Journal of Hydrology 531 (2015) 2–16

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Frequency dependent hydraulic properties estimated from oscillatory pumping tests in an unconfined aquifer

Avinoam Rabinovich [a,*], Warren Barrash [b,c], Michael Cardiff [d], David L. Hochstetler [c], Tania Bakhos [c], Gedeon Dagan [e], Peter K. Kitanidis [c]

[a] Department of Energy Resources Engineering, Stanford University, Stanford, CA, USA
[b] Department of Geosciences, Boise State University, Boise, ID, USA
[c] Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, USA
[d] Department of Geoscience, University of Wisconsin-Madison, Madison, WI, USA
[e] Faculty of Engineering, School of Mechanical Engineering, Tel-Aviv University, Tel-Aviv, Israel

ARTICLE INFO

Article history:
Available online 17 August 2015

Keywords:
Periodic pumping
Oscillatory pumping
Field tests
Equivalent properties
Effective properties
Specific yield

SUMMARY

Oscillatory pumping tests were conducted at the Boise Hydrogeophysical Research Site. A periodic pressure signal is generated by pumping and injecting water into the aquifer consecutively and the pressure response is recorded at many points around the source. We present and analyze the data from the field test after applying Fourier analysis. We then match the data with a recently derived analytical solution for homogeneous formations to estimate the equivalent aquifer properties: conductivity K, specific storage S_s and specific yield S_y. The estimated values are shown to be in agreement with previous estimates conducted at this site. We observe variations in the estimated parameters with different oscillation periods of pumping. The trend of the parameters with changing period is discussed and compared to predictions by existing theory and laboratory experiments dealing with dynamic effective properties. It is shown that the results are qualitatively consistent with recent works on effective properties of formations of spatially variable properties in oscillatory flow. To grasp the impact of heterogeneity, a simple configuration is proposed, helping explain the observed increase in effective conductivity with decreasing period.

1. Introduction

Estimation of aquifer properties is essential in applications such as aquifer management, remediation of contaminants, and oil or gas exploration. Numerous approaches have been reported and tested throughout the years. Pressure-based methods are those for which changes in water pressure associated with aquifer stimulations are measured and the most prominent of these are constant rate pumping tests and slug tests. Oscillatory or periodic pumping tests are alternative methods involving consecutive periods of pumping and injection resulting in alternating flow. These tests have the following advantages. First, there is no net water extraction from or injection into the aquifer avoiding possible costs and risks associated with handling and treating contaminated water. Second, periodic pumping should cause less contaminant plume movement than a constant-rate pumping test. Third, the oscillating signal of known frequency is separable from changing background pressure. In petroleum applications, this means the tests can be conducted without disrupting the production process. Furthermore, testing over a range of frequencies is possible, a widely applied and powerful tool in signal processing (see e.g., Oppenheim et al. (1989) and Zhao et al. (2009)). Finally, the zone in which flow is influenced by pumping expands as period increases, allowing gradual exploration of the spatial properties of the aquifer.

In this work we present and analyze results from oscillatory pumping field tests conducted at the Boise Hydrogeophysical Research Site (BHRS) (Barrash et al., 1999). The experiments involve short periods of oscillation between 10 and 75 s. We arrive at large-scale equivalent or effective aquifer properties by matching the field measurements with an analytical solution to a three-dimensional partially penetrating well model of a homogeneous medium (Dagan and Rabinovich, 2014). Our first goal is to evaluate the feasibility of using oscillatory tests for characterizing aquifer properties. Our second goal is to investigate the behavior of equivalent properties, namely conductivity K, specific storage S_s

---

[*] Corresponding author at: Department of Energy Resources Engineering, Stanford University, Stanford, CA 94035, USA. Tel.: +1 650 723 1594.

E-mail address: avinoamr@stanford.edu (A. Rabinovich).

http://dx.doi.org/10.1016/j.jhydrol.2015.08.021
0022-1694/

Table 1
Summary of oscillatory tests performed.

Test name	Pumping interval elevation [m]	Period [s]	Stroke length [m]	Discharge amplitude [liter/s]
0712 Test 1	836–837	73	0.7	0.06
0712 Test 2	836–837	46.5	0.7	0.095
0712 Test 3	836–837	65	0.7	0.068
0712 Test 4	836–837	30	0.7	0.147
0715 Test 4	839–840	69	0.7	0.064
0715 Test 6	839–840	40	0.7	0.11
0715 Test 7	839–840	28.5	0.7	0.154
0715 Test 9	841.5–842.5	59	0.7	0.075
0715 Test 10	841.5–842.5	40	0.7	0.11
0715 Test 12	841.5–842.5	31.5	0.7	0.14
0717 Test 2	836–837	15	0.22	0.092
0717 Test 3	836–837	9.8	0.22	0.141
0717 Test 8	841.5–842.5	24	0.22	0.058
0717 Test 9	841.5–842.5	18	0.22	0.077

and specific yield S_y with changing period of pumping oscillation. This may have important implications for future use of oscillatory pumping, being a first step towards a more detailed and complex investigation of aquifer properties.

