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Measuring well hydraulic connectivity in fractured bedrock using periodic slug tests

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SUMMARY

Periodic hydraulic experiments were conducted in a five-spot well cluster completed in a single bedding plane fracture. Tests were performed by using a winch-operated slug (submerged solid cylinder) to create a periodic head disturbance in one well and observing the phase shift and attenuation of the head response in the remaining wells. Transmissivity (*T*) and storativity (*S*) were inverted independently from head response. Inverted *T* decreased and *S* increased with oscillation period. Estimated *S* was more variable among well pairs than *T*, suggesting *S* may be a better estimator of hydraulic connectivity among closely spaced wells. These estimates highlighted a zone of poor hydraulic connection that was not identified by a constant rate test conducted in the same wells. Periodic slug tests appear to be a practical and effective technique for establishing local scale spatial variability in hydraulic parameters.

1. Introduction

Flow channelization has long been recognized as a hallmark of groundwater flow in fractured bedrock systems (Tsang and Neretnieks, 1998). The physical nature of the problem is described simply through the cubic law which dictates that water flow rate is related cubically to the local fracture aperture. Prediction of flow in a natural bedrock system is not so simple, however, as the distribution of aperture and its interaction with water flow is highly variable even within a single fracture. Understanding flow in bedrock consequently requires site specific hydraulic characterization to be conducted.

Typical pumping and slug test configurations are not well suited to bedrock environments. Because of the small water storage in bedrock, the hydraulic radius of influence of a pumping well extends rapidly outward implying that only the earliest drawdown contains local information. Early drawdown is often dominated by well-bore storage and formation damage effects in open boreholes. Slug test responses are weighted more toward local hydraulics but are even more sensitive to borehole influences.

A periodic hydraulic test potentially overcomes some of the limitations of pumping and slug tests. Periodic (also called harmonic, oscillatory, or sinusoidal) tests are conducted by creating an oscillating head in one well and observing the corresponding oscillatory head response in one or more observation wells. Because the head signal is in a constant state of transience, periodic tests highlight the influence of formation storativity on drawdown response. The repeatability of the transience allow initial effects of well bore storage and pump priming to be isolated. Most interestingly, periodic tests are capable of interrogating different portions of the formation without the addition of observations wells. This is because the spatial weighting of hydraulic response to transmissivity (*T*) and storativity (*S*) is sensitive to the frequency of the head oscillation (Cardiff et al., 2013; Renner and Messar, 2006). Periodic tests have also been shown to be more sensitive than constant rate tests to the length of a flow path between an oscillating source and observation well (Fokker et al., 2012). By conducting periodic tests at varying frequency, different regions of the formation can be tested for hydraulic conductivity and storativity. While this is true for any type of groundwater system, it is particularly effective in bedrock systems because the small storage coefficients means a small head perturbation propagates far from the test well.

Periodic hydraulic testing is by no means a new measurement technique. Periodic hydraulic testing was used in the oil industry as early as 1966 (Black and Kipp, 1981). During the 1970s it was put to use in oil production wells using alternating periods of flow and shut-in (Hollaender et al., 2002). The earliest report of periodic tests in the groundwater literature regards the use of naturally

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occurring periodic oscillations such as earth tides or barometric changes (Black and Kipp, 1981). These natural periodic influences have the advantage of extending over many kilometers but are generally limited to only a few frequencies (diurnal, seasonal, tidal) and are difficult to isolate due to the complexity of these systems and the mixing of different processes (Rasmussen et al., 2003).

We demonstrate here the use of periodic testing in a single bedding plane fracture at the 10 m scale. In our experiments, head is varied in the test well by oscillating a slug up and down at the level of water in the well. The periodic head response is observed at four observation wells. Because we limit our experiment to a single fracture we highlight aperture variability rather than fracture network connectivity in our experiments. Matrix porosity is negligible so the hydraulics are dictated by the fracture only.

The development of this characterization tool is particularly relevant to geologic fluid circulation systems such as those used in groundwater remediation, petroleum recovery, and geothermal plants. In all of these systems, flow channeling can lead to a short circuiting of the circulation system that may result in inefficient extraction of contaminated groundwater, petroleum reserves, or geothermal heat, respectively. Periodic tests may provide a means for characterizing problematic channeling either before or during operations. Because it is not necessary to extract water or shut down pumps to conduct these tests, they are likely to be much more cost effective than shut-in hydraulic or cross-hole tracer tests.

2. Methods

2.1. Experimental site

The Altona Flat Rock Site is located in Clinton County, New York, approximately 25 km northwest of Plattsburgh, New York. It is situated in an exposed pavement of the Cambrian aged Potsdam formation, laid bare by a glacial dam burst at the end of the most recent glacial advance (Rayburn et al., 2007). The upper Potsdam is highly cemented with silica and thin sections from the site reveal local matrix porosity that is around 1–2%. Consequently, fractures are the dominant conduit for flow with insignificant flow and storage in the matrix at local scales.

