Hydraulic Pulse Interference Tests for Integrity Testing of Containment and Reactive Barrier Systems

by

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ABSTRACT: Hydraulic pulse interference tests involve a cyclic injection of fluid into the source well, and by high precision measurement of the pressure pulse in a neighboring well, detailed hydraulic characterization between wells can be made. The pulse interference test is highly sensitive to hydrogeological properties between the pulse source and receiver wells. The transient nature of the test, involving the time delay and attenuation of the hydraulic pulse, enables the formation's complete hydraulic properties to be computed. The advantages of the pulse interference test are the short duration of the test, the high resolution and directional characterization data obtained, and the lack of any generated contaminated groundwater. To maximize the pulse test's resolution, a small section of the injector well is isolated by packers, the flow rate into the source injector well is rate controlled and set at a constant flow rate depending on the site hydraulic conditions. High precision pressure transducers are located in receiver wells and isolated from receiver borehole storage effects by straddle packers. Thus the pulse is basically a point source, and borehole storage effects are eliminated from both the injector and receiver wells. The injector well is pulsed for a set time, shut in for the same time period, and the cycle repeated. The pulse source and receivers can be located at differing depth locations in their respective wells and a detailed image of the site's hydraulic conditions can be determined. The hydraulic pulse interference test is ideal to test the integrity of a hydraulic containment system or to determine whether a permeable reactive barrier (PRB) impacts groundwater flow. Pulse interference tests are presented pre and post PRB installation for integrity testing of an iron PRB constructed in a confined aquifer from a depth of 45 feet down to a total depth of 110 feet.

INTRODUCTION

Hydraulic pulse interference tests have been utilized in the petroleum industry since the mid sixties, Johnson et. al. (1966), Earlougher (1977), Lee (1982), Kamal (1983) and Horne (1995), primarily as full penetrating aquifer tests, but in some cases as vertical pulse interference tests, Burns (1969) and Hirasaki (1974). The test involves a cyclic injection or withdrawal of fluid from the source well followed by a shut in period, and by high precision measurement of the pressure pulse in a neighboring well, detailed hydraulic characterization between wells can be made, see Figure 1. The hydraulic pulse interference test is highly sensitive to hydrogeological properties between the pulse source and receiver wells. The time delay and attenuation of the hydraulic pulse enable the formation hydraulic properties to be computed. Since the test is a transient test, both the formation transmissivity and storativity can be calculated for a full aquifer penetrating test. Type curves are available for interpreting pulse interference tests, either as a fully penetrating wellbore, with and without borehole storage effects, or partially penetrating wellbore system.

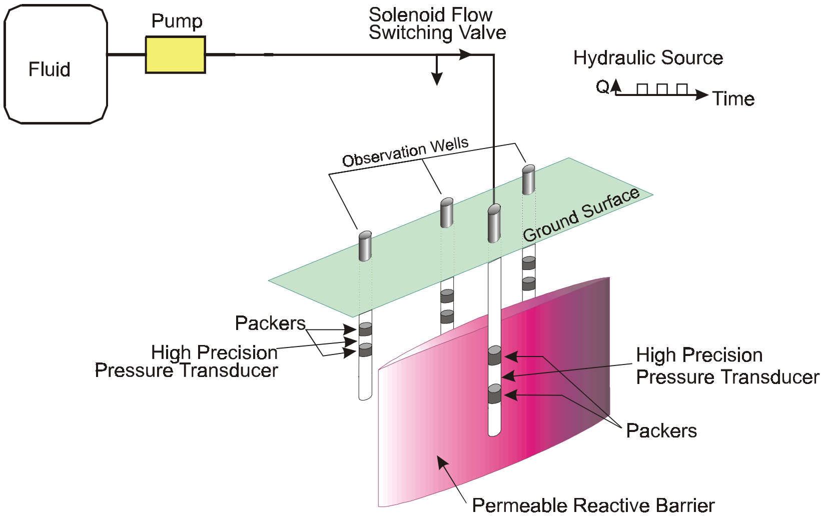

FIGURE 1. Point Source Hydraulic Pulse Interference Test.

