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Slug Interference Tests: Performance and Comparison

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Abstract

This study presents procedure and analysis method for not well known slug interference tests. Results of the slug interference tests were compared with those of pumping and recovery tests and conventional slug tests.

key word : slug interference test, pumping test, slug test

1. Introduction

Aquifer test methods available for characterizing hazardous waste sites are sometimes restricted because of problems with disposal of contaminated groundwater (Spane, 1996). And the perturbations like pumping of large amounts of groundwater may cause operating pressure problem for underground gas storage station. For these reasons, slug test has been a popular method for estimating hydraulic parameters at such sites. However, as is well known, in highly permeable formations, single-well slug test results often cannot be analyzed and are erroneous (Spane, 1996). Slug interference test is one method that seems to hold promise for characterizing such sites. This method requires at least one more well except a stress well. This test is conducted by applying a stress at one well by instantaneous manner like a conventional slug test. Thereafter the responses are monitored at one or more observation wells. Because the amplitudes of the responses at the observation wells may be so small, this technique is only useful in wells in proximity. Reported slug interference tests have been conducted in confined aquifers and fractured rock formations with small values of storativity. Discussions relating to slug interference responses for fully penetrating wells in isotropic confined aquifers are contained in Ramsey et al. (1975), Sageev (1986), Karasaki et al. (1988) and Novakowski (1989). But recently Spane (1996) applied this method to an unconfined aquifer.

2. Analysis method

For analyzing of slug interference tests an analytical solution suggested by Cooper et al. (1967) was used. They presented the Laplace space solution of pulse interference test and pumping test with considering wellbore storage and wellbore skin effects. And Novakowski (1990) provided the type curve generating program of the aquifer tests on the basis of the solution. In this study, the program was used to analyze responses of the slug interference tests conducted. The program was obtained by personal contact. A detailed analytical justification of the slug interference and pumping solution derivation is not concern of this study. But shortly stated, the governing equation for transient groundwater flow with wellbore storage in the source well is given as ;

$$\frac{\partial^2 h_D}{\partial r_D^2}+\frac{1}{r_D}\frac{\partial h_D}{\partial r_D}=\frac{\partial h_D}{\partial t_D} \quad (1)$$

Dimensionless parameters for head (h_D), time (t_D), distance (r_D) and wellbore storage constant (C_D) are defined below.

$$h_D=\frac{h}{h_o},\quad t_D=\frac{Tt}{r_w^2 S} \quad (2)$$

$$r_D=\frac{r_o}{r_w},\quad C_D=\frac{r_c^2}{2\,r_w^2 S} \quad (3)$$

where h = observed head at time t , minus pretest static head level in observation well; h_o = instantaneous head change applied to stress well at the start of the slug perturbation; r_o = radial distance between stress and observation wells; r_w = effective stress well radius; r_c = stress well casing radius. Wellbore storage is described in dimensionless form by;

$$\frac{dh_{WD}}{dt_D}=\frac{1}{C_D}\left.\frac{\partial h_D}{\partial r_D}\right|_{r_D=1} \quad (4)$$

The Laplace domain solution of equation (1) in consideration of (4) is given as;

$$\overline{h}_D(r_D)=\frac{K_o(r_D\sqrt{p})}{\sqrt{p}[\sqrt{p}K_o(\sqrt{p})+(1/C_D)K_1(\sqrt{p})]}$$

where K_o and K_1 are modified Bessel functions of integer order and p is the Laplace variable. All of the type curves used here are generated by numerically inverting the solution from Laplace domain.

3. Results and Discussion

Four sets of slug interference tests were conducted in the same well couple in January 1997. The two wells, P.W and C-I are distant of radially 5.02 meters. Firstly, a stress to P.W well was applied by injecting known volume of stainless steel dummy. And responses at C-I well and the stress recession at P.W well were monitored. When the first perturbation of the two wells disappeared, the dummy was again withdrawn to create another stress in P.W well. In this manner one more test was performed. Now, the first stress well, P.W was replaced by the observation well, C-I as a stress well. A stress to C-I well was applied and a response of P.W well was observed. Time lag between the stress of P.W well and the response of C-I well nearly can't be detected. But according to time series analysis, about 4.5 and 6.5 seconds of time lags with stress wells of P.W and C-I wells respectively were noticed. This rapid propagation of stress indicates a direct hydraulic connectivity of the two wells by major fractures. The major fractures are also identified by borehole cores and borehole camera data. As stated before, the responses were matched with type curves obtained from the slug interference type curve generating program presented in Novakowski (1990). The analysis proceeded iteratively by changing hydraulic property input values until an optimal match with the observed interference response was obtained. When the iteration was completed, we can get the dimensionless head (h_D), time (t), t_D/C_D and C_D by selecting one match point. From these determined variables, transmissivity and storativity can be calculated through equations (2) and (3). Estimated parameters are summarized in Table 1. As noted in the table, transmissivities T of different slug types, injection and withdrawal were estimated nearly the same. But the storativity S shows some variation by one order. Like pumping and slug test analysis, this test analysis method also don't provide storativity estimation stability. This is explained by the results of the sensitivity analysis of the type curve presented in Novakowski (1990) that transmissivity exerts a strong influence on the transmission time of the slug interference response while storativity primarily influences response amplitude and shape. With large variation of S, the type curve shows little noticeable variation.

Table 1. Results of the slug interference tests conducted at P.W and C-I wells.

Stress Well	Observation Well	Stress Type	Transmissivity (m^2/min)	Storativity
P.W	C-I	Injection	1.94E-02 1.81E-02	5.0E-06 5.0E-07
		Withdrawal	1.63E-02 2.00E-02	2.5E-06 5.6E-06
C-I	P.W	Injection	2.04E-03 3.99E-03	1.0E-06 1.25E-07
		Withdrawal	1.92E-03 1.02E-02	2.5E-07 1.0E-06

In particular, results from different stress wells are noticeable. For a stress at P.W well, estimates of transmissivity are larger than those of C-I well by one order. This may have two explanations. First, P.W well was slightly upgradient in natural flow condition before the tests. Transmission of a stress applied at P.W well might be accelerated by this gradient. But only small portion can be explained by this effect. More reasonable cause is wellbore radius. Originally, the solution used in data analysis was suggested for the same radius of stress and observation wells. Therefore effects from different radii can't be considered. In reality, P.W and C-I wells have 10.16 and 6.5 cm of well radii respectively. Both wells have different basic time lags in borehole responses to a stress. From Neuman and Gardner (1989), basic time lags of both wells are 5.2 minutes and 0.15 minutes respectively. Therefore effects from skin and instrument lag can't be disregarded. These effects can't be quantified in the present but deserve further study.

Transmissivities obtained from these tests are about five times larger than those of the pumping and slug tests conducted at the same wells while storativities of the tests are ten to one hundred times as small as those of the pumping and slug tests. Those larger values of transmissivities and smaller values of storativities may be attributed to the major fractures developed between two wells, P.W and C-I wells. As is widely known, fractures have large transmissivities and small storativities. Interference stresses propagate quickly through main fractures. For pumping tests, flow over entire aquifer thickness were assumes for analysis easiness. In fractured media like the study aquifer, lumped hydraulic parameters of both fractures and rock matrix are likely to be underestimated for transmissivity and to be overestimated for storativity of the fractures.

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