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CROSS-HOLE PERIODIC HYDRAULIC TESTING OF INTER-WELL CONNECTIVITY

Matthew W. Becker, Eric Guiltinan

California State University Long Beach
1250 Bellflower Blvd.
Long Beach, CA 90815 USA
e-mail: mbecker3@csulb.edu

ABSTRACT

Harmonic (periodic) hydraulic tests can establish formation hydraulic properties during active production of geothermal wells. Field experiments were conducted in a fractured sandstone to establish the value of these tests for establishing inter-well connectivity. Sinusoidal head oscillation was induced in well and the propagation of the pressure pulse through a single fracture was measured in four observation wells. Pressure response was interpreted by non-linear regression fitting of the hydraulic diffusion equation to drawdown. Hydraulic diffusivity (transmissivity / storativity) inverted from these tests were found to be much more sensitive to local heterogeneity than traditional constant rate (Theis) tests. The method may be particularly useful for anticipating hydraulic short circuiting in fractured geothermal reservoirs.

INTRODUCTION

Hydraulic connectivity among geothermal wells is a crucial parameter for fluid circulation: too poor of a hydraulic connection leads to insufficient circulation rates between injectors and producers and too strong of a connection leads to hydraulic short-circuiting and inefficient heat transfer. The establishment of hydraulic connectivity is even more important in Enhanced Geothermal Systems (EGS) where permeable fractures are artificially created in an otherwise impermeability rock. In EGS reservoirs, poor connectivity may mean zero circulation.

The importance hydraulic connectivity has led to the use of chemical tracers for formation evaluation. Tracers have been shown to be quite effective in establishing hydraulic connections among wells [*Chrysikopoulos*, 1993; *Rose et al.*, 2001; *Shook*, 2001]. However, tracer tests typically last weeks or more and may incur expensive analytic costs. In addition, tracer selection must be tailored to the specific geochemical and thermodynamic conditions in the reservoir to avoid degradation or adsorption of the tracer in the reservoir [*Chrysikopoulos*, 1993].

Hydraulic communication between wells are better characterized using tracer tests than standard hydraulic tests because the latter are relatively insensitive to local changes in permeability [e.g. *Butler and Liu*, 1993; *Oliver*, 1993]. This is particularly true when a Cooper-Jacob analysis is used because the late time drawdown data are emphasized. *Meier et al.* [1998] showed that late-time drawdown is largely independent of position of the monitoring well. Some researchers have improved upon the spatial resolution of hydraulic transmissivity by inverting cross-hole tests among multiple boreholes [*Li et al.*, 2007]. Although these methods have demonstrated some success in shallow environments, the large number of wells necessary for such inversions is not available in geothermal fields.

Transmissivity and storativity are difficult to decouple in hydraulic testing. For example, numerical synthetic pumping tests conducted in heterogeneous transmissivity fields result in an overestimation of storativity variability caused as a result of the transmissivity variability [*Meier et al.*, 1999; *Meier et al.*, 2001]. Thus, some researchers have looked to the ratio of T/S, or the hydraulic diffusivity (D) as an indicator of hydraulic conductivity. *Knudby and Carrera* [2006] used Monte Carlo simulations of a hypothetical two-dimensional aquifer to show that hydraulic diffusivity was a reasonable indicator of tracer connectivity among wells. Traditional constant rate tests, on the other hand, were shown to be poor predictors of both tracer and hydraulic communication.

In this article we explore the use of harmonic hydraulic testing to measure hydraulic connectivity. Harmonic testing involves the variation of head and/or discharge rate in a periodic manner. Harmonic testing dates back to the 1970's in the petroleum field where it is used to establish formation characteristics [*Hollaender et al.*, 2002]. More recently it has been applied to at least one geothermal field [*Nakao et al.*, 2005]. The practical advantage of the harmonic test is that production or injection need only be varied, not stopped. The practical disadvantage is that tests generally need to be run longer than a constant-rate test to detect distant boundaries [*Hollaender et al.*, 2002].

We performed harmonic testing in a well-characterized sandstone formation in New York State, USA. Hydraulic experiments were conducted among wells isolated in a single fracture within a 100 m^2 area. Head was varied in the source well in a sinusoidal manner. The results of harmonic tests are compared here to constant-rate (Theis) tests among the same wells.

