

Effect of Non-Instantaneous Release of Air Pressure on Pneumatic Slug Tests

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Abstract

Pneumatic initiation of slug tests has been used for many years and is an efficient technique, since water is not added or withdrawn from the well and no mechanical slug is required. However, for very permeable aquifers the release of air pressure or vacuum can not be considered instantaneous, as is usually assumed. This paper investigates the response time at the lower end of an air column where the water interface would be by using a pressure transducer, which can measure both positive and negative pressures. As the valve at the upper end of the air column is opened the disturbance propagates through the air column and bounces off the bottom of the air column. The disturbance continues propagating and bouncing off the ends while the air escapes from the valve. The net result is an oscillatory air column response that decays exponentially with time. The step function release that is usually assumed is not obtained in practice. Detailed measurements show that the decay is an exponential function of the square root of time and a decay constant. The period of the oscillation is dependent on the length of the air column, with shorter lengths giving higher frequencies. The decay constant seems to vary inversely with the square root of the initial pressure and directly with the air column length for a given initial pressure. For configurations tested and typical field situations the air column goes to atmospheric pressure within about 2 seconds. This means that for slow responding aquifers the effect is minimal. However, for very highly permeable aquifers where the slug test lasts only a few seconds (we have tested many in this category), the deviation from step function release of air pressure or vacuum might have a significant effect on the data analysis using a specific model for slug test response. We have simulated the aquifer response for various sizes of release valve outlet diameters, covering a wide range of values. There is little difference in the aquifer responses for any of the tested outlet diameters. It seems that the size of the outlet is not a major factor and most field setups will not cause a problem due to non-instantaneous release of the air pressure, unless very small valves are used with large casing air volumes.

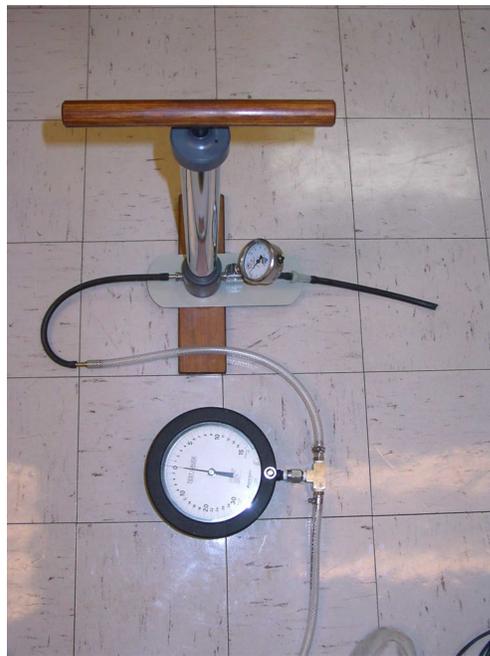
Multilevel Slug Tests at a Field Site

We have developed an experimental field site in the Kansas River alluvium. The alluvium at the site consists of an upper layer of silt and clay about 35 feet thick and a lower unit of sand and gravel, also about 35 feet thick. The sand and gravel forms the main aquifer in the area and exhibits some very large values for hydraulic conductivity. However, the aquifer is heterogeneous and we have embarked on a study of the vertical distribution of hydraulic conductivity at several fully screened 2 inch PVC wells (McElwee and Ross, 2001). The vertical distribution of hydraulic conductivity is being measured with multilevel pneumatically induced slug tests. The slugged interval is isolated with a double packer and the slug test is performed inside a 1 1/4 inch flush thread PVC pipe inserted into the well. The field setup is shown in the figure below. The wells are distributed over the study area and should also give us an indication of the lateral variation in hydraulic conductivity. Slug tests in the main aquifer only last a few seconds; so, we were concerned about the possible effect of non-instantaneous release of pressure about the water column. This is the impetus for work reported here. Zurbuchen et al. (2002) have done some preliminary work on this question also.



