. 2. It is evident from Fig. 5 (left upper plot) that when acknowledging Colebrook and Borda-Carnot-type wellbore-internal head losses all tests can consistently be modeled for the following set of aquifer and well parameters: k_r=$4.2\cdot10^{-4}$ m/sec., S=$1.0\cdot10^{-6}$, B_2=0, C=23.500 sec.^{p}/m^{3p-1}, and p=1.6 (Zenner, 2009). The matched hydraulic conductivity clearly is too large for flow exclusively taking place inside the porous limestone matrix and suggests that there is a high-permeability compartment governing flow in the limestone formation. Fig 5 also displays that acquired head responses are all concave in shape and shifted toward larger times for increasing magnitude of the initial displacement H_0. These characteristics can only be modeled when invoking a pronounced rate-dependent skin effect characterized by non-vanishing values of C and p, respectively (Fig. 5, left upper and lower plot).

The upper and lower plot on the right side of Fig. 5 finally show the simulated responses obtained when neglecting the rate-dependent skin effect, and when simultaneously reducing the hydraulic conductivity k_r (right lower plot). It is motivated by this latter plot that the measured data cannot be modeled by neglecting the rate-dependent skin and reducing k_r, as simulated responses then approach classical convex system characteristics with diminishing time-shift between response curves belonging to different initial displacements H_0. Although not explicitly shown here, it is worth noting that the measured head responses cannot be modeled by the generalized linear fractional flow model of Barker (1988) either. The latter model produces either convex or linear head response curves for different H_0 with these curves always collapsing onto one another for any specific flow dimension (see accompanying oral presentation*)). In summary, the only process we have identified so far reproducing the concave and shifted-in-time head responses shown in Fig. 5 is strong nonlinearity. We would like to invite other researchers to cope with this phenomenon and try to identify additional processes.

Conclusions

This work showed that an identification of near-well nonlinear flow processes in high-permeability aquifers is possible by conducting several well response tests with significantly different initial displacements H_0 in a well along with representing wellbore-internal nonlinear head losses by known head loss formulas from steady-state pipe hydraulics. We indicated that various displacement well response testing along with an application of nonlinear mathematical models to analyze acquired head data may allow for an identification of near-well nonlinear flow in fractured rock. This testing methodology seems to be promising at characterizing the hydraulic behaviour of fractured formations envisioned for ground water and geothermal energy exploitation, at characterizing the tightness of fractured reservoir cap rocks and potentially also when applied in the framework of nuclear waste repository investigations. Various displacement well response testing should be supplemented by production logging or by high-resolution borehole imaging methods (e.g. formation micro- or ultrasonic borehole imaging) whenever possible to maximize structural and hydraulic information on investigated fractured systems.

Acknowledgement

This work was supported in part by the German National Science Foundation (DFG) under Grant No. PE-362/24-2. The views and conclusions contained in this presentation are those of the author and do not necessarily reflect the official policies or positions, either expressed or implied, of the German Government.

References

Barker, J.A. (1988). A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock, Water Resources Research 24(10), p. 1796–1804.

Zenner, M.A. (2008). Experimental Evidence of the Applicability of Colebrook and Borda Carnot-type Head Loss Formulas in Transient Slug Test Analysis, ASCE, Journal of Hydraulic Engineering 134(5), p. 644–651.

Zenner, M.A. (2009). Near-Well Nonlinear Flow Identified by Various Displacement Well Response Testing, Ground Water 47(4), p. 526-535.

*) The content of this poster was also prepared for an oral presentation held at the Karlsruhe Institute of Technology (KIT), December 15, 2011, Karlsruhe, Germany.