METHODS

Field Site

Field tests were conducted at the Altona Flat Rock experimental site . Altona Flat Rock is part of a large system of Cambrian Potsdam Sandstone (well-sorted quartzose) pavements that were stripped of overburden during the last glaciation and remain exposed today [*Rayburn et al.*, 2005]. There are laterally extensive sub-horizontal (dipping ~3º) bedding plane partitions visible in numerous outcrops surrounding the site. Because the sandstone is highly cemented with silica, primary porosity is insignificant in comparison to secondary porosity. Extensive tracer experiments have been conducted among five 15-cm-diameter open-hole wells arranged in a 5-spot configuration with 10 meters on a side. The wells intersect a major sub-horizontal fracture 7.6 meters below ground surface that has been the focus of those investigations. The thin overburden has been cleared in this area to present a clean sandstone pavement for GPR imaging of the 7.6 m fracture. The Altona Flat Rock site is part of the William H. Miner Agricultural Research Institute which has granted us permission to develop the site and has provided us with logistical support.

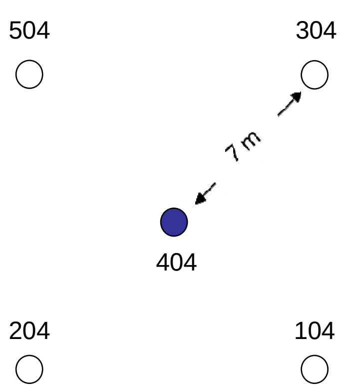

Figure 1: Well field configuration at the Altona Flat Rock Site.

Harmonic Testing

Harmonic testing was conducted by oscillating a solid cylinder or slug in and out of Well 404 while recording head variations in the surrounding wells (*Figure 1*). All wells were isolated to the single bedding plane fracture at 7.6 m depth using inflatable packers in the 15 cm diameter boreholes. Head was disturbed in Well 404 by raising and lowering the slug in a sinusoidal manner using a winch driven by a computer-controlled stepping motor (*Figure 2*). Head could be precisely controlled using this system but discharge could not be measured independently. Head in the disturbed well and the surrounding monitoring wells was monitored using pressure transducers (Druck) read by a datalogger (Campbell Scientific).

Constant Rate Testing

Constant rate tests were conducted by pumping Well 404 with a Grundfos Rediflo2 pump at a rate of 4.2 lpm and monitoring drawdown in the surrounding wells using pressure transducers (Druck) connected to a datalogger (Campbell Scientific). Transmissivity and storativity were determined by curve fitting a Theis well function (completely confined infinite extent) to the drawdown for each of the monitoring wells. It should be noted that the constant rate tests are not entirely comparable to the harmonic tests because only the pumping well was isolated by packers in the constant rate tests. Consequently, in the constant rate tests monitoring wells may be more affected by well bore storage.

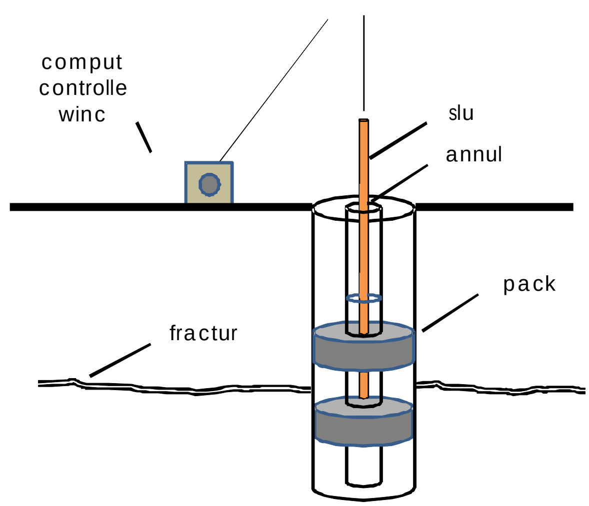

Figure 2: Well field configuration at the Altona Flat Rock Site.