Pulse interference testing has not been used extensively in the groundwater or environmental fields. However, considering the advantages of the test; namely, it's short duration, high resolution and directional characterization data obtained, and the lack of any generated contaminated groundwater, the test has considerable merit for both groundwater and environmental applications. To obtain maximum hydraulic property resolution (Hocking and Wells, 1997), the pulse interference test can be constructed as a point source utilizing straddle packers in the injector well. The flow rate into the source injector well is rate controlled and set at a constant flow rate, which will depend on the site hydrogeological conditions. High precision pressure transducers are located in receiver wells and isolated from receiver borehole storage effects by straddle packers. Thus the pulse is basically a point source, and borehole storage effects are eliminated from both the injector and receiver wells. The injector well is pulsed for a set time, shut in for the same time period, and the cycle repeated. The pulse source and receivers can be located at differing depth locations in their respective wells yielding a detailed quantification of the site's hydrogeological properties.

Point source hydraulic pulse interference tests are presented for both the hydrogeological characterization of a site and also for integrity testing of groundwater containment systems, such as slurry or cutoff walls, and permeable reactive barriers (PRB). The mathematical solution of the point source pulse interference test is presented along with a generated type curve for a point source pulse test in a finite confined aquifer system. Quantification of a site hydrogeological parameters both from type curves and non-linear regression analysis are presented. Hydraulic pulse integrity testing of an iron PRB system is presented by comparing pulse interference tests conducted across the proposed PRB alignment both before and after PRB construction. The objective of these tests was to quantify that the PRB had minimal impact on the site's groundwater flow.

MATHEMATICAL MODEL

The point source hydraulic pulse interference test can be modeled from the solution of a continuous point source in an infinite isotropic homogeneous medium (Carslaw and Jaeger, 1986) as given by equation (1). This fundamental solution can be modified to incorporate finite aquifer systems, confined and unconfined conditions, anisotropic and heterogeneous conditions in a similar manner as the line source solution has been modified in the petroleum literature. The line source solution for continuous injection is the exponential integral, whereas the point source solution is the complimentary error function. The pressure response in a receiver well, denoted as $\Delta p(t)$ for a continuous flow rate injection of q in the injection/source well, is given by equation (1).

$$\Delta p(t) = \frac{q}{4\pi K r_w r_D} erfc(r_D / \sqrt{4t_D}) \tag{1}$$

where K is the formation hydraulic conductivity, S_s is the formation specific storage, r_w is the wellbore radius of the source well, r_D is the dimensionless distance being equal to r/r_w, in which r is the distance from the receiver well to the source well, and t_D is denoted as dimensionless time as defined in equation (2).

$$t_D = \frac{Kt}{r_w{}^2 S_s} \tag{2}$$

where t is the elapsed time since start of injection and p_D is denoted as the dimensionless pressure as defined in equation (3).

$$p_D = \frac{4\pi K r_w \Delta p(t)}{q} \tag{3}$$

For the solution of the pulse interference test, equation (1) needs to account for the periodic nature of the injection flow rate in the source well. The time intervals of injection and shut in do not need to be the same, but account for their periodic nature needs to be included. The dimensionless time interval for injection and shut in have been assumed to be the same in this paper with the dimensionless time interval for injection tp_D as defined in equation (4).

$$tp_D = \frac{Ktp}{r_w{}^2 S_s} \tag{4}$$

where tp is the pulsed injection time interval.

PULSE TEST PROCEDURE

The source well injection system consists of inflatable straddle packers to isolate the injection horizon, and a pressure transducer is placed in the source well to monitor injection pressures. The receiver well system also consists of straddle packers isolating the high precision pressure transducer from wellbore storage effects. The injection flow rate is controlled by a constant flow rate direct drive pump with solenoid adjustable time interval switching values to modulate the periodic timed injection and shut in of the source well. A typical hydraulic pulse interference test system is shown in photographs on Figure 2.

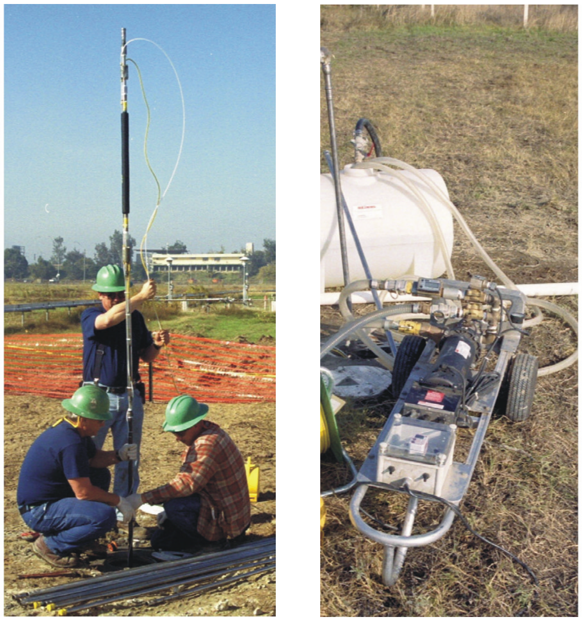

FIGURE 2. Typical Hydraulic Pulse Interference Test Setup.