Experimental Setup

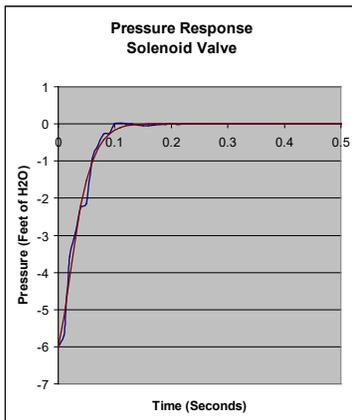
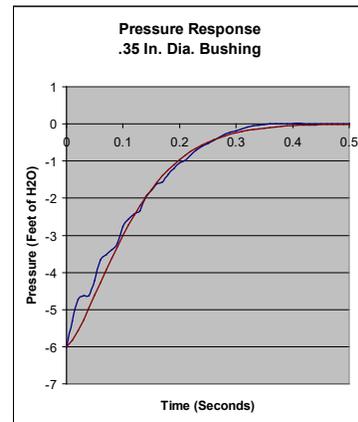
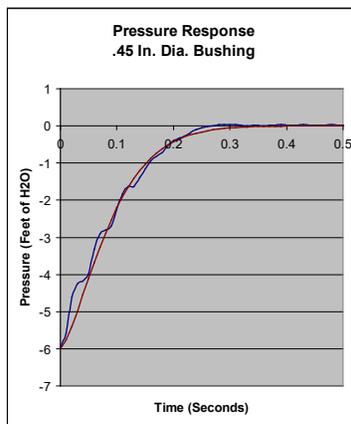
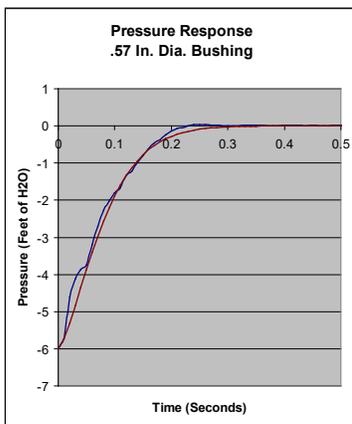
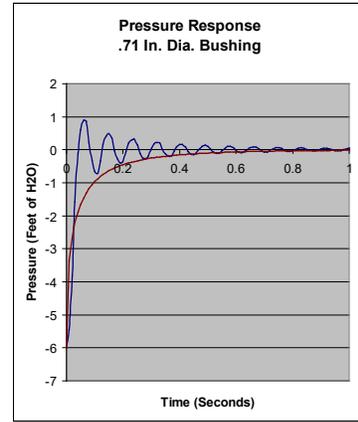
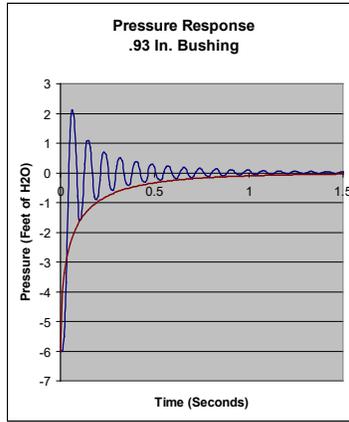
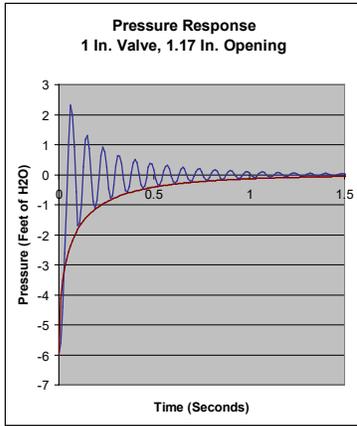
In order to investigate the release of air pressure or vacuum above the water column in a slug test, we used 1.25 inch flush thread casing of various lengths with a transducer at the lower end and a valve release mechanism at the top. This setup was arranged in the laboratory to allow measurements of the air pressure response at the lower end when the release valve is opened. The measured response should be indicative of what is felt at the top of the water column in a pneumatically induced slug test. Pictures of the setup are shown below.



The pressure transducer used at the bottom was an Omega PX243 capable of reading pressure and vacuum with a one millisecond response time. Its response range was ± 15 PSIG. The pressure or vacuum was applied with a Soil Moisture Equipment Corp. hand pump. It is normally used with tensiometers and lysimeters; however, it works well for applying pressure or vacuum to a pneumatically induced slug test. The pressure in the column was monitored with an Ashcroft test gauge capable of measuring pressure or vacuum to ± 15 PSIG with an accuracy of .25%. The data were recorded on a National Instruments 16 bit data logger at 100 Hz and 1000Hz sample rates. The valve at the top is a 1 inch ball valve and has a discharge opening diameter of 1.17 inches. To measure the effect of various diameter discharge openings, we took data with bushings threaded into the discharge opening to decrease the diameter.

Measured Responses

Experiments were performed for a variety of air column lengths and for several initial pressure or vacuum values for various outlet valve diameters. The flush thread casing came in 5 foot lengths and could be screwed together to achieve various air column lengths. We used 2, 4 and 6 of the 5 foot lengths. The 1 inch valve shown in the experimental setup earlier had a 1.17 inch diameter opening. We also used bushing that reduced the outlet diameter to .93, .71, .57, .45, and .347 inches. In addition, we had a commercial 1 inch electrically operated solenoid valve that was tested. This valve did not open very wide, so we believed it could be fairly restrictive. The measured responses at the lower end of the air column are shown for 4 sections of casing and for an initial vacuum (P_o) of -6 feet of water.



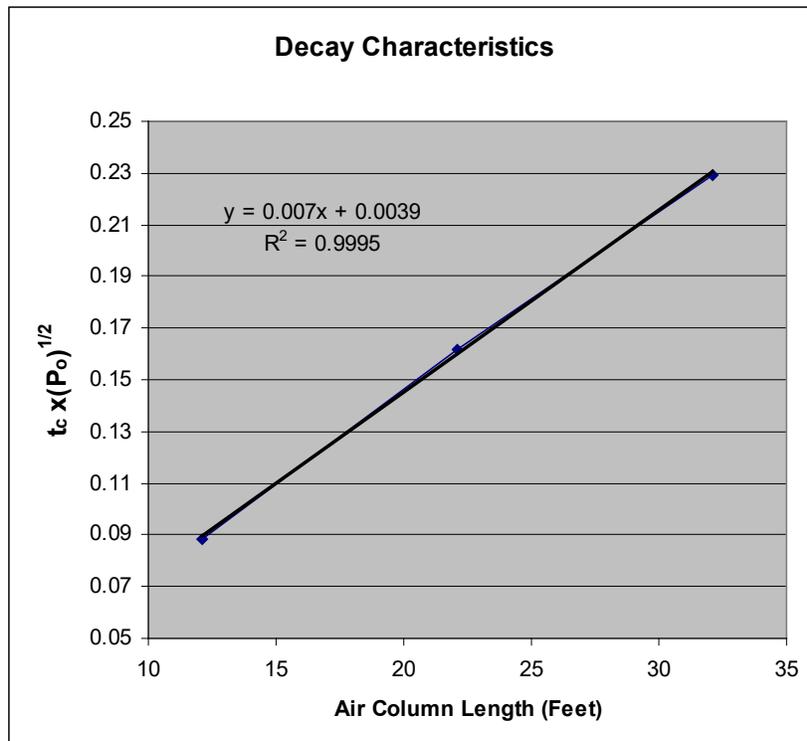
Comments on Measured Responses

The measured responses are oscillatory for the larger outlet diameters; but, for the smaller opening only exponential decay occurs. The frequency of oscillation is easily calculated based on the rules for organ pipes given in most general physics texts. For an organ pipe open on one end and closed

on the other, the length of the air column is 1/4 of the wavelength. The frequency can be calculated from the usual wave equation: $v = f\lambda$. The velocity of sound in dry air is 1087 ft/sec. Measuring the length of the casing gives a very good estimate of the frequency observed in the measured responses. For the data shown with 4 sections of casing and the end pieces the total length is about 22 feet, giving a wavelength of about 88 feet and a frequency of about 12 Hz. This is in very good agreement with data shown here. Similar data not shown for 2 sections of casing give a resonant frequency of about 21 Hz and for 6 sections a resonant frequency of about 8 Hz, all in very good agreement with the theoretical calculations. Originally, the measured responses were recorded with at sample rate of 100 samples per second. As a check on the measured frequency, some data were taken at 1000 samples per second to make sure no aliasing of the frequencies was occurring. In the graphs of measured responses there is a solid red line indicating a type of exponential decay. In the case of oscillating responses the red line decays exponentially with the square root of time and represents a decay envelope for the oscillating signal.

$$\text{Amplitude} = \text{Original Amplitude} \times \exp\left[-(t/\tau)^{1/2}\right]$$

τ is the decay constant and seems to vary inversely with the square root of the initial pressure and directly with the air column length, as shown in the following plot.



For all the measured responses that do not oscillate, the response seems to decay exponentially with time to the 1.4 power.

$$\text{Amplitude} = \text{Original Amplitude} \times \exp[(-t/\tau)^{1.4}]$$

Notice that the decay constant for the non-oscillating responses increases as the diameter of the outlet decreases. It seems that the commercial solenoid valve is pretty good at restricting the oscillation and at the same time allowing the decay to occur rapidly. The red curves on the measured response plots showing exponential decay with time to the 1.4 power seem to represent the experimental data fairly well.

Calculated Model Response

A general nonlinear model based on the Navier-Stokes equation, nonlinear frictional loss, non-Darcian flow, acceleration effects, radius changes in the wellbore, and a Hvorslev model for the aquifer has been developed (McElwee and Zenner, 1998) for slug tests.

$$(h + z_o + b + \beta) \frac{d^2 h}{dt^2} + A \left| \frac{dh}{dt} \right| \frac{dh}{dt} + \frac{g \pi r_c^2}{FK} \left(\frac{dh}{dt} \right) + gh = 0$$

The nonlinear model has three parameters: β is related to radius changes in the water column, A is related to the nonlinear head losses, and K is the hydraulic conductivity. We find that the model is quite robust in its estimates of K over varying conditions and allows a wide range of slug test data to be analyzed with a greater accuracy than traditional linear methods. F is the Hvorslev form factor, r_c is the casing radius, z_o is the depth of the screen below static water level, and b is the screen length. This model reduces to the Hvorslev model when the first two terms are negligible. However, in the case of pneumatically induced slug tests, the pressure or vacuum above the water column in the casing must be included in this equation. We assume that originally a pressure P_o is applied and allowed to equilibrate with the water column before being released rapidly with a valve, that it decays exponentially with time, and that an oscillatory response is possible. Under these assumptions, the gh term in the above equation is modified to

$$g \left(h + \frac{P_o}{\gamma} e^{-(t/\tau)^{pow}} \cos(2\pi ft) \right)$$

where f is the frequency of oscillation of the air column and pow is the power of the exponential decay.

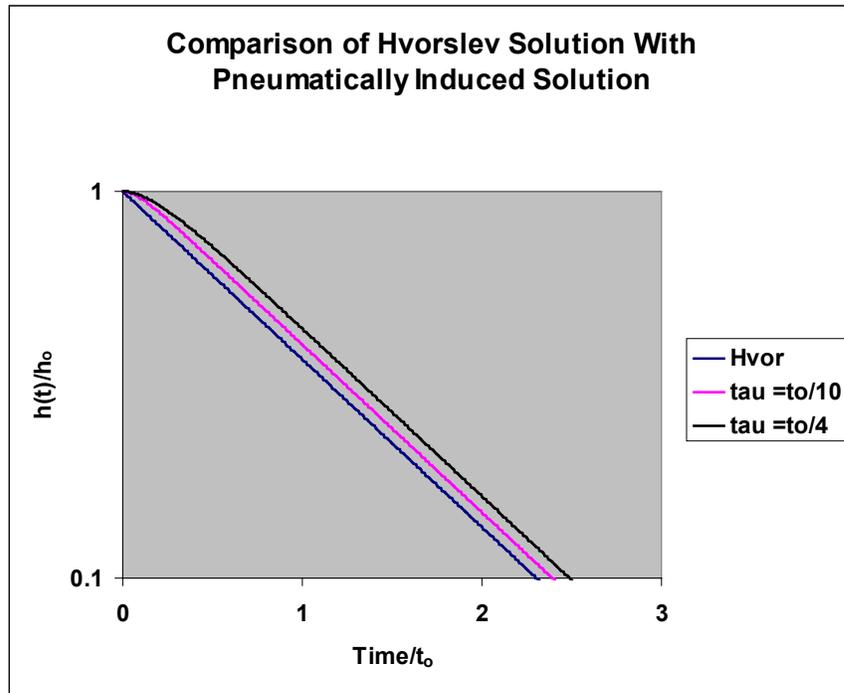
In the case of no air column oscillation and $pow = 1$, there is an analytic solution when the first two terms of the full equation are negligible. This corresponds to the Hvorslev solution for a pneumatically induced slug test and it can be obtained by standard methods for solving differential equations.

$$h(t) = h_o e^{-t/t_o} \left\{ 1 + \frac{\left[1 - e^{-t/\tau} e^{-t/t_o} \right]}{\left[\frac{t_o}{\tau} + 1 \right]} \right\}$$

The characteristic Hvorslev decay time is

$$t_o = \frac{\pi r_c^2}{FK}$$

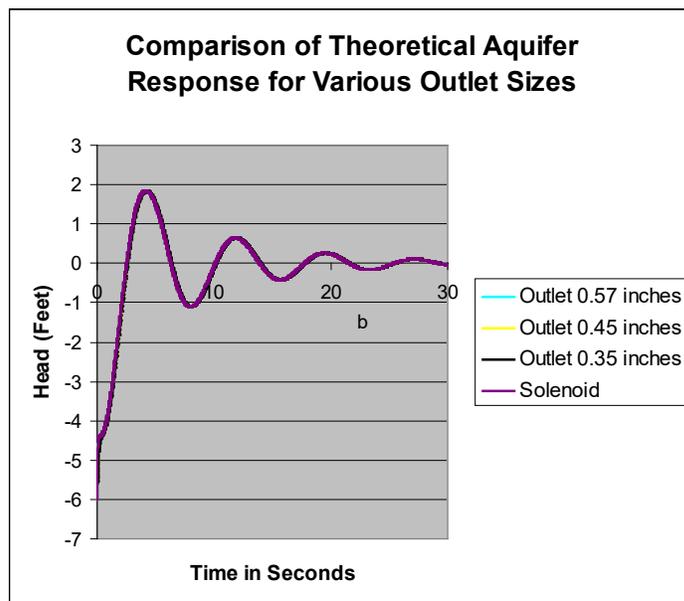
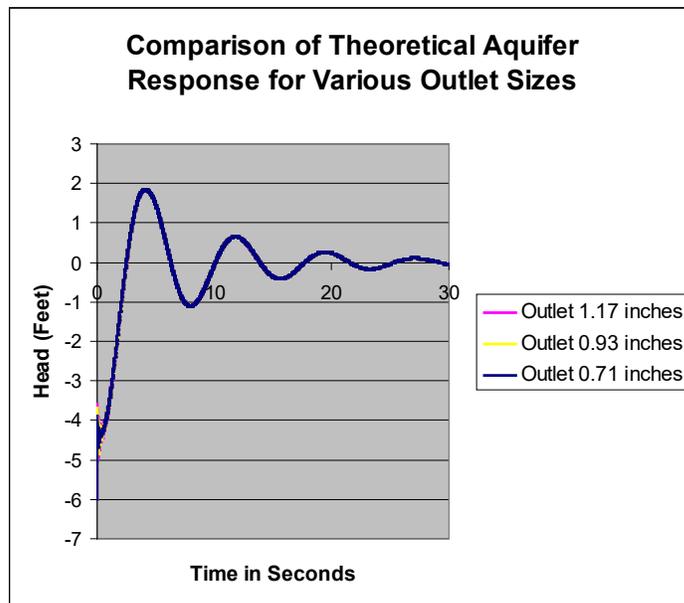
In the case where τ goes to zero, corresponding to instantaneous initiation of the slug test, the above solution reduces to the Hvorslev solution. The solution is plotted in the figure below for two cases, $\tau = t_o/10$ and $\tau = t_o/4$.



Notice that at $t = 0$ the slope dh/dt is zero for the pneumatically induced solution. At long times the pneumatically induced solution is parallel to the regular Hvorslev solution. These two properties can be shown from the analytical solution. Errors can be made in estimating K from the pneumatically induced curves if care is not exercised. Measuring the slope at long time and using that to estimate the K value gives a correct value. However, if one measures the time to achieve the traditional .37 value and uses that to estimate the K , the estimated value for K will be too small.

A smaller K will also be obtained if a best fit straight line through 1 at time zero is used to estimate K . It is seen that the extension of the straight line segment to time zero goes through a value greater than one, implying that a larger initial head was used than the actual value. In the case of $\tau = t_0/10$ in the above figure the K value can be under estimated by about 9%. For the case of $\tau = t_0/4$ in the above figure K can be under estimated by about 18%. Aquifers that respond according to the original Hvorslev solution are usually relatively slow responding and it will normally not be a problem to select experimental equipment that will make τ very much smaller than t_0 .

In the more general case, when ρ is not equal to one and an oscillatory response of the air column is allowed, a numerical solution of the general equation with the expanded gh term is required. The values of τ , ρ , and f can be obtained from the experimental data presented earlier and used in the numerical solution to see how the response of the air column affects the response of the aquifer. The theoretical aquifer responses are shown below for the various outlet diameters for $K = 0.01$ ft./sec., which is about the highest value we have measured experimentally. The first graph shows the outlet diameters for which we have significant air column oscillation. The second graph shows the responses for the smaller outlet diameters where no significant air column oscillation occurred.



Conclusions

There is little difference in the calculated aquifer responses for any of the outlet valve diameters, which is a little surprising. The oscillating air column causes some oscillation near time zero in the first graph above. Even though the measured air column oscillations may continue for significant time periods, it appears that the oscillation about atmospheric pressure gives about the same result as a rapid decrease to atmospheric pressure. This is consistent with the known calculus result that integration of a sine or cosine wave over a cycle will give zero. The smallest diameter outlet does cause a little shift to longer times and slightly decreased aquifer oscillations in the second graph above. However, it seems that the size of the outlet is not a major factor and most field setups will not cause a problem due to non-instantaneous release of the air pressure, unless very small valves are used with large casing air volumes.

References

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