RESULTS

An example of the head variation in the disturbed well (404) and the monitoring wells is shown in *Figure 3*. Note that the head is disturbed in Well 404 by only about 6 cm. Pressure scatter at maximum drawdown is due to water running off the slug as is raised from the water.

The wells show a highly varying pressure response to the oscillation of the slug in Well 404. Well 204 responds with almost no attenuation of amplitude or phase lag. Wells 304 and 504 show a moderate attenuation of amplitude and an evident phase lag. Well 104 shows a highly dampened response to the oscillation in Well 404 but it is also influenced by a longer period pressure boundary. This long wavelength influence does not correlate with barometric pressure. Wind-driven fluctuation in the level of a nearby surface water body is one feasible explanation but we have not yet explained satisfactorily the behavior.

Because discharge was not measured in these tests, it is impossible to decouple T and S from hydraulic diffusivity [*Renner and Messar*, 2006]. To determine hydraulic diffusivity we fit the hydraulic diffusion equation to the drawdown data. The formation acts as a transfer function affecting the propagation of the pressure pulses in the disturbed well. The analysis is completed in Laplace space and inverted numerically. In this manner, convolution of the impulse function and the transfer function is accomplished through multiplication in the Laplace domain. The sinusoidal input function that describes the perturbation of head from the initial level is

$$\bar{\delta}_s = p_0\left(\frac{\omega}{s^2+\omega^2}\right)\exp\left(\frac{\theta s}{\omega}\right) \tag{1}$$

where p_0 is the amplitude of the pressure disturbance in the input well, ω is the frequency of the disturbance, θ is the phase shift from reference time, and s is the Laplace variable. The formation transfer function is

$$\bar{\delta}_f = \frac{K_0\left(r\sqrt{\frac{s}{D}}\right)}{K_0\left(r_w\sqrt{\frac{s}{D}}\right)} \tag{2}$$

where K_0 is the Bessel Function, r is the radial distance to the observation well, r_w is the radius of the disturbed well, and D is the hydraulic diffusivity. The total response at the observation well is then

$$\bar{\delta}_t = \bar{\delta}_s \cdot \bar{\delta}_f \,. \tag{3}$$

Equation 3 is inverted to the time domain numerically [*Becker and Charbeneau*, 2000].

We fit *Equation 3* to observed head oscillations in all four observation wells for four different sinusoid

