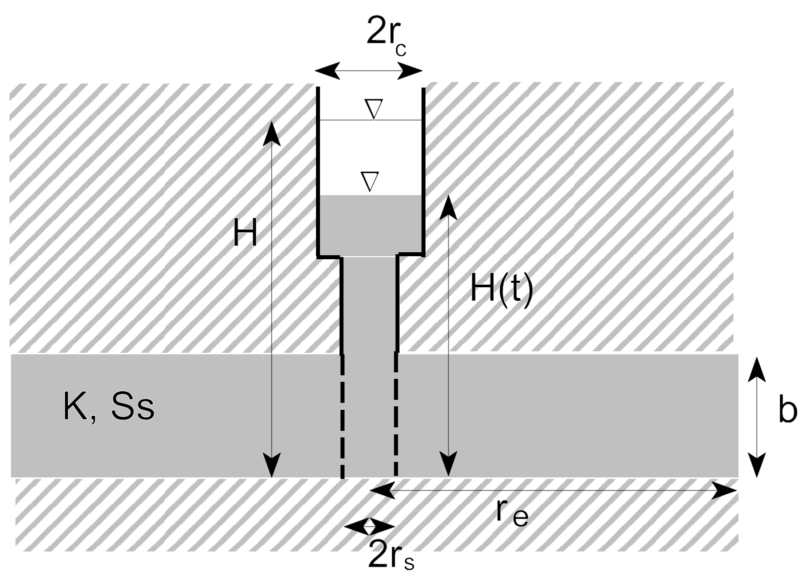
Slug test

Slug test is one of the common techniques that has been widely used in the field to determine the hydraulic properties of aquifers. It is rapid, economical, and simple. The slug test field procedure imposes a relatively fast initial change in water level within a well and then observes the return to original water level within the well.

Hvorslev (1951) may have been the first to point out that a slug test can be used to estimate *in-situ* hydraulic conductivity. He developed mathematical models for a variety of well, piezometer, and standpipe geometries with full or partial penetration in an infinite, semi-infinite below, or confined homogeneous, anisotropic aquifer. All the models assume no aquifer storage (this is equivalent to assuming incompressible fluid and rigid aquifer matrix) so that the flow system is under quasi-steady flow. It also assumes finite wellbore storage.

Consider a slug test setup as illustrated in Figure 1.



If the medium is rigid and the fluid is incompressible, the governing partial differential equation for flow in the porous medium around the well can be written as:

$$\frac{\partial q_r}{\partial r} = 0$$
$$= -\frac{\partial}{\partial r}\left(bKr\frac{\partial h}{\partial r} \right)$$

This equation describes the flow field at $r > r_s$ at any given time. The boundary condition at $r = r_s$ at any time is:

In this study, the slug test was selected as the means for estimating hydraulic conductivity because of the size of the well, the simplicity, and the cost of the instrumentation for the slug test. The apparatus for the slug tests was designed by Williams et al. (1994) and is illustrated in Figure 2. It consisted of a water reservoir, three air venting valves, and a PVC pipe which connected the reservoir through a flexible tube. At the end of the PVC pipe, twelve 0.63 cm holes were drilled over an approximately 15 cm section and a screen was installed. . Three O-rings were installed at the top and bottom of the screened interval as packers to isolate the flow. The PVC pipe can be placed at any given location along the well.

The test procedure consisted of 1) placing the screened tip at a desired depth, 2) pumping water from the aquifer through the PVC pipe up to Valve #2 level (see Figure 2), 3) closing Valves' #2 and 3 and opening Valve #1 to allow water from the reservoir to enter the system and vent the entrapped air. Then, 4) the simultaneous opening of the three valves, letting water flow back to the aquifer. The decline of the water level in the reservoir was then recorded as a function of time. At each well, the slug test was performed at eleven depths at 15 cm intervals.

METHODS OF ANALYSIS.

Methods for analyzing the slug test data developed by Hvorslev (1951), Bouwer and Rice (1976), and Cooper et al. (1967), were employed in this study. All the three methods assume aquifer homogeneity and isotropy. A brief description of each method is given in the following paragraphs.

The Hvorslev (1951) Method. This method states that the rate of flow from the well, q, at any time t is proportional to the hydraulic conductivity, K, of the aquifer and to the decline of the head level in the well, so that

$$q = KF\left(H_0 - h(t)\right) \tag{1}$$

where F is a shape factor which depends on the geometry and dimensions of the well intake and its location within the aquifer, H_0 is the initial head level, and $h(t)$ represents the water level in the well at any given time, t.