During the pulse interference test, the source well's flow rate and pressure are monitored along with all of the receiver pressure transducers. It is essential that the pressure transducers are of high precision and that the flow rates and pressures are all continuously monitored and recorded at high data acquisition rates. To ensure the tests are repeatable, the pulse switching mechanism needs to be automatically controlled and recorded on the data acquisition system. To optimize the resolution of the test, the injection/shut in time interval and/or injection flow rate will need to be varied depending on site conditions and the distances between source and receiver wells.

A series of hydraulic pulse interference tests were conducted in a confined aquifer overlain by an upper confining layer from ground surface down to 35 feet below ground surface (bgs) and underlain by a lower confining layer at a depth of 110 feet bgs. Both the source and receiver wells were straddled packed in a screened well section of 2" diameter from a depth of 100 feet down to 105 feet bgs. The receiver well was located 50 feet from the source well. The injection flow rate into the packed off section of the source well was 20 gpm with a pulsed injected time interval of 20 seconds and a shut in time interval also of 20 seconds. The receiver well response is shown on Figure 3 for a series of five (5) pulsed intervals. The maximum receiver pressure response during the first pulsed period is approximately 0.03 psi, with an extremely small time delay between the receiver well response from the source well flow rate change. The injection pressure in the source well was typically less than 5 psi throughout the test. It is imperative that the source well is well developed to enable high injection flow rates to maximize the pulse test resolution, and also minimize source well skin effects. This pulse interference test for the evaluation of formation hydrogeological properties highlights the advantages of the method; namely, its short duration, a single pulse plus shut in period of 40 seconds, and the injection of only seven (7) gallons of water into the formation.

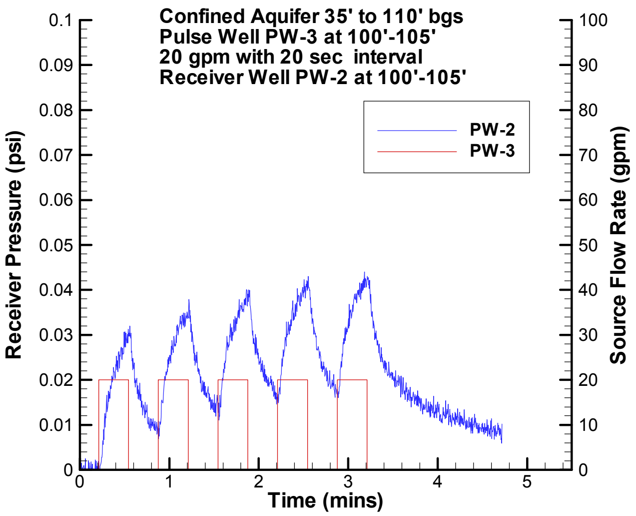

FIGURE 3. Receiver Well Pressure Response during Pulse Test.

PULSE TEST INTERPRETATION

The interpretation of the point source hydraulic pulse interference test follows similar procedures to line source interpretation procedures such as type curves and non-linear regression analysis. The type curve for the confined aquifer test described above was generated using equation (1) modified by the method of images to incorporate the periodic nature of the injections and also the confined nature and finite thickness of the aquifer system. The type curve generated is shown on Figure 4 as a plot of dimensionless pressure versus dimensionless time. The dimensionless pulsed time interval is labeled on the type curves for the respective shut in time periods as seen on the pressure descending portion of the curve. The receiver well pressure response in the pulse interference test is overlain on the type curve and matched in response as shown on Figure 4. The receiver well pressure is plotted as pressure in psi versus time in minutes.