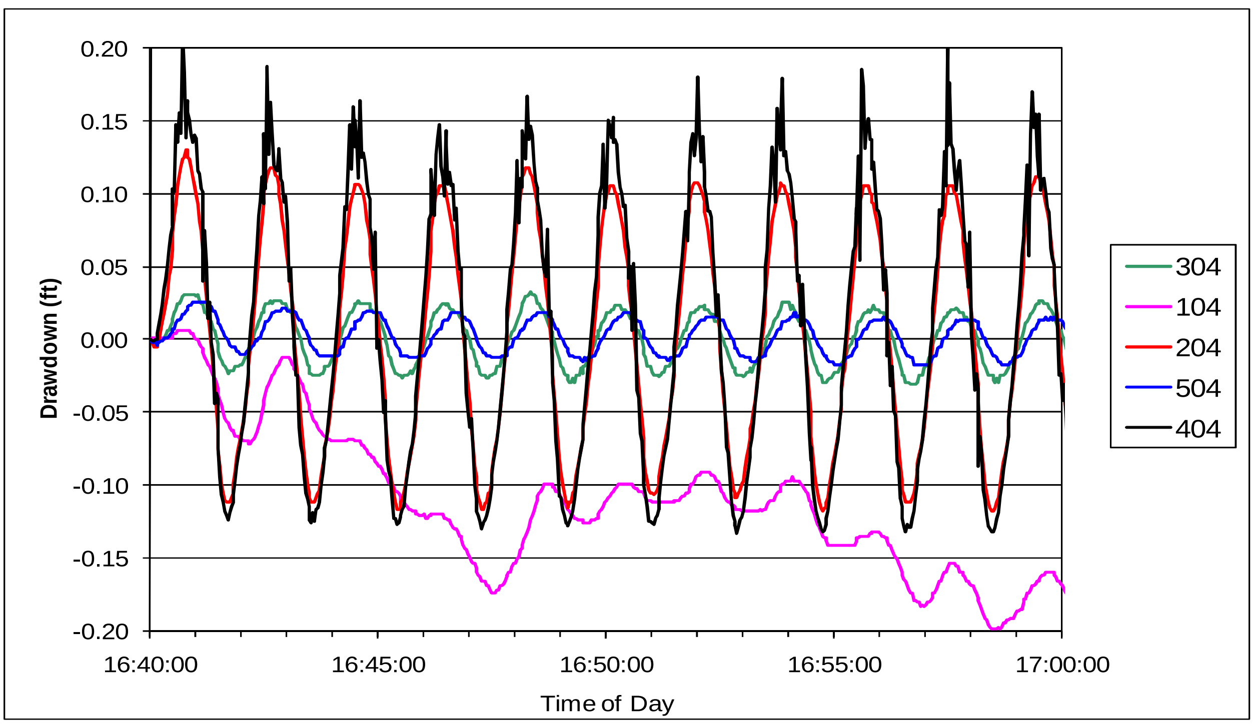

Figure 3: Example harmonic test for a 113 second period of oscillation. Well 404 was the disturbed well.

periods. *Figure 3* show an example fit to the data. First the input signal is fit with a sinusoid function (1) then the observation well data are fit by varying hydraulic diffusivity (2). Best fit hydraulic diffusivity is determined though a Levenberg-Marquardt non-linear regression.

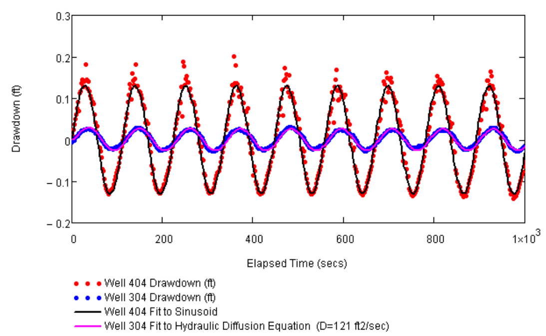

Figure 4. Fit of sinusoid (1) to drawdown in disturbed Well 404 and hydraulic diffusion equation (3) to drawdown in observation Well 304.

The model derived hydraulic diffusivity for wells 304 and 504 are show in *Figure 5*. Note that diffusivity decreases as a power law with increasing period. The decrease in hydraulic diffusivity implies a decrease in transmissivity or increase in storativity with period. We consider a variation in storativity to be more likely. The use of storativity implies that water is removed or added to storage as a linear function of head. This is not necessarily the case in a fractured formation where elastic storage is a function of rock stiffness. The expansion and contraction of a fracture is not likely to be a linear function of pressure in realistic systems [*Cappa et al.*, 2006].

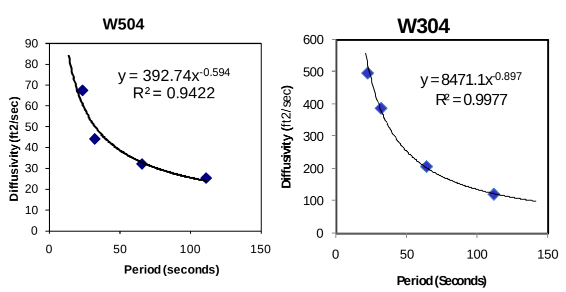

Figure 5. Variation in estimated hydraulic diffusivity with period.

Nakao et al. [2005] saw a similar relationship between the separation in time of pressure pulses and derived hydraulic diffusivity in a Sumikawa Geothermal Field in Japan. They attributed this relationship to the fractured nature of the reservoir and used the relative contribution of matrix and fracture storage to derive fracture spacing. In our case, however, we work in only a single fracture and the primary matrix permeability is essentially negligible. *Renner and Messar* [2006] conducted periodic tests in a fractured sandstone and observed a decrease in hydraulic diffusivity with increasing period. They attributed this behavior to the channelized nature of flow in a fracture. Water moves primarily through a "backbone" of channels with storage of water in smaller aperture regions. Longer harmonic periods, they conjecture, allow for more water exchange with these tighter regions and, consequently, a larger effective storativity and smaller hydraulic diffusivity. We are presently comparing multiple conceptual models to interpret the data.