The idea of periodic pumping tests is found in the literature as far back as Kuo (1972) and the related method of pulse pumping even earlier (Johnson et al., 1966). However, few oscillatory pumping field tests have been previously reported. Rasmussen et al. (2003) conducted a field test using a fully penetrating pumping well with a large period of oscillation (1–2.5 h). They estimate the aquifer properties using analytical solutions. Their results are only for a single pumping frequency with no discussion of frequency dependent properties. A more comprehensive field test was performed in Renner and Messar (2006) on a fractured sandstone bedrock. A wide range of periods (10–5400 s) were applied to a fully penetrating pumping well. The aquifer properties were estimated using a simple analytical solution of infinite radial flow. The variation of aquifer properties with pumping period was analyzed, however no detailed physical mechanism explaining the period dependence was suggested. Additional analysis of data from the Renner and Messar (2006) field test was presented in Fokker et al. (2012b, 2013). Recently, Becker et al. (2010) and Guiltinan and Becker (2015) performed periodic slug tests with periods of 1-4 min on a water-bearing bedding plane fracture. Parameters were obtained by fitting data with an analytical solution of a fully penetrating pumping well in a confined aquifer. The parameter variation with period was closely examined in this work. Results showed transmissivity decreases while specific storage increases with increasing period and diffusivity varies by more than an order of magnitude across the range of pumping periods tested. The authors suggest this behavior is associated with flow in fractured media and the details of this behavior were considered by them to be an open question that deserves further analysis. Other related, but less relevant, field tests are mentioned in Cardiff and Barrash (2014) and summarized in their Table 1.

Analytical, numerical, and laboratory investigations on oscillatory pumping tests have also been performed. Analytical solutions and theoretical tools are presented in Black and Kipp (1981), Dagan and Rabinovich (2014), Cardiff and Barrash (2014) and Hollaender et al. (2002). Numerical methods tested on synthetic data are reported in Ahn and Horne (2010), Fokker and Verga (2011), Fokker et al. (2012a), Cardiff et al. (2013a) and Bakhos et al. (2014). Laboratory experiments on oscillatory flow in rock samples have been previously conducted, e.g., in Song and Renner (2007).

Many pumping tests attempt to predict the aquifer properties by matching field data to a solution assuming homogeneity. We refer to such estimated properties as “equivalent”. Our approach uses measured periodic head fluctuations in observation wells to identify aquifer hydraulic properties, which are estimated using the best fit between measured and computed heads over all measurements in space. These equivalent parameters assume spatial homogeneity, but are allowed to vary with period of testing by estimating them for each oscillation period independently. One of the main findings is a change of equivalent properties with period, which can be attributed to spatial heterogeneity. Equivalent properties are also related to effective ones, defined as a ratio between average quantities, for example mean flux and mean head gradient in the case of effective conductivity (e.g., Renard and De Marsily, 1997). Here, we use the term “effective” to refer to such properties, specifically we will discuss effective properties derived stochastically (e.g., Dagan, 1986). This was the topic of recent works (Rabinovich et al., 2013a,b) dealing with the dependence of effective properties on frequency for one-dimensional mean flow and we show by a simple model that the results are qualitatively consistent. However, the quantitative analysis of the impact of heterogeneity is beyond the scope of the present study.

The discussion on effective properties in oscillatory flows is relatively new. In Rabinovich et al. (2013a), frequency dependent effective hydraulic properties were derived for a heterogeneous media composed of randomly distributed spherical inclusions, for the mean one-dimensional configuration of a semi-bounded domain, with an oscillatory uniform head applied on the boundary. This approach was extended to a log-normal distribution of permeability in Rabinovich et al. (2013b). In these works the effective properties were considered complex numbers. An important finding is that for large periods the dynamic effective conductivity is real and equal to the steady state property while for small periods it increases with decreasing period. The analysis of the equivalent and effective properties for the more complicated three-dimensional oscillatory well flow is a topic not yet explored in the stochastic context.

Even for analyses using homogeneous aquifer solutions, all of the previous oscillatory pumping field tests did not consider the impact of the presence of a water table and assume a confined aquifer, neglecting specific yield. In constant rate pumping tests, the specific yield is important and commonly computed assuming instantaneous drainage (Moench, 2004). However, in high frequency oscillatory flow the specific yield does not comply with this assumption. The topic of specific yield in oscillatory flow has been studied both theoretically, e.g., Green and Ampt (1911), Barry et al. (1996) and in laboratory experiments, e.g., Nielsen and Perrochet (2000) and Cartwright et al. (2003, 2005). Similar to the effective conductivity and specific storage, the effective specific yield is defined as a complex parameter and found to vary substantially with frequency. The real part of the complex specific yield changes from the steady state value (i.e., instantaneous drainage) at low