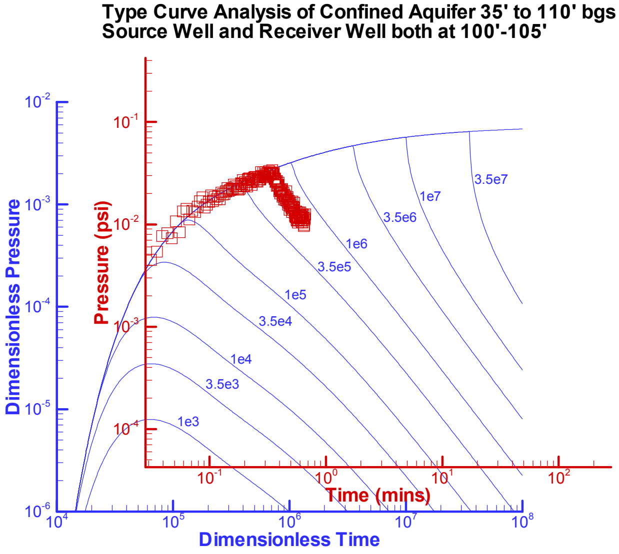

FIGURE 4. Type Curve Match for Hydraulic Pulse Interference Test.

The match point in pressure from Figure 4 is $\Delta p = 1\text{x}10^{-2}$ psi with $p_D = 7.6\text{x}10^{-4}$. Rearranging equation (3), the formation hydraulic conductivity is given by the following:

$$K = \frac{q p_D}{4 \pi r_w \Delta p} \tag{5}$$

yielding a formation hydraulic conductivity of 105 feet per day.

The match point in time from Figure 4 is t=1 min with $t_D = 2.04\text{x}10^{6}$. Rearranging equation (2), the formation specific storage is given by the following:

$$S_s = \frac{K t}{r_w^2 t_D} \tag{6}$$

yielding a formation specific storage of $5.2\text{x}10^{-6}$ 1/foot.

The receiver well response for the interpreted values of hydraulic conductivity of 105 feet per day and a specific storage of $5.2\text{x}10^{-6}$ 1/foot generated from equation (1) modified to incorporate the correct image conditions for the confined aquifer geometry is shown as predicted on Figure 5 along with the measured receiver well response. As can be seen from this figure the predicted or matched response is in close agreement with the recorded data. Non-linear regression analysis of the pulse test data yielded similar hydrogeological properties for the formation as quantified by the type curve analysis. The type curve analysis though is significantly less sensitive to noise in the receiver well response compared to the non-linear regression analysis method.

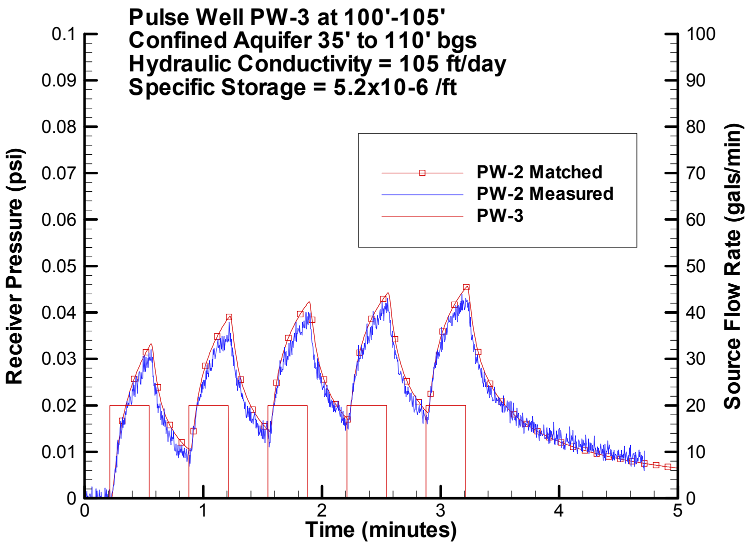

FIGURE 5. Predicted/Matched and Measured Receiver Well Response.

PULSE INTERFERENCE INTEGRITY TESTS

The hydraulic pulse interference test is an ideal test for the integrity testing of hydraulic containment systems such as cut off or slurry walls. The test can determined the extent and location of any holes or deficiencies in the wall's hydraulic containment and provided such integrity testing is carried out concurrent with wall construction can enable these deficiencies to be corrected immediately in the field. The pulse interference test requires monitoring wells installed on both sides of the wall; however, such monitoring wells are generally required as part of the verification and long term performance monitoring of the system.