Well 204 also demonstrates a general decrease in diffusivity with period but the trend is not regular as in Well 304 and 504. We attribute the poor trend to the highly connected nature of Well 204 with Well 404, which makes model fitting problematic. Hydraulic diffusivity inverted from model fits to the hydraulic response range between 10^{15} to 10^{19} ft^2/sec. This is more than 13 orders-of-magnitude greater than hydraulic diffusivities determined from Wells 304 and 504. At these diffusivities Darcy's Law may not be valid. Well 104 is not interpreted here due to the long wavelength influence on the heads that were alluded to previously.

Finally, we compare the hydraulic diffusivity determined through these harmonic tests to those derived through a Theis well function fitting of constant rate drawdown tests. *Figure 6* shows the drawdown versus log-time plot for a test in which Well 404 was pumped at 4.2 lpm [*Talley*, 2005].

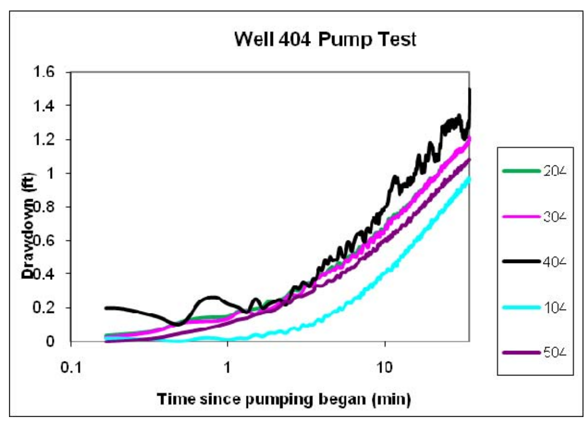

Figure 6. Drawdown from a constant rate pumping tests conducted in the same wells in which the harmonic tests were conducted.

In agreement with the harmonic tests, Well 104 shows a poor hydraulic connection to Well 404. Also in agreement with the constant rate tests, the harmonic tests show a very good connection between

Well 204 and 404. There is a slight discrepancy between the two methods, however, in that Well 304 and 204 behave very similarly in the constant rate test, while 304 and 504 behave similarly in the harmonic tests (*Figure 3*).

The hydraulic diffusivities derived from fitting of the standard Theis equation to the constant rate tests are shown in *Table 1*. Hydraulic diffusivities determined from the harmonic test vary over a much greater range than those determined from the constant rate test. Constant rate tests produce hydraulic diffusivities that are within 5% for Well 304 and 504, for example, while the harmonic tests produce estimates that differ by about an order-of-magnitude between the wells.

Table 1: Hydraulic parameters derived from constant rate tests.

Well	T (ft^2/s)	S	D (ft^2/s)
204	4.9E-04	2.3E-04	2.18
104	4.4E-04	4.6E-04	0.97
304	4.7E-04	2.4E-04	1.91
504	5.1E-04	2.8E-04	1.81

CONCLUSIONS

The practical advantages of periodic hydraulic tests are well known and have been exploited in the petroleum industry for decades. Periodic tests do not require an additional net withdrawal or injection of fluid so they can be conducted without cessation of operations. In geothermal fields, this means injection or pumping rates can be varied in a periodic manner to determine hydraulic properties, even after wells are put into production. Such post-completion information can be valuable for well infilling.

There is a potential advantage in periodic tests beyond the purely practical. The harmonic hydraulic tests conducted here by oscillating a slug in a bedrock well showed greater sensitivity to formation heterogeneity than more traditional constant-rate (Theis) tests. All four monitoring wells showed distinctly different responses in the harmonic tests while only one well was obviously less connected as interpreted from the constant rate tests.

Harmonic tests may provide information regarding scaling of heterogeneous hydraulic properties. Although interpretation varies, harmonic tests in this fractured formation and at least two others [*Nakao et al.*, 2005; *Renner and Messar*, 2006] show a decrease in hydraulic diffusivity with increasing period of pressure pulsing. This result deserves more attention as it may provide a method by which the channelization of flow may be quantified in geothermal fields. Channelization or "short-circuiting" of flow has important implications for heat transfer in geothermal reservoirs.

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