Ground penetrating radar testing revealed a major water-bearing bedding plane fracture (dipping ~3°) at 7.6 m below ground surface (Becker and Tsoflias, 2010; Talley, 2005; Talley et al., 2005; Tsoflias and Becker, 2008). A well field was installed at the site in a "five spot" configuration in 2004 (Fig. 1).

2.2. Periodic hydraulic testing

To create the sinusoidal head signal in the hydraulic source well, a "slug" consisting of a 1.9 cm diameter watertight cylinder was lifted and lowered in the well annulus via a winch operated by a computer controlled stepper motor (Driver: ST10-Si, Motor: HT34-486, Applied Motion Products, Watsonville, CA). A straddle packer system (specially constructed of PVC by RocTest, Lakewood, Colorado) with a 10.2 cm (4 in.) inner diameter was used to isolate the hydraulic disturbance to the target fracture. Fig. 2 depicts the field setup for the source well during the tests. Pressure transducers were installed to observe the head response in the source and monitoring wells (Druck 1230 Series and a Solinst Levelogger model #3001). The transducers in the monitoring wells were placed within straddle packers (Vanderlans and Sons, Lodi, California) and routed to a datalogger (CR1000, Campbell Scientific, Logan, Utah) allowing the transducers to be monitored in real-time. The field design assured that all flow occurred in the single bedding plane fracture, i.e. constrained to two dimensions. Three different frequencies were created at each well while all were monitored for head changes.

Interpretation was performed by assuming confined conditions and a formation of infinite extent. The boundary value problem is then

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{1}{D}\frac{\partial s}{\partial t} \tag{1}$$

$$s(r,0) = 0 \tag{2}$$

$$s(\infty,t) = 0 \tag{3}$$

$$\lim_{r\to 0} r\frac{\partial s}{\partial r} = -\frac{Q}{2\pi T} \tag{4}$$

where s is the observed drawdown, r is the distance from the center of the pumping well, T is the formation transmissivity, and D is the hydraulic diffusivity. The hydraulic diffusivity is the ratio of the transmissivity to the storativity ($D = T/S$). The flux of water from the well, Q, is the real part of the complex periodic function:

$$Q(t) = Q_0 e^{i\omega t} \tag{5}$$

where i is the complex variable and ω is the frequency of the oscillation.

A solution for periodic drawdown was first presented by Black and Kipp (1981) and later by Rasmussen et al. (2003) who provide a method for T and S to be derived independently from observed drawdown. The solution for drawdown is

$$s(r,t) = \frac{Q}{2\pi T} K_0\left(r\sqrt{\frac{i\omega}{D}}\right) \tag{6}$$

where K_0 is the zero-order modified Bessel function of the second kind. Eq. (6) neglects a period of early time in which the signal has not yet become steady periodic. The amplitude of the drawdown oscillation in an observation well is

$$|s| = \frac{Q_0}{2\pi T}\left|K_0\left(r\sqrt{\frac{i\omega}{D}}\right)\right| \tag{7}$$

and the phase shift between the flux at the test well and the drawdown at the observation well is

$$\varphi_0 = \varphi_s - \varphi_Q = \arg\left\{K_0\left(r\sqrt{\frac{i\omega}{D}}\right)\right\} \tag{8}$$

where φ_s is the phase of the drawdown signal and φ_Q is the phase of the flux of water at the test well.

Following Rasmussen et al. (2003), parameters T and D (and therefore $S = T/D$) were obtained by fitting periodic functions to the measured flux and drawdown data. At the test well, the oscillating flux is fit with the cosine function

$$Q(t) = Q_0\cos(\omega t - \varphi_Q) = Q_1\cos\omega t + Q_2\sin\omega t \tag{9}$$

where Q_0 is the amplitude, ω the frequency, and φ_Q this phase of the flux signal at the test well. The coefficients Q_1 and Q_2 represent $Q_0\cos\varphi_Q$ and $Q_0\sin\varphi_Q$, respectively. Likewise, the drawdown at the observation well is fit with the function

$$s(t) = s_1\cos\omega t + s_2\sin\omega t \tag{10}$$

where the coefficients s_1 and s_2 represent $s_0\cos\varphi_s$ and $s_0\sin\varphi_s$, respectively, and s_0 is the amplitude of the drawdown. After fitting the functions (9) and (10) to the flux and drawdown signals, respectively, the phase lag, φ_0, is found from

$$\varphi_0 = \arctan\left(\frac{s_2}{s_1}\right) - \arctan\left(\frac{Q_2}{Q_1}\right) \tag{11}$$