For an infinitesimal time interval, dt, the volume of outflow is

$$q\,dt = A\,dh \tag{2}$$

where A is the area of the upper reservoir that contains the slug of water ($A = \pi r_c^2$, where r_c is the radius of the reservoir), and dh is the head drawdown during dt. Solving (1) and (2) results in the following expression for the hydraulic conductivity

$$K = 2.303 \frac{A}{F} \frac{\log[H_1/H_2]}{t_1 - t_2} \tag{3}$$

where H_1 and H_2, are the heads recorded at times t_1 and t_2, respectively.

The shape factor F chosen for this analysis corresponds to the case of a point piezometer (see Fig. 12-8 or 18-G in Hvorslev, 1951). That is, the length of the screened interval is less than one tenth of the saturated thickness of the aquifer. Assuming that the flow lines are symmetrical about a horizontal plane through the center of the well, the shape factor can be expressed as

$$F = \frac{2\pi L}{\left[\ln\left(\frac{L}{2r_w} + \sqrt{1 + \left(\frac{L}{2r_w}\right)^2}\right)\right]} \tag{4}$$

where L is the length of the screen, and r_w is its radius.

The Bouwer and Rice (1976) Method. Although this model was originally derived from Thiem's equation, the final formula resembles that of the Hvorslev method (equation 3). The shape factor used by Bouwer and Rice involves the radius of influence or effective radius, R_e, over which the hydraulic head difference is dissipated and is given by

$$F = \frac{2\pi L}{\ln \frac{R_e}{r_w}} \tag{5}$$

Using a resistance network analog model, Bouwer and Rice (1976) developed an empirical relation between the effective radius, R_e, thickness of the aquifer, b, depth of the well, d, length of the screened interval, L, and the radius of the screen, r_w. This empirical relation is expressed as

$$\ln\left(\frac{R_e}{r_w}\right) = \left[\frac{1.1}{\ln\frac{d}{r_w}} + \frac{A + B\ln\frac{b-d}{r_w}}{\frac{L}{r_w}}\right]^{-1} \tag{6}$$

where A and B are dimensionless coefficients which are a function of L/r_w, and are given in Bouwer and Rice (1976). Bouwer and Rice (1976) also reported that the values of $\ln R_e/r_w$ calculated by equation (6) are within 10% of the actual value as evaluated by the analog if $L > 0.4d$, and within 25% if $L << d$ (e.g., $L = 0.1d$). Butler (1993) reported that the Bouwer and Rice method provides estimates that are within 30% of the hydraulic conductivity of the formation for aspect ratios commonly employed in the field.

The Cooper et al. (1967) method. This method is the only one among the three that allows a simultaneous estimation of the conductivity and storage coefficient of an aquifer. It is based on an analytical solution of the governing equation for two-dimensional radial flow toward/from a fully penetrating well in a confined aquifer

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad r > r_w \tag{7a}$$

where T is the transmissivity and S is the storativity of the aquifer. The boundary conditions associated with the analysis are

$$h(r_w, t) = H(t), \qquad t > 0 \tag{7b}$$

$$h(\infty, t) = H_0, \qquad t > 0 \tag{7c}$$

$$(2\pi r_w T)\frac{\partial h(r_w, t)}{\partial r} = \pi r_c^{\,2}\frac{\partial H(t)}{\partial t}, \qquad t > 0 \tag{7d}$$

The initial conditions outside (equation 7e) and inside the well (equation 7f) are

$$h(r,0) = 0, \qquad t > 0 \tag{7e}$$

$$H(0) = H_0 = \frac{V}{\pi r^2{}_c} \tag{7f}$$

Cooper et al. derived the solution to these equations and provided a set of type curves which allows the estimation of the transmissivity, *T*, and the storativity, *S*, of the aquifer. The hydraulic conductivity can be calculated by the relationship *K* = *T/b*, where *b* is the thickness of the aquifer and in this study, *b* was taken as the length of the screened interval. A study by Dax (1987) indicated that, as the ratio of the aquifer thickness to well radius increases, Cooper's solution can be used in unconfined aquifers.

To apply the Hvorslev, and Bouwer and Rice methods, the log of water level was plotted against time; a continuous straight line was obtained in most data and linear regression was used. The very early time portion of some data sets showed the effect of the disturbed annulus created by the installation of the well (Bouwer, 1989), and it was avoided in the regression. Equation (3) was then used to estimate the hydraulic conductivity with the shape factors given for the test apparatus. During the application of the Bouwer and Rice method, effective radii were calculated using equation (6).

The Cooper et al. method was applied to the data through the use of a non-linear optimization routine (Heidari and Hemmat, 1992), which automatically determines the best fit *T* and *S* values. Neither of these two variables were constrained, except that *S* was kept between 0 and 1.