Permeable reactive barrier systems are being installed as an alternative method to remediate contaminated groundwater. The most significant difference between a permeable reactive barrier and a containment system is the need to ensure the barrier's permeability does not impede or modify the groundwater flow regimes. The issues such as fines, smearing, filter cake clogging, etc. that benefit slurry wall systems as containment structures have major detrimental impacts on a PRB hydraulic performance. In general, such reductions in PRB permeability can not be retroactively removed and in certain construction techniques are difficult to avoid. Since any impediment to flow by a PRB system can have serious consequences to overall system performance, it is imperative to conduct hydraulic integrity testing of such a system to ensure it is constructed as planned.

Hydraulic pulse interference tests conducted across a barrier's alignment prior, during and after construction provide a simple means of quantifying the barrier's hydraulic characteristics and enable detailed quality assurance of the barrier during construction. An iron PRB was constructed within the confined aquifer system described earlier, from a depth of approximately 45 feet bgs down to a total depth of 110 feet bgs. The PRB was installed by the azimuth controlled vertical hydraulic fracturing technology and as a part of the quality assurance program on barrier hydraulic performance, pre and post construction pulse interference tests were conducted across the PRB alignment from pulse wells located 25 feet up and down gradient from the PRB. Pre and post PRB construction pulse interference test results are shown on Figure 6. The receiver well pressure response, amplitude, signature and time delay, shows no attenuation when comparing pre- and post- construction tests. These tests confirm that the PRB has an in placed hydraulic conductivity of at least that of the formation's highest conductive horizon. Since the hydraulic pulse interference test, utilizing pre and post test data is a high precision transient test, even minor impediments to flow by the PRB can be quantified.

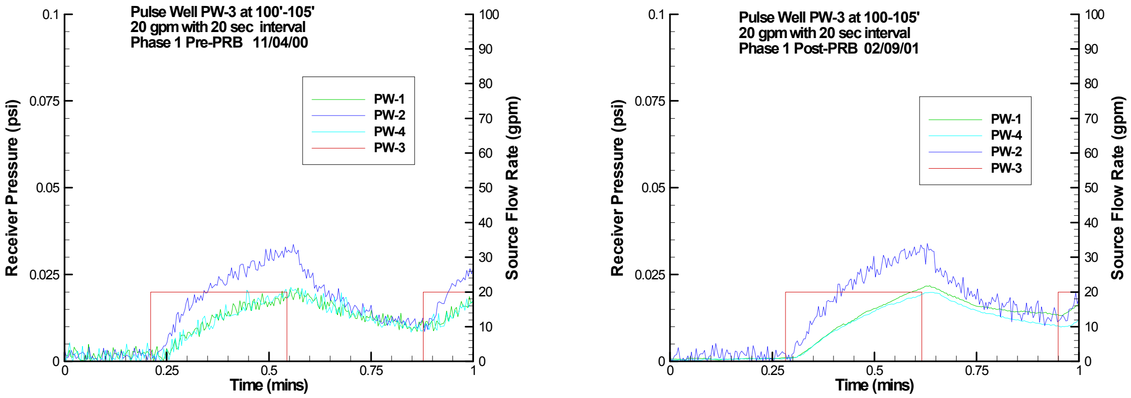

FIGURE 6. Pre and Post PRB Construction Pulse Interference Tests.

CONCLUSIONS

The hydraulic pulse interference test is an ideal test for the quantification of a site's hydrogeological properties. The pulse interference test is highly sensitive to hydrogeological properties between the pulse source and receiver wells. The transient nature of the test, involving the time delay and attenuation of the hydraulic pulse, enables the formation's complete hydraulic properties to be computed. The method is equally applicable to porous media and fractured bedrock systems. The advantages of the pulse interference test are the short duration of the test, the high resolution and directional characterization data obtained, and the lack of any generated contaminated groundwater during the test.

The pulse test has considerable merit as an integrity test for quantification of the hydraulic performance of containment and permeable reactive barrier systems. Considering the cost implications of poor performance of either a containment system, such as a slurry wall, or a permeable reactive barrier system, then using the pulse interference test as a quality assurance hydraulic test during construction can ensure the system is constructed as designed. Pre and post PRB construction pulse interference tests quantified that the azimuth controlled vertical hydraulic fracturing technology installed the PRB with an in placed permeability equivalent to or greater than the formation's highest hydraulic conductive